Design & Construction Optimization of Driven Precast/Prestressed Concrete Piles (PPC)

presentation to: NCDOT Geotechnical Engineering Unit
Geo3T2 2019 Conference (April 9, 2019)

by: David A. Tomley, P.E.
Senior Structural Engineer
Thompson Engineering (Mobile, AL)

Photo: Alabama Gulf State Park Pier (Orange Beach)
Design & Construction Optimization of Driven PPC Piles

Topics:
- Code Manuals & Select Published Literature
- Project Types & Procurement Methods
- Design Pile Loads
  - Working or Allowable (ASD)
  - Factored (LRFD)
- Pile Capacity
- Factors that influence the Design & Construction of Driven PPC Piles
- Factors that Influence Total Foundation Costs
- Foundation Cost Option Example
- Key Points
Code Manuals and Select Published Literature

- PCI’s Bridge Design Manual Chapter 20 publication number BM-20-04 “Precast Prestressed Concrete Piles”
- U.S. Department of Transportation Federal Highway Administration, Publication Nos.
  - FHWA/RD-83/059 “Allowable Stresses in Piles”
- ASTM STP 670 Behavior of Deep Foundations Symposium
- PCI Journal
- The Pile Driving Contractors Association’s (PDCA) PileDriver Magazine
- AASHTO LRFD Bridge Design Specifications
- AASHTO Standard Specifications for Highway Bridges
- International Building Code (IBC), Chapter 18-Soils and Foundations, Section 1810 Deep Foundations
- American Society of Civil Engineers (ASCE), “Standard Guidelines for the Design and Installation of Pile Foundations 20-96”
- American Society for Testing and Materials (ASTM)
Project Types & Procurement Methods

- **Project Types**
  - Bridges
  - Parking Structures
  - Marine Structures
  - Loading Docks
  - Bulkheads
  - Private vs. Public
    - Specifications

- **Procurement Methods**
  - Traditional (Design-Bid-Build)
  - Design-Build
  - A+B Contracting
  - Construction Manager/General Contractor (CM/GC)
  - Value Engineering Change Proposals (VECP)
    - Although not a specific type of procurement method; VECP allows for proposed modifications by the contractor after bid-award with either time or cost savings or both (for cost savings, the savings is split between the owner agency and the contractor)

Depending on the project type, specifications, and procurement methods; could dictate and/or influence the design & construction of PPC piles.
Although this presentation primarily focuses on PPC piles that are fully embedded in soils providing lateral support with primarily axial/compressive loads (AASHTO STD Spec. 4.5.7.3); (e.g., pile footings and pile end bents) the information can also be extended/applied to interior pile bents and/or other foundation types using PPC piles with axial/compressive, lateral, and/or moment loads.
Design Pile Loads

Working or Allowable (ASD)
- Allowable stress formula introduced in the 1970s
  \[ 0.33f’c – 0.27 \text{ fpe} \]
  Where: \( f’c \) is the concrete compressive strength of the pile and \( \text{fpe} \) is the effective prestress after losses in the pile
- IBC Section 1810.3.2.8 allows higher allowable stresses if a load test is performed in accordance with Section 1810.3.3.1.2 with reference to ASTM D1143 (Static) or ASTM D4945 (Dynamic) and a geotechnical investigation is performed in accordance with Section 1803

Factored (LRFD)
- Several State DOTs publish factored pile loads that appear to be derived from ASD allowable pile loads increased by a composite load factor
- Other State DOTs do not publish factored pile design loads
  “Transportation agencies that are taking advantage of modern design and construction control methods have reduced foundation costs while obtaining greater confidence in the safety and the service life of their structures.”
The various State DOTs have criteria for prestress losses and values for effective prestress.

Some State DOTs do not publish design pile loads:

- Per NCDOT Structure Design Manual, Chapter 7 Substructures, Pile Resistance; coordinate with Geotechnical Engineering Unit (GEU) to optimize the pile resistance vs. pile length and to develop the final Foundation Recommendations in accordance with the GEU’s LRFD Driven Pile Foundation Design Policy.

- MSDOT does not have published maximum pile capacities for LRFD as MSDOT considers the limits to be site specific and are based on the AASHTO compression limits with unsupported pile length, seismic conditions, etc. taken into account.

<table>
<thead>
<tr>
<th>Pile Size</th>
<th>Florida DOT</th>
<th>Mississippi DOT</th>
<th>Alabama DOT</th>
<th>Louisiana DOT</th>
<th>Texas DOT</th>
<th>Georgia DOT</th>
<th>NC DOT</th>
<th>Tennessee DOT</th>
<th>Arkansas DOT</th>
<th>SC DOT</th>
<th>PCI</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 sq</td>
<td>****</td>
<td>****</td>
<td>**</td>
<td>**</td>
<td>176</td>
<td>50</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>105</td>
</tr>
<tr>
<td>14 sq</td>
<td>200</td>
<td>45-48</td>
<td>60</td>
<td>90</td>
<td>55-85</td>
<td>60</td>
<td>237</td>
<td>50</td>
<td>75</td>
<td>40</td>
<td>143</td>
</tr>
<tr>
<td>16 sq</td>
<td>55-60</td>
<td>80</td>
<td>120</td>
<td>45-65</td>
<td>70-100</td>
<td>125</td>
<td>82</td>
<td>318</td>
<td>75</td>
<td>50</td>
<td>45</td>
</tr>
<tr>
<td>18 sq</td>
<td>* 152</td>
<td>300</td>
<td>100</td>
<td>150</td>
<td>50-75</td>
<td>75-115</td>
<td>175</td>
<td>95</td>
<td>410</td>
<td>50</td>
<td>236</td>
</tr>
<tr>
<td>20 sq</td>
<td>* 180</td>
<td>360</td>
<td>**</td>
<td>**</td>
<td>125</td>
<td>110</td>
<td>503</td>
<td>100</td>
<td>55</td>
<td></td>
<td>292</td>
</tr>
<tr>
<td>20 void</td>
<td>* 225</td>
<td>450</td>
<td>160</td>
<td>220</td>
<td>80-120</td>
<td>120-180</td>
<td>300</td>
<td>138</td>
<td>732</td>
<td>125</td>
<td>420</td>
</tr>
<tr>
<td>24 sq</td>
<td>* 303</td>
<td>600</td>
<td>190</td>
<td>310</td>
<td>130-195</td>
<td>200-300</td>
<td>180</td>
<td>1112</td>
<td></td>
<td></td>
<td>291</td>
</tr>
<tr>
<td>24 void</td>
<td>* **</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td></td>
<td>405</td>
</tr>
<tr>
<td>30 sq</td>
<td>* **</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td></td>
<td>528</td>
</tr>
<tr>
<td>36 sq</td>
<td>250</td>
<td>410</td>
<td>260-400</td>
<td>220</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>36 void</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td></td>
<td>**</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* assuming 1.5 load factor and 0.75 resistance factor
** DOT STD DWG includes these piles but the Bridge Design Manual does not provide allowable pile design loads
*** DOT prestressed pile details include these piles but the Bridge Design Manual does not provide allowable pile design loads
**** DOT square prestressed concrete pile details include these piles but the Structures Manual does not provide allowable pile design loads

Note: Design Pile Loads in Tons

Load Factor = 1.5
Resistance Factor = 0.75
What information is considered in determining the pile geotechnical capacity?

1. Pile Type & Size
2. Design Considerations & Geotechnical Resistance Factors for Driven Piles
   1. Loads (lateral, axial compression, axial tension, uni-axial moment, bi-axial moment)
   2. Limit States (strength, extreme, service) & Analysis and Method of Determination
3. Drivability Analysis
4. Pile Testing Control Methods (static & dynamic)
5. Pile Capacity Curves (include factor of safety)
6. Minimum pile spacing (if pile group bearing resistance is applicable)
7. Tip Elevations
   1. Estimated
   2. Minimum (e.g., scour considerations)

Construction Control Methods

- AASHTO Standard Specification Table 4.5.6.2A
  Depending on the specific construction control, the factor of safety on the Ultimate Geotechnical Capacity will vary between 1.90 to 3.50
  - Subsurface exploration
  - Static calculation
  - Dynamic formula
  - Wave equation
  - Dynamic measurement and analysis
  - Static load test

- AASHTO LRFD Bridge Design Specifications Table 10.5.5.2.3-1 provides resistance factors for each condition/resistance determination method. Factored loads according to LRFD Section 3. A safety index ($\beta$), analogous to the AASHTO Standard factor of safety, is the ratio between the various combinations of load factors and resistance factors. What types of field validation/controls/testing is allowed per scope of work and project specifications?
Utilizing 12” PPC for Short-Span Bridges
Pile Capacity Curve (ASD & LRFD)

Square Precast Concrete Pile Capacity Curve

Pipe Tip Elevation, Feet

Compressive Capacity, Tons

Compressive Safety Index = 1.45/0.7 = 2.07

80(1.45) = 116

Note the same pile tip elevation -21 ft using LRFD factored resistance (for same working load) compared to the ASD compressive capacity using a FS = 2.07.
Factors that influence the Design & Construction of Driven PPC Piles

- Geotechnical Capacity
- Structural Capacity
- Pile Driving Stresses
  - Hammer Types & Energy
  - Pile Cushion Thickness
- Pile Length
- Handling and Transportation
- Normal vs. Severe Corrosive Environments
- Construction Control Methods
- Site Selection & Contractor Access

- Concrete strength
- Number of strands (i.e., effective prestressing)
- Reinforcing
  - Lateral
  - Longitudinal
- Cost
- PPC Pile Production Capabilities & Scheduling
Maximum pile lengths that can be transported to the project site (by truck) along with contractor site access and handling should be considered.

- Longer design pile lengths will require a splice

### Table: Maximum Pile Lengths (transported by truck)

<table>
<thead>
<tr>
<th>PPC Pile Size</th>
<th>Approximate Maximum Pile Length (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 square</td>
<td>76</td>
</tr>
<tr>
<td>14 square</td>
<td>94</td>
</tr>
<tr>
<td>16 square</td>
<td>96</td>
</tr>
<tr>
<td>18 square</td>
<td>103</td>
</tr>
<tr>
<td>20 square</td>
<td>115</td>
</tr>
<tr>
<td>24 square</td>
<td>123</td>
</tr>
<tr>
<td>24 void</td>
<td>131</td>
</tr>
<tr>
<td>30 square</td>
<td>153</td>
</tr>
<tr>
<td>36 square</td>
<td>171</td>
</tr>
</tbody>
</table>

Photo provided by Gulf Coast Pre-Stress (Pass Christian, MS)
Site Selection & Contractor Access
Site Selection and Contractor access is site-specific and can influence the total foundation cost. In addition to pile testing and/or construction control methods, labor & equipment, materials; site selection & contractor access must be evaluated.

1. The upper pie chart depicts a project location that is not influenced as much by site selection & contractor access.
2. The lower pie chart depicts a project location that has greater amount of influence of site selection & contractor access.
What happens if we add 4 more strand to a pile section and keep the same $f''c$?

1. Allowable driving tensile stress increases due to the adding compression from the additional strands

2. Allowable pile load and allowable driving compressive stress decrease slightly
Increase Concrete Strength ($f'c$)

What happens if we keep the same number strands and increase $f'c$?

1. allowable driving compressive stress and allowable pile load increase
2. allowable driving tensile stress increases slightly
What happens if we add 4 more strand to a pile section and increase $f'c$?

1. Allowable driving compressive stress increases
2. Allowable pile load increases
3. Allowable driving tensile stress increases slightly
Maximum Allowable Pile Service Loads (16” PPC)
AASHTO Standard Bridge Design Specs (4.5.7.3)

Note: The following calculations are based on AASHTO STD BDS section 4.5.7.3 for prestressed concrete piles fully embedded in soils providing lateral support, using $0.33f'c - 0.27fpe$ on the gross cross-sectional area of the concrete.

5 ksi and 8 strands (16” PPC, Area = 254 in2) for $fpe = 781$ psi

\[ Q_{\text{max}} = [0.33(5000 \text{ psi}) - 0.27(781 \text{ psi})] \times (254 \text{ in}^2)/2000 = 183 \text{ tons} \]

6 ksi and 12 strands (16” PPC, Area = 254 in2) for $fpe = 1171$ psi

\[ Q_{\text{max}} = [0.33(6000 \text{ psi}) - 0.27(1171 \text{ psi})] \times (254 \text{ in}^2)/2000 = 211 \text{ tons} \]

Conclusion:
For 16” PPC pile, maximum allowable pile service load ($Q_{\text{max}}$) increases by 15.3% by increasing $f'c$ from 5 ksi to 6 ksi and adding 4 additional strands (12 strands total). 

where: $fpe$ = effective prestress
Allowable Driving Stresses (16” PPC)  
AASHTO Standard Bridge Design Specs (4.5.11)

5 ksi and 8 strands  
\[ fpe = (8 \text{ strands})(202.5-40.5 \text{ ksi})(0.153 \text{ in}^2)/(254 \text{ in}^2) = 0.781 \text{ksi} \]
\[ C = 0.85f’c - fpe = 0.85(5 \text{ ksi}) - 0.781 \text{ ksi} = 3.469 \text{ ksi} \]
\[ T = 3\sqrt{f’c} + fpe = \frac{3\sqrt{5000 \text{ psi}} + 0.781 \text{ ksi}}{1000} = 0.993 \text{ ksi} \]

6 ksi and 12 strands  
\[ fpe = (12 \text{ strands})(202.5-40.5 \text{ ksi})(0.153 \text{ in}^2)/(254 \text{ in}^2) = 1.171 \text{ksi} \]
\[ C = 0.85f’c - fpe = 0.85(6 \text{ ksi}) - 1.171 \text{ ksi} = 3.929 \text{ ksi} \]
\[ T = 3\sqrt{f’c} + fpe = \frac{3\sqrt{6000 \text{ psi}} + 1.171 \text{ ksi}}{1000} = 1.403 \text{ ksi} \]

Conclusion:  
For 16” PPC pile, allowable driving stresses increase by 13.3% and 41.3% for compression and tension respectively by increasing f’c from 5 ksi to 6 ksi and adding 4 additional strands (12 strands total)
Axial-Moment (P-M) Interaction Diagrams can be generated for various combinations of concrete strengths and number of strands to facilitate pile design/foundation options.
## Proposed Number of Strands & Concrete Strength (f’c)

<table>
<thead>
<tr>
<th>PPC pile size</th>
<th>Florida DOT</th>
<th>MS DOT</th>
<th>AL DOT</th>
<th>LA DOT</th>
<th>TX DOT</th>
<th>GA DOT</th>
<th>NC DOT</th>
<th>TN DOT</th>
<th>AR DOT</th>
<th>SC DOT</th>
<th>PCI</th>
<th>proposed</th>
<th>maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>4, 8, 12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8</td>
<td>4, 5</td>
<td></td>
<td></td>
<td></td>
<td>5</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>14</td>
<td>8, 12, 16</td>
<td>6-8</td>
<td>8</td>
<td>8</td>
<td>12</td>
<td>6-14</td>
<td>6-10</td>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>16</td>
<td>7-8</td>
<td>8</td>
<td>12</td>
<td>8</td>
<td>12</td>
<td>8</td>
<td>8-16</td>
<td>7-13</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>12</td>
<td>16</td>
</tr>
<tr>
<td>18</td>
<td>12, 16, 20, 24</td>
<td>9-12</td>
<td>12</td>
<td>12</td>
<td>10</td>
<td>12</td>
<td>10-22</td>
<td>9-16</td>
<td>7, 8, 9</td>
<td>10</td>
<td>16</td>
<td>16</td>
<td>20</td>
</tr>
<tr>
<td>20</td>
<td>12, 16, 20, 24</td>
<td>11-12</td>
<td>16</td>
<td>16</td>
<td>14</td>
<td>16</td>
<td>12</td>
<td>11-20</td>
<td>9, 10, 11</td>
<td>12</td>
<td>20</td>
<td>20</td>
<td>24</td>
</tr>
<tr>
<td>20 void</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>16, 20, 24</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>24</td>
<td>18</td>
<td>16</td>
<td>16-28</td>
<td>18</td>
<td>28</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>24 void</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>16</td>
<td>16</td>
<td>20</td>
<td>20</td>
<td>12</td>
<td>24</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>20, 24, 28</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20</td>
<td>17</td>
<td>28</td>
<td>32</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>30 void</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>22</td>
<td>36</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>28</td>
<td>32</td>
<td>36</td>
<td>36</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>40</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>36 void</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>22</td>
<td>36</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>f’c (ksi)</td>
<td>6 &amp; 8.5</td>
<td>5</td>
<td>5</td>
<td>6</td>
<td>5</td>
<td>5</td>
<td>7.5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5 to 8.5</td>
<td>10</td>
</tr>
<tr>
<td>f’ci (ksi)</td>
<td>4 &amp; 6.5</td>
<td>4</td>
<td>4.5</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>3.5</td>
<td>3.5</td>
<td>4 &amp; 6.5</td>
<td>6.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>size strand</td>
<td>3/8, 1/2, 7/16, 9/16, 0.6</td>
<td>1/2</td>
<td>1/2</td>
<td>1/2</td>
<td>1/2</td>
<td>7/16</td>
<td>1/2, 0.6</td>
<td>3/8, 7/16, 1/2</td>
<td>7/16, 1/2</td>
<td>1/2, 9/16, 0.6</td>
<td>1/2</td>
<td>1/2</td>
<td>1/2</td>
</tr>
</tbody>
</table>

Depending on Precast/Prestressed Concrete PPC Pile Manufactures capabilities specific to concrete strengths (at release and 28-days) and bed capacity; recommend investigating several options related to concrete strength in combination with number of strands to optimize the design pile load used in tandem with pile/foundation options

(e.g., 4 & 6 ksi, 5 & 7 ksi, 6 & 8 ksi for release & 28-day concrete strengths)
Overall Foundation Costs
(Using Increased Design Pile Loads)

Bridge Design Example:
2-spans at 120-120 ft.
3 column pier
48 ft. gutter-gutter width
7-PCI BT-63” girders

Images taken from Bentley Systems, Inc.
LEAP Bridge Concrete Connect Edition
### Overall Foundation Costs
(Using Increased Design Pile Loads)

<table>
<thead>
<tr>
<th>Option</th>
<th>Method</th>
<th>Size</th>
<th>Design PPC Pile</th>
<th>Design Pile Load</th>
<th>No. of Footings</th>
<th>Total No. of Piles</th>
<th>Pile Length (ft)</th>
<th>Total Pile Price (per ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LRFD</td>
<td>16&quot;</td>
<td>116</td>
<td>120</td>
<td>3</td>
<td>9</td>
<td>80</td>
<td>$110</td>
</tr>
<tr>
<td>2</td>
<td>LRFD</td>
<td>14&quot;</td>
<td>136</td>
<td>125 to 175</td>
<td>3</td>
<td>9</td>
<td>90</td>
<td>$95</td>
</tr>
<tr>
<td>3</td>
<td>LRFD</td>
<td>16&quot;</td>
<td>179</td>
<td>150 to 250</td>
<td>3</td>
<td>7</td>
<td>95</td>
<td>$114</td>
</tr>
<tr>
<td>4</td>
<td>LRFD</td>
<td>12&quot;</td>
<td>136</td>
<td>100 to 250</td>
<td>3</td>
<td>9</td>
<td>100</td>
<td>$82</td>
</tr>
<tr>
<td>5</td>
<td>LRFD</td>
<td>12&quot;</td>
<td>179</td>
<td>100 to 250</td>
<td>3</td>
<td>7</td>
<td>105</td>
<td>$90</td>
</tr>
<tr>
<td>6</td>
<td>LRFD</td>
<td>18&quot;</td>
<td>261</td>
<td>200 to 375</td>
<td>3</td>
<td>5</td>
<td>110</td>
<td>$130</td>
</tr>
<tr>
<td>7</td>
<td>LRFD</td>
<td>20&quot;</td>
<td>261</td>
<td>250 to 475</td>
<td>3</td>
<td>5</td>
<td>115</td>
<td>$150</td>
</tr>
</tbody>
</table>

Option 1 - LRFD design using current maximum factored design pile loads
Option 2 - using same number of piles as current LRFD design and smaller pile size
Option 3 - using same pile size as current LRFD design and less number of piles
Option 4 - using same number of piles as current LRFD design and smaller pile size
Option 5 - using smaller pile size as current LRFD design and less number of piles
Option 6 - using less number of piles as current LRFD design and larger pile size
Option 7 - using less number of piles as current LRFD design and larger pile size
Overall Foundation Costs  
(Using Increased Design Pile Loads)

<table>
<thead>
<tr>
<th>Option</th>
<th>Cost</th>
<th>Pile Width</th>
<th>Footing Length</th>
<th>Footing Thickness</th>
<th>Total Footing Volume</th>
<th>Reinforcing Price</th>
<th>Reinforcing (per cy)</th>
<th>Reinforcing (per lbs)</th>
<th>Footing Cost</th>
<th>Footing and Pile Cost</th>
<th>Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$237,600</td>
<td>10.67</td>
<td>10.67</td>
<td>4.00</td>
<td>50.6</td>
<td>12642</td>
<td>$600</td>
<td>$1.00</td>
<td>$42,983</td>
<td>$280,583</td>
<td>n/a</td>
</tr>
<tr>
<td>2</td>
<td>$230,850</td>
<td>9.67</td>
<td>9.67</td>
<td>4.25</td>
<td>44.1</td>
<td>11032</td>
<td>$600</td>
<td>$1.00</td>
<td>$37,508</td>
<td>$268,358</td>
<td>$12,225</td>
</tr>
<tr>
<td>3</td>
<td>$228,228</td>
<td>10.67</td>
<td>10.67</td>
<td>4.50</td>
<td>56.9</td>
<td>15644</td>
<td>$600</td>
<td>$1.00</td>
<td>$49,778</td>
<td>$278,006</td>
<td>$2,577</td>
</tr>
<tr>
<td>4</td>
<td>$221,400</td>
<td>9.67</td>
<td>9.67</td>
<td>4.25</td>
<td>44.1</td>
<td>11032</td>
<td>$600</td>
<td>$1.00</td>
<td>$37,508</td>
<td>$258,908</td>
<td>$21,675</td>
</tr>
<tr>
<td>5</td>
<td>$198,891</td>
<td>10.67</td>
<td>10.67</td>
<td>4.50</td>
<td>56.9</td>
<td>15644</td>
<td>$600</td>
<td>$1.00</td>
<td>$49,778</td>
<td>$248,669</td>
<td>$31,914</td>
</tr>
<tr>
<td>6</td>
<td>$214,500</td>
<td>8.50</td>
<td>8.50</td>
<td>5.00</td>
<td>40.1</td>
<td>12042</td>
<td>$600</td>
<td>$1.00</td>
<td>$36,125</td>
<td>$250,625</td>
<td>$29,958</td>
</tr>
<tr>
<td>7</td>
<td>$258,750</td>
<td>8.50</td>
<td>8.50</td>
<td>5.00</td>
<td>40.1</td>
<td>12042</td>
<td>$600</td>
<td>$1.00</td>
<td>$36,125</td>
<td>$294,875</td>
<td>-$14,292</td>
</tr>
</tbody>
</table>

Option 1 - LRFD design using current maximum factored design pile loads  
Option 2 - using same number of piles as current LRFD design and smaller pile size  
Option 3 - using same pile size as current LRFD design and less number of piles  
Option 4 - using same number of piles as current LRFD design and smaller pile size  
Option 5 - using smaller pile size as current LRFD design and less number of piles  
Option 6 - using less number of piles as current LRFD design and larger pile size  
Option 7 - using less number of piles as current LRFD design and larger pile size
Conclusions:
Compared to current factored design pile loads, total foundation cost savings are realized by utilizing increased factored design pile loads that result in:
1. Smaller size piles with same number of piles and/or
2. Less number of piles using same size piles
3. Smaller or larger size piles and less number of piles

Other factors that can influence Overall Foundation Costs:
- Pile lengths
- Handling & driving
- Site Selection & Contractor access
- Geotechnical capacity
Benefits: Optimizing the design and construction of driven PPC piles

1. Increasing f’c and # strands will:
   - Increase the allowable pile design load (i.e., working load) & factored (LRFD) pile design load
   - Increase the allowable pile driving stresses
   - Enhance the performance of PPC piles during handling and transportation
   - Provide solutions in corrosive environments

2. Increasing the allowable pile design load compared to past ASD specified values can lead to cost savings and reduce overall bridge foundation costs
Key Points: Optimizing the design and construction of driven PPC piles

- Understanding driving stresses can lead to improved performance during pile driving
- Utilizing construction control methods to confirm and/or validate the geotechnical capacity
- Investigate utilizing pile group factor of safety’s considering all load combinations rather than using only the maximum pile reaction
- Use a range of factors of safety’s (1.5-2.5) considering all combinations of load effects together with geotechnical capacities rather than a single value
- IBC permits the use of higher allowable pile design loads where supporting data justifies higher stresses
- Consider zero tension during pile handling and transportation to enhance the performance of PPC piles
Key Points: Optimizing the design and construction of driven PPC piles

- Use the allowable stress formula to provide a lower-bound for the design service load (i.e., working load); use lower-bound working load values as a starting point in the design process.

- **Close collaboration between the Geotechnical Engineer and the Structural Engineer**

- Procedurally; first utilize the geotechnical capacity/pile capacity curves, then verify the structural design/capacity, then check handling, transportation, driving stresses, and consider influence of site selection & contractor access.

- Perform overall foundation cost analysis that includes all costs in order to gain insight to the most cost effective design and construction solution; keeping in mind that not all projects and soils are the same and the magnitude of design & construction optimization can vary depending on the project size & project location.

- Consider lower and upper limits for strand patterns and concrete compressive strengths
  - Confirm production capabilities of PPC Pile Manufacturers

- Consider using 12” PPC for short-span bridges. The Precast/Prestressed Concrete (PCI) Industry has produced thousands of lin. ft. of 12” PPC piles with lengths varying from 40 to 90 ft.

- Generate Axial-Moment (P-M) interaction curves for various pile sizes, available number of strand (and/or size of strand), and concrete strength (f’c) ranges/values.

- Create summary tables for each pile size and combination of number of strands and f’c that includes effective prestress, allowable driving stresses, and design pile loads.
“The road to success is always under construction.”