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

Photo: Alabama Gulf State Park Pier (Orange Beach)

presentation to: NCDOT Geotechnical Engineering Unit
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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 NHI-05-042 "Design and Construction of Driven Pile Foundations"
  - 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

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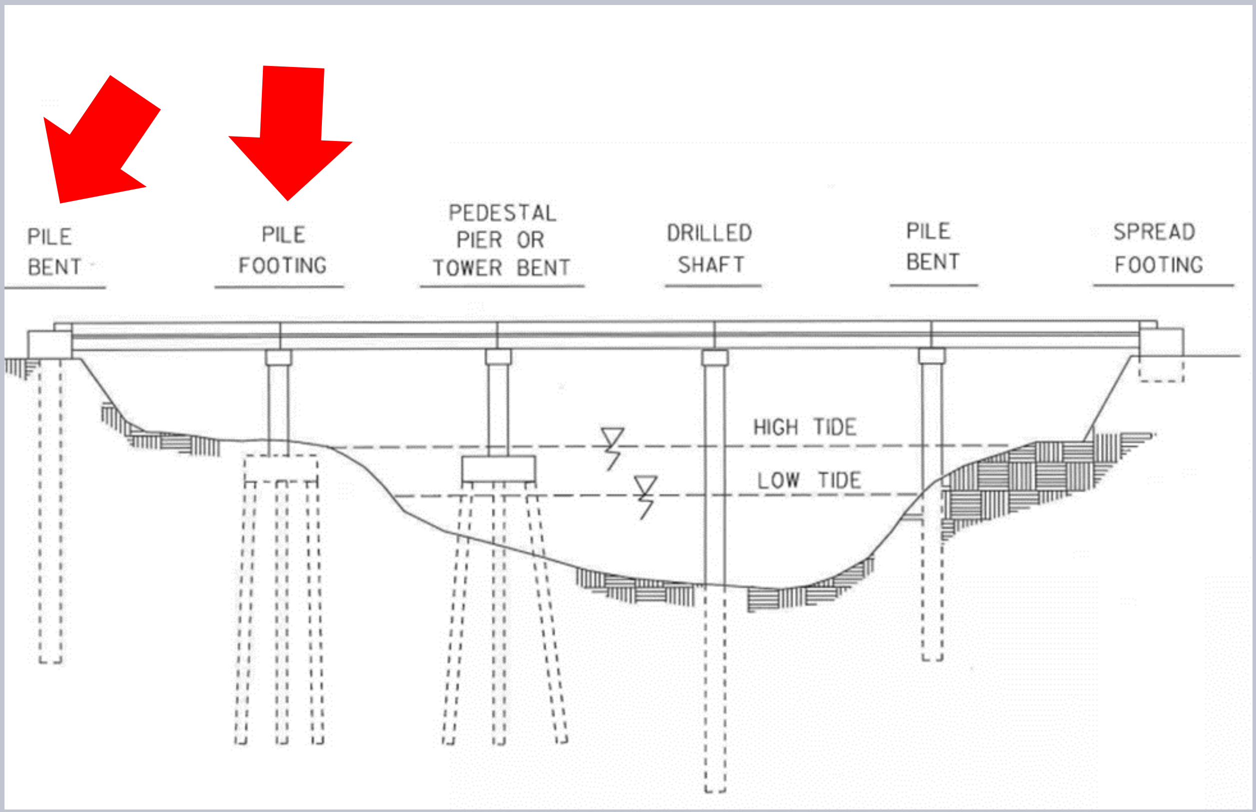
Bridge Foundation Types



Bridge Foundation Types (taken from Georgia DOT Bridge Foundation Types 3.4.5, Bridge Foundation Investigation (BFI) Guidelines

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.

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Design Pile Loads

Working or Allowable (ASD)

- Allowable stress formula introduced in the 1970s

  0.33f'c – 0.27 fpe

  Where: f'c is the concrete compressive strength of the pile and 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
- As stated in FHWA NHI-05-042's Publication "Design and Construction of Driven Pile Foundations" Section 3.2 – Examples of Cost Savings by Utilizing Modern Design and Construction Control Practices

  "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."

Design Pile Loads
(State DOT scan as of March, 2019)

	Florida DOT		Mississippi DOT		Alabama DOT		Louisiana DOT		Texas DOT		Georgia DOT		NC DOT		Tennessee DOT		Arkansas DOT		SC DOT		PCI	
Pile Size	ASD	LRFD	ASD	LRFD	ASD	LRFD	ASD	LRFD	ASD	LRFD	ASD	LRFD	ASD	LRFD	ASD	LRFD	ASD	LRFD	ASD	LRFD	ASD	LRFD
12 sq	****	****										176	50								105	
14 sq	****	200	45-48		60	90	35-55	55-85			60	237			50	75	40				143	
16 sq			55-60		80	120	45-65	70-100	125		82	318	75		50	75	45				187	
18 sq	* 152	300	70-75		100	150	50-75	75-115	175		95	410			50	75	50				236	
20 sq	* 180	360	***		120	180			225		110	503	100				55				292	
20 void																					222	
24 sq	* 225	450			160	220	80-120	120-180	300		138	732	125				75				420	
24 void			***		**	**						579									291	
30 sq	* 303	600			190	310	130-195	200-300			180	1112										
30 void			***		**	**						853									405	
36 sq					250	410		260-400			220											
36 void			***		**	**															528	

* 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

Load Factor = 1.5

Resistance Factor = 0.75

Note: Design Pile Loads in Tons

- 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

Pile Capacity

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 (β), 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?

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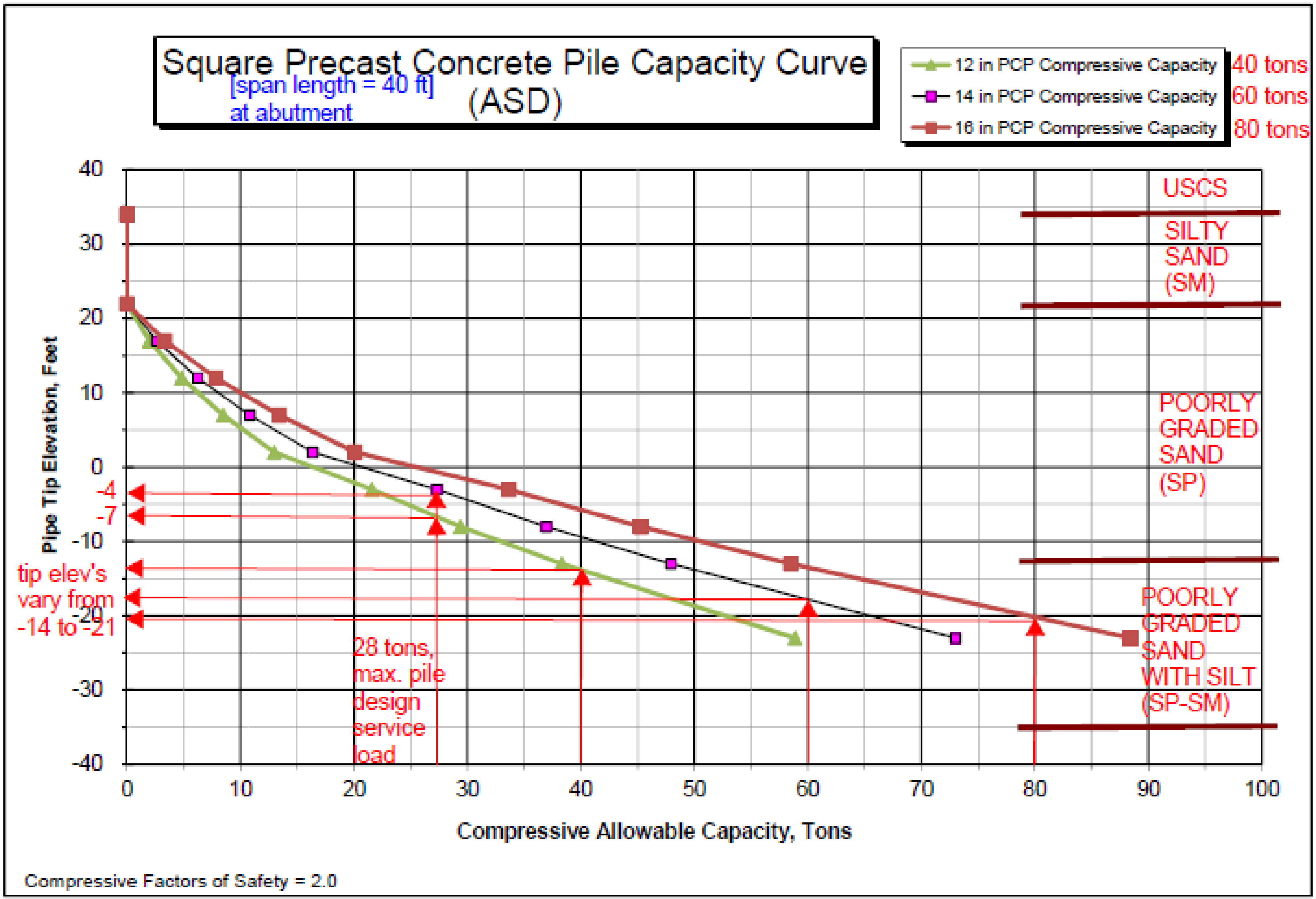
Utilizing 12" PPC for Short-Span Bridges



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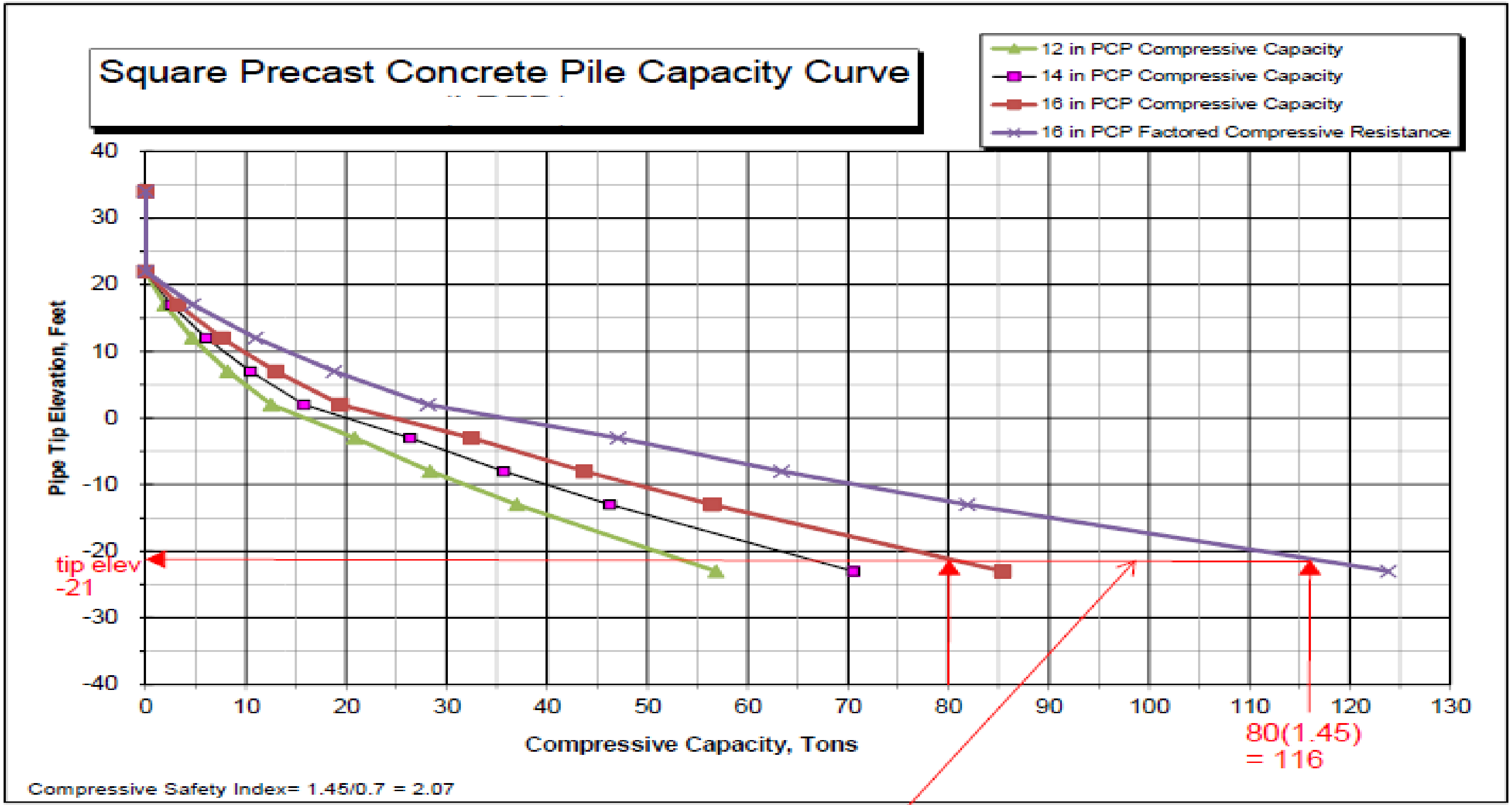
Pile Capacity Curve (ASD & LRFD)



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 (transported by truck)

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

Photo provided by Gulf Coast Pre-Stress (Pass Christian, MS)

PPC Pile Size	Approximate Maximum Pile Length (ft)
12 square	76
14 square	94
16 square	96
18 square	103
20 square	115
24 square	123
24 void	131
30 square	153
36 square	171

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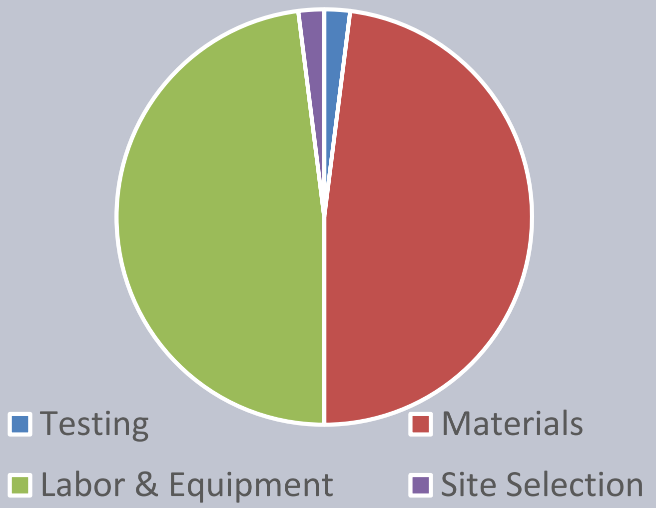
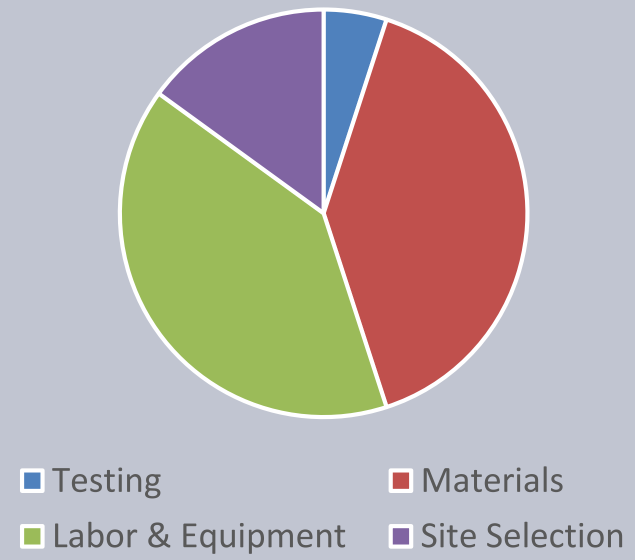
Site Selection & Contractor Access

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





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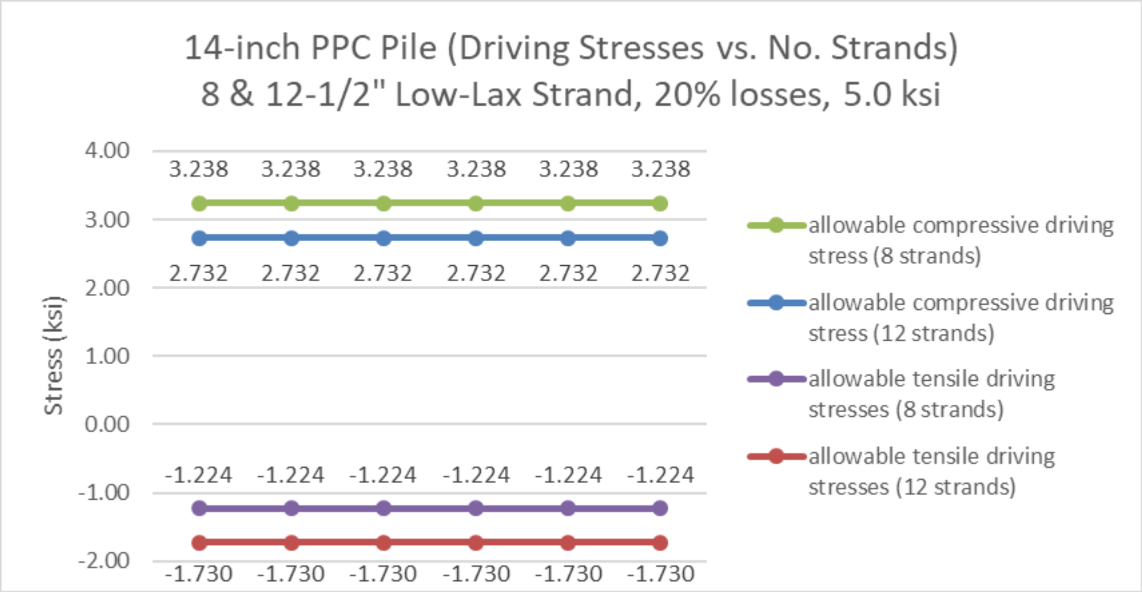
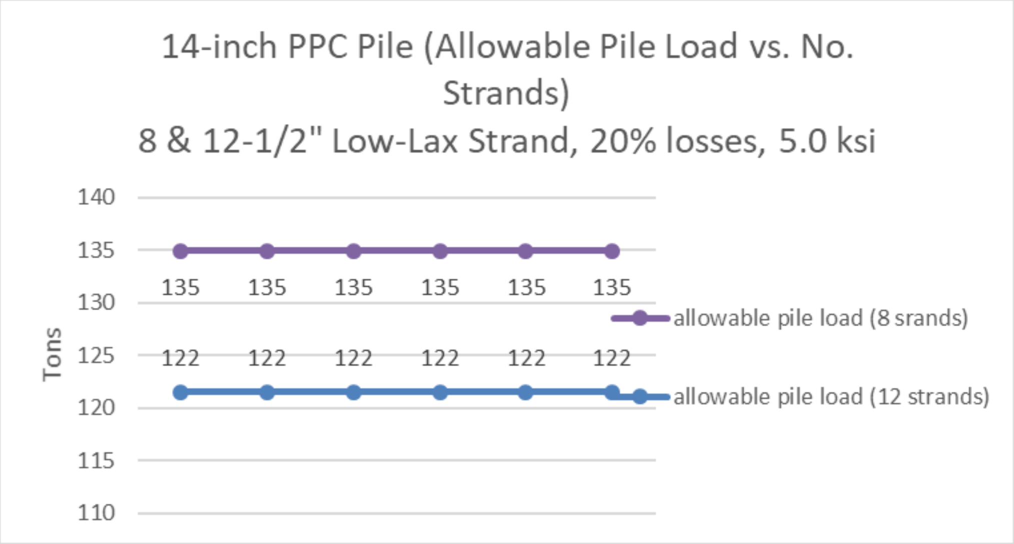
Increase No. Strands

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





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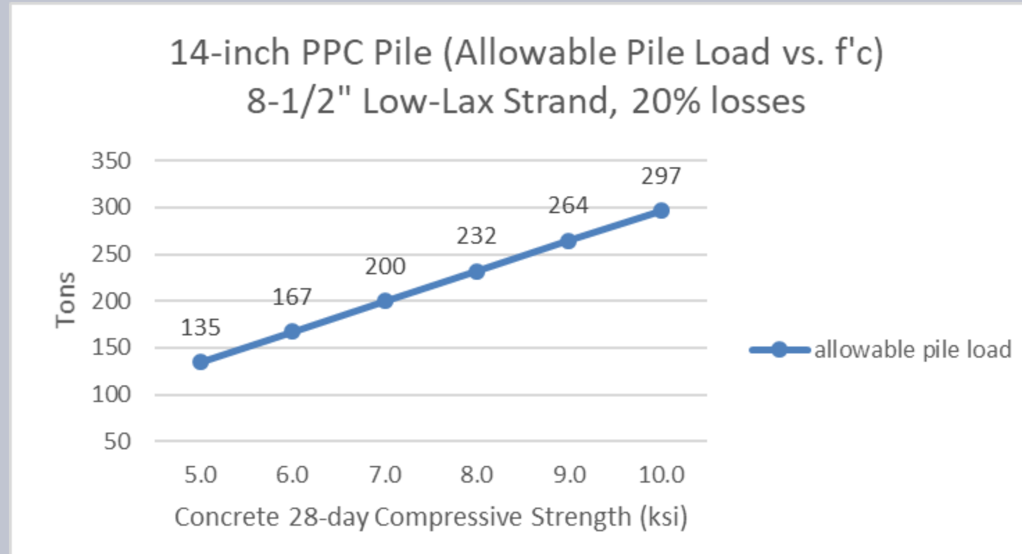
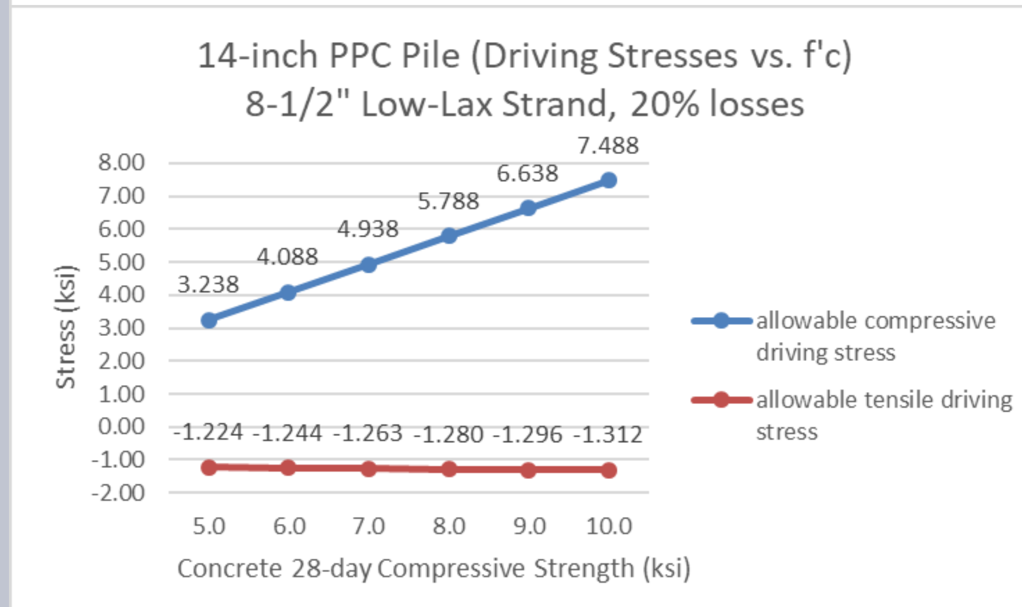
Increase Concrete Strength (f’c)

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





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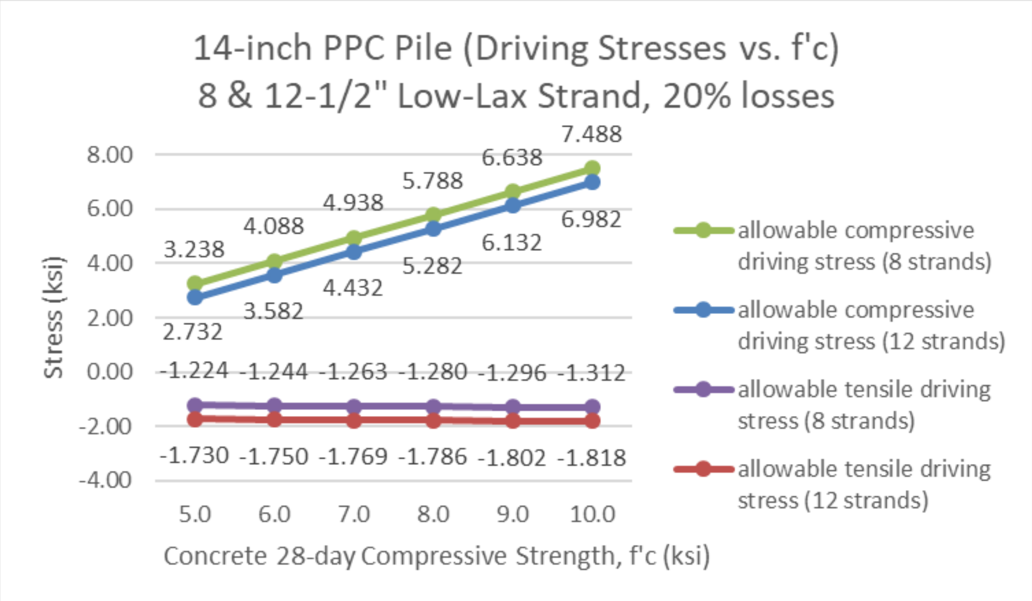
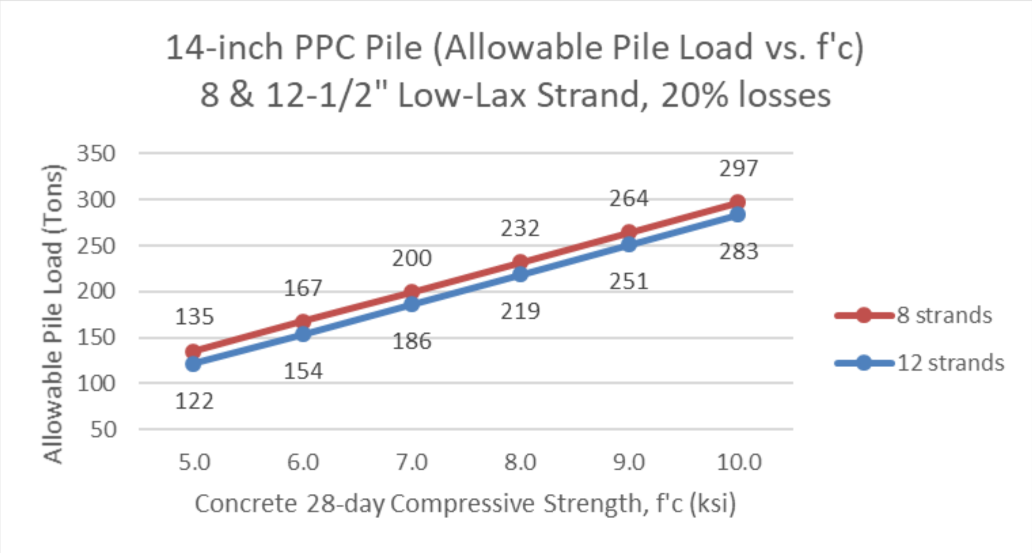
Increase No. Strands & Concrete Strength (f'c)

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





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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.

where: fpe = effective prestress

5 ksi and 8 strands (16” PPC, Area = 254 in2)

for fpe = 781 psi

Qmax = [0.33(5000 psi)-0.27(781 psi)] x (254 in2)/2000 = 183 tons

6 ksi and 12 strands (16” PPC, Area = 254 in2)

for fpe = 1171 psi

Qmax = [0.33(6000 psi)-0.27(1171 psi)] x (254 in2)/2000 = 211 tons

Conclusion:

For 16” PPC pile, maximum allowable pile service load (Qmax) increases by 15.3% by increasing f’c from 5 ksi to 6 ksi and adding 4 additional strands (12 strands total)

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Allowable Driving Stresses (16” PPC)
AASHTO Standard Bridge Design Specs (4.5.11)

Should final losses be applied during pile driving? If not effective prestress will increase resulting in an increase in the allowable tension pile driving stress by approx. 5% but will decrease the allowable compression pile driving stress by approx. 1%

5 ksi and 8 strands

fpe = (8 strands)(202.5-40.5 ksi)(0.153 in2)/(254 in2) = 0.781 ksi

C = 0.85f’c – fpe = 0.85(5 ksi) – 0.781 ksi = 3.469 ksi

T = 3sqrt(f’c) + fpe = $\frac{3\text{sqrt}(5000\text{ psi})}{1000}$ + 0.781 ksi = 0.993 ksi

Should final design or actual concrete strength be used to compute the allowable tension pile driving stress? Actual concrete strengths (20-30% increase 6-6.5 ksi) will increase the allowable tension pile driving stress by approx. 2-3%

6 ksi and 12 strands

fpe = (12 strands)(202.5-40.5 ksi)(0.153 in2)/(254 in2) = 1.171 ksi

C = 0.85f’c – fpe = 0.85(6 ksi) – 1.171 ksi = 3.929 ksi

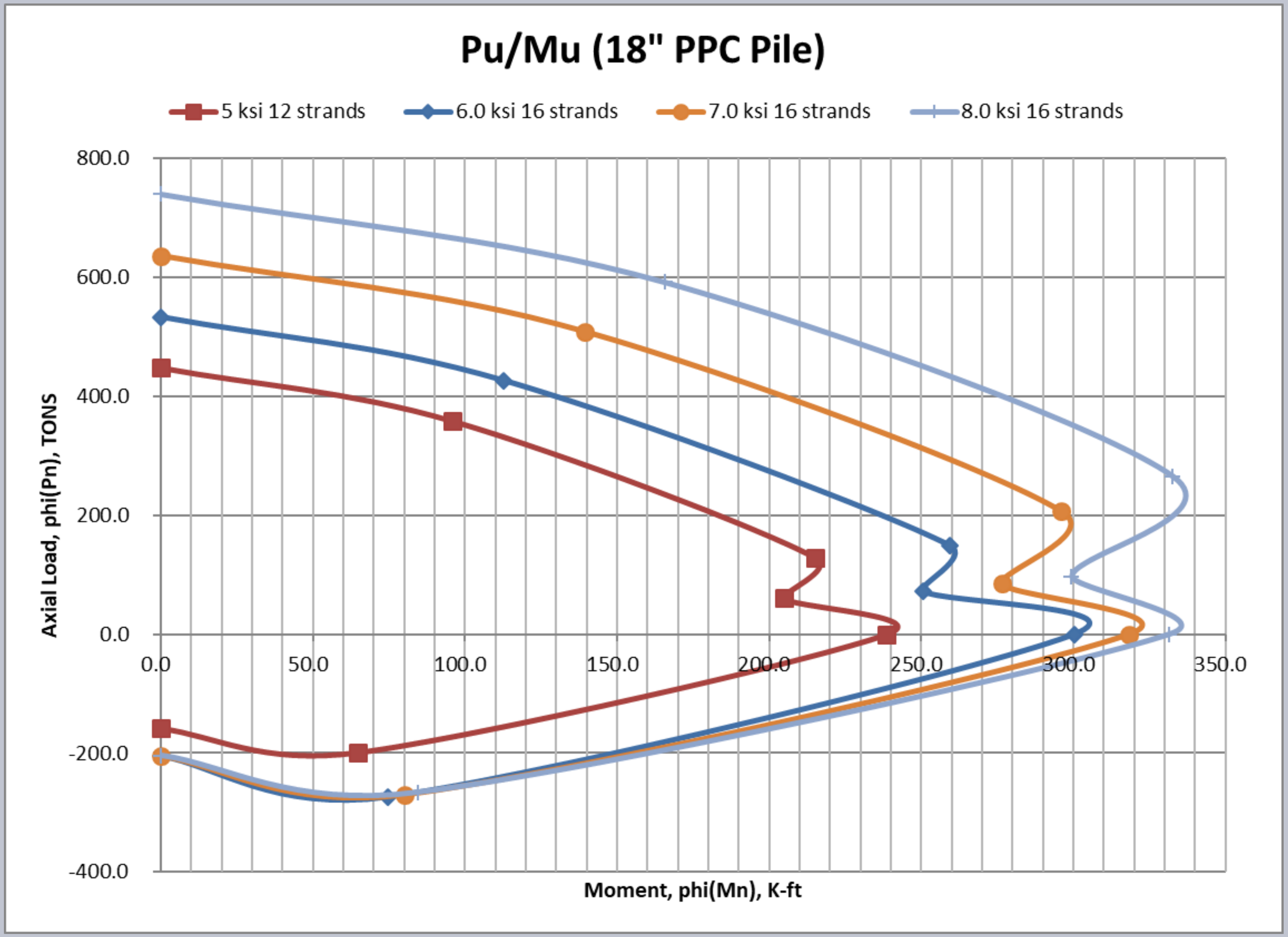
T = 3sqrt(f’c) + fpe = $\frac{3\text{sqrt}(6000\text{ psi})}{1000}$ + 1.171 ksi = 1.403 ksi

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 Diagram

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



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Proposed Number of Strands & Concrete Strength (f'c)

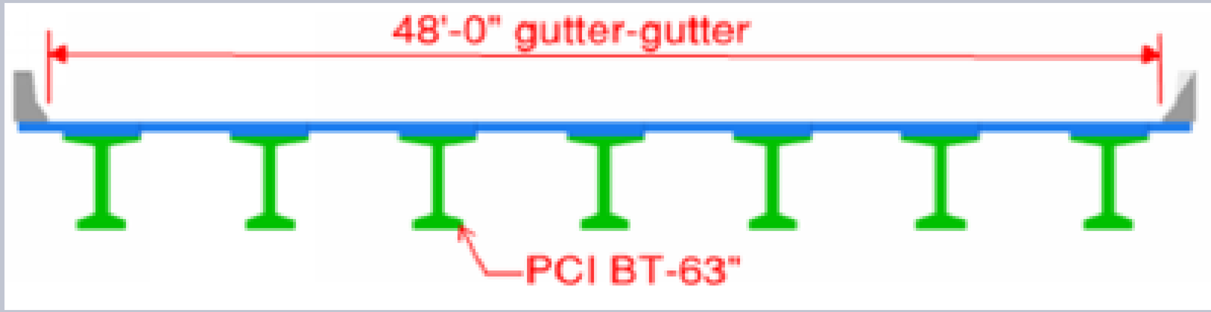
	number of strands												
PPC pile size	Florida DOT	MS DOT	AL DOT	LA DOT	TX DOT	GA DOT	NC DOT	TN DOT	AR DOT	SC DOT	PCI	proposed	maximum
12	4, 8, 12			4		8	4, 5				5	8	8
14	8, 12, 16	6-8	8	8		12		6-14	6-10		6	12	12
16		7-8	8	12	8	12	8	8-16	7-13		8	12	16
18	12, 16, 20, 24	9-12	12	12	10	12		10-22	9-16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

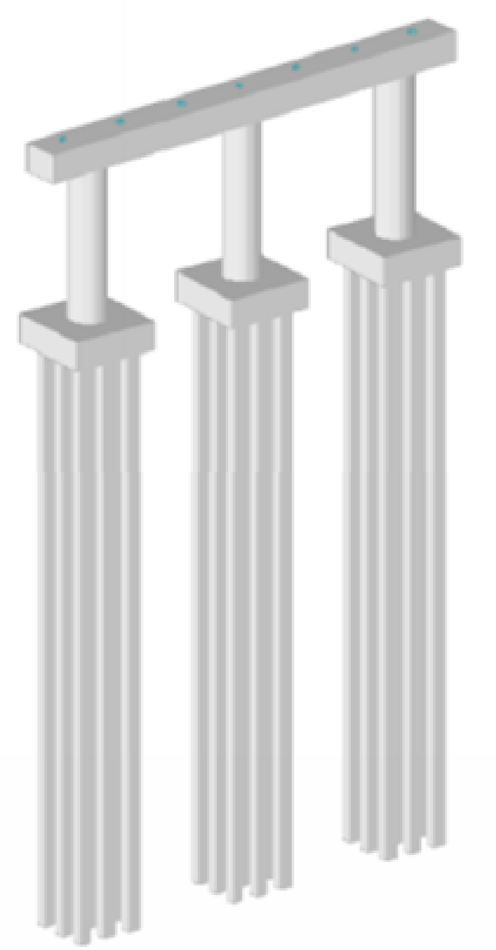
Depending on Precast/Prestressed Concrete PPC Pile Manufactures capabilities specific to concrete strengths (at release and 28-days) and bed capacity; recommend investigating several options related to concrete strength in combination with number of strands to optimize the design pile load used in tandem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

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Overall Foundation Costs (Using Increased Design Pile Loads)

Option	Design Method	PPC Pile Size	Factored Design Pile Load (Tons)	Maximum Factored Design Pile Load (Tons)	No. of Footings	No. of Piles per Footing	Total No. of Piles	Pile Length (ft)	Total Pile Length (ft)	Unit Price (per ft)
1	LRFD	16"	116	120	3	9	27	80	2160	$110
2	LRFD	14"	136	125 to 175	3	9	27	90	2430	$95
3	LRFD	16"	179	150 to 250	3	7	21	95	1995	$114
4	LRFD	12"	136	100 to 250	3	9	27	100	2700	$82
5	LRFD	12"	179	100 to 250	3	7	21	105	2205	$90
6	LRFD	18"	261	200 to 375	3	5	15	110	1650	$130
7	LRFD	20"	261	250 to 475	3	5	15	115	1725	$150

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)

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

Option 1 - LRFD design using current maximum factored design pile loads
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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)

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

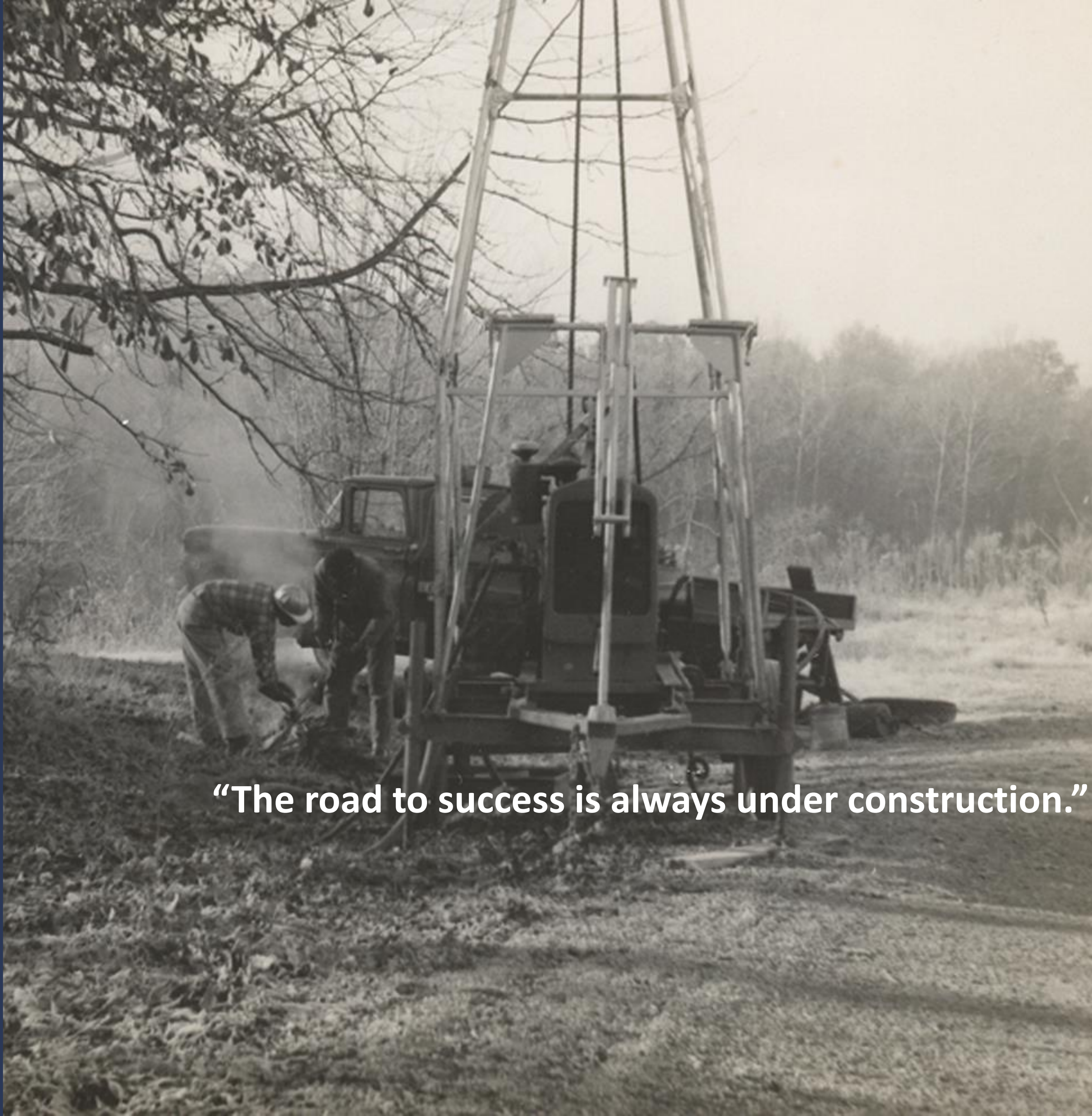
1. Increasing f’c and # strands will:
   - Increase the allowable pile design load (i.e., working load) & factored (LRFD) pile design load
   - Increase the allowable pile driving stresses
   - Enhance the performance of PPC piles during handling and transportation
   - Provide solutions in corrosive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