PCI_PSCPILE: PCI PRESTRESSED CONCRETE PILE INTERACTION DIAGRAM SPREADSHEET

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ABSTRACT

The Precast/Prestressed Concrete Institute (PCI) has published interaction diagrams for prestressed concrete piles for many years. While diagrams were provided for typical pile sizes, shapes, and strand patterns, some design situations were not covered.

The PCI Prestressed Piling Spreadsheet (PCI_PSCPile) was developed as a general design aid to assist designers in determining the appropriate pile type/size that is required for a particular design situation. The first version of the PCI Prestressed Piling Spreadsheet was released in 2004, with an updated and expanded version to be released in 2005. New features include computing spiral or tie requirements and information on lifting locations. The spreadsheet is based on Chapter 20 of the PCI Bridge Design Manual, so it uses AASHTO bridge design requirements. However, it can also be used for the design of piles for other types of structures.

This paper introduces the main functionality of the spreadsheet, demonstrating and describing the required input values and features of the output.

KEYWORDS: Piling, Prestressed Concrete, Interaction Diagrams, Moment Curvature, Bridges, Lifting, Handling

INTRODUCTION

The Precast/Prestressed Concrete Institute (PCI) has published interaction diagrams for prestressed concrete piles for many years. Diagrams were provided for typical pile sizes, shapes, and strand patterns. However, the appropriate diagram for a particular prestressed concrete pile being used by an engineer or designer was sometimes not included. In these cases, interpolation between similar interaction diagrams and/or hand calculations were required.

In 2004, PCI offered the first version of the PCI Prestressed Piling Spreadsheet which allowed the designer to customize the prestressed pile and compute the interaction diagram. In 2005, PCI will release an updated version of the Piling Spreadsheet which includes additional features.

OVERVIEW

The piling spreadsheet allows a designer to obtain an interaction diagram for a prestressed concrete pile by specifying several elements such as the cross-section used, strand pattern, concrete strength and others items. These variables are discussed in following sections. The spreadsheet, through the use of Visual Basic macros, computes the interaction diagram for the specified prestressed concrete pile. In addition to creating the interaction diagram, the program assists the designer in computing spiral reinforcement requirements and lifting locations.

The spreadsheet utilizes a series of worksheets or tabs to organize the operation of the spreadsheet. Tabs also correspond to pages that can be printed for including in design calculations. The main tabs are discussed in the following, with references to other tabs.

Throughout the spreadsheet, green cells are used to indicate input locations. In this paper, screen captures are presented as figures. Numbers in brackets (e.g., **[1]**)are placed next to items in the figures as keys to the discussion in the text.

TITLE TAB

This tab includes the title and version number, along with information regarding the development of the spreadsheet and a disclaimer.

INSTRUCTIONS TAB

This tab includes background information on the use of the spreadsheet. Much of this information is included in this paper. A design example is also presented in this tab.

INPUT TAB

In this tab, each of the variables required to define a pile is briefly discussed. The tab is divided into several subheadings, each of which are discussed in the following.

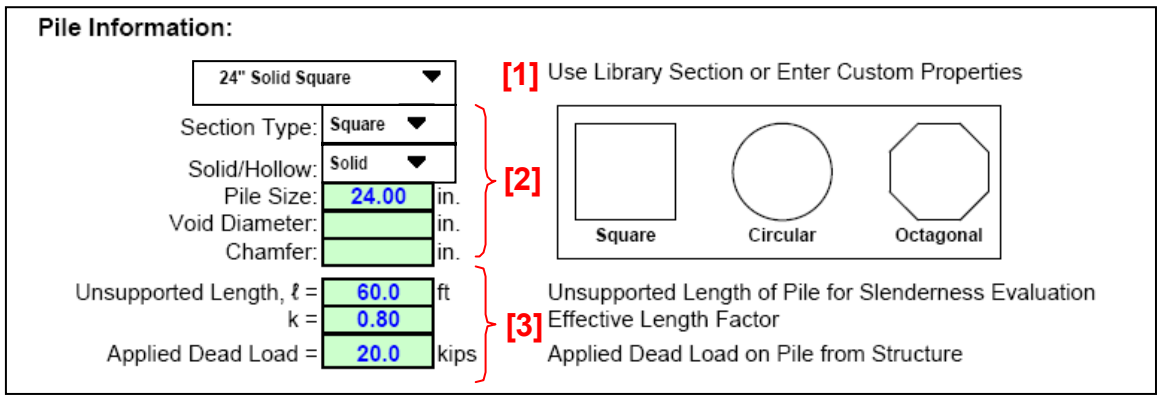
Pile Information (Figure 1)

There are two methods available for defining a pile cross-section in the spreadsheet.

The first method consists of selecting the section from the Pile Library by using the drop-down box **[1]**. The sections listed are those provided in Appendix B of the PCI Bridge Design Manual (BDM). The user has the option of adding other sections as needed (see **Pile Library Tab**).

The information in section **[2]** is automatically filled in when a section is selected from the Pile Library. The information in the Pile Library can be modified or sections can be added as needed.

Figure 1



The second method is to enter each of the cross-section parameters in the cells below the Pile Library drop-down box **[2]**. The user has the option of selecting a square, circular or octagonal section shape (square, circular or octagonal) and indicating whether the section is solid or hollow. After establishing the shape, the user must enter the pile size (outer dimension) and, if required, the void diameter (inner dimension). A chamfer dimension can also be entered if needed.

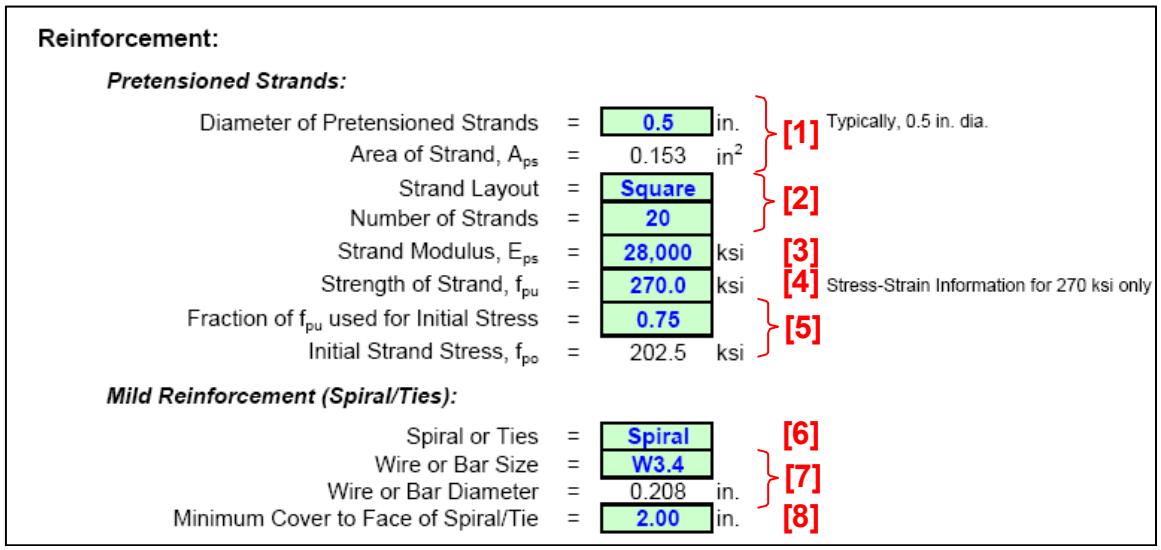
The input items in section **[3]** are the unsupported length of the pile which is used for slenderness calculations, the effective length factor appropriate for the pile end conditions, and the service dead load acting on the pile. The dead load is only used to compute the prestress losses due to creep.

Reinforcement (Figure 2)

Pretensioned Stands

The strand size, layout and number of strands, strand modulus, ultimate strength of the strand (GUTS), and the fraction of the strength of the strand used for initial stress are entered in this portion of the spreadsheet.

Figure 2



Strand diameters from 3/8 in. to 0.6 in. are available for selection using a drop-down box **[1]**. The area of the strand is automatically selected based on the size of strand.

The strand layout can be specified as square, circular or rectangular using a drop-down box **[2]**. The number of strands entered may be subject to restrictions based on the selected strand layout.

- For a square strand layout, an equal number of strands must be placed on each face of the pile, which means that the number of strands must be divisible by four. If an incorrect number of strands is entered, a warning message will appear beside the input box.
- For a circular strand layout, any number of strands may be used.
- For a layout with a different number of strands on adjacent faces of the pile, select Rectangle. An even number of strands must be entered. The strand pattern must be defined using the Custom Strand Pattern Tab.

The strand layout also defines the shape of the spiral or tie. Some specifications or owner requirements may not allow the use of square spirals or ties for some design conditions.

Any value may be used for the elastic modulus of the pretensioned strands, E_{ps} **[3]**. For designs using the *Standard Specifications*, E_{ps} is generally taken as 28,000 ksi; for designs using the *LRFD Specifications*, E_{ps} is generally taken as 28,500 ksi.

The tensile strength of the strand, f_{pu}, is typically taken as 270 ksi **[4]**. A stress-strain curve is automatically generated based on 270 ksi and E_{ps} of the strands entered. The stress-strain curve for the prestressing strands may be customized in the **Stress-Strain Curve Tab**.

The initial strand stress is typically taken as 0.75 times the strand strength **[5]**.

Mild Reinforcement

In this spreadsheet, mild reinforcement is only considered as confinement and shear reinforcement. The input values required for mild reinforcement follow.

The mild confinement reinforcement may be either a continuous spiral or ties. The selection of the type is made in a drop-down box **[6]**. The shape of the spiral or tie depends on the selected strand arrangement (square, circular or rectangular). The selection of spiral or ties is used to determine the maximum axial load limit.

The selection of the wire or bar size can be accomplished by either selecting a library item as listed in the drop-down box or a custom size may be entered **[7]**. Wire reinforcement is typically used in piles, with W3.4 for pile sizes ≤ 24 in. and W4.0 for pile sizes > 24 in. (for non-seismic applications).

The minimum cover to the face of the spiral or tie must be entered **[8]** to determine the core area of concrete as well as the locations of the prestressing strands. The user must specify a cover that meets the applicable specification requirements.

Concrete Properties (Figure 3)

The input parameters for the concrete properties are straightforward and include:

- Minimum concrete compressive strength at transfer, f'_{ci}
- Specified concrete compressive strength, f'_c
- Unit weight of plain concrete, w_c, typically taken as 145 pcf
- Ambient relative humidity, H, used for shrinkage loss calculations

See PCI BDM Chapter 20 for further discussion of concrete properties for piles.

Figure 3

Concrete Properties:

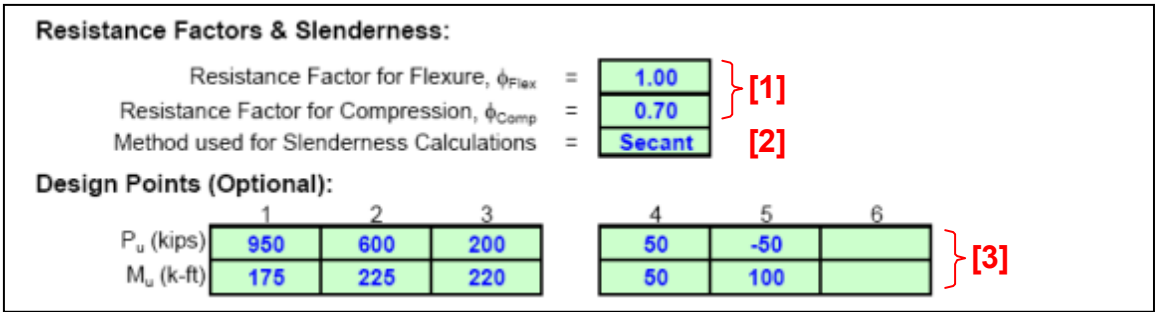
Concrete Strength at Transfer, f'_{ci}	=	4.00	ksi	
Specified Concrete Strength f'_c	=	6.00	ksi	
Concrete Unit Weight, w_c	=	0.150	kcf	
Ambient Relative Humidity, H	=	75	%	(Used for Shrinkage Loss)
Concrete Ultimate Strain, ε_{cu}	=	0.003	in./in.	

Resistance Factors & Slenderness (Figure 4)

Capacity reduction factors are required for strength design calculations. The capacity reduction factors for flexure and compression **[1]** are required to develop the interaction diagrams for the pile. These factors vary depending on the specification used. For compression, the *Standard Specifications* use a resistance factor of 0.70 for members with ties and 0.75 for members with spirals. The *LRFD Specifications* use a factor of 0.75 for members with either ties or spirals. The resistance factor for flexure and tension for prestressed concrete is taken as 1.0 for both AASHTO specifications. Linear interpolation

of the resistance factor between the compression and flexure values is performed according the AASHTO specifications. The earlier interaction diagrams published by PCI used 0.9 as the resistance factor for flexure and tension, which is the resistance factor used in ACI 318 for buildings.

Figure 4



Slenderness effects are considered in the interaction diagrams. Two methods for considering slenderness are available in this spreadsheet: the ACI approach and the Secant Method. The method to be used is selected using the drop-down box **[2]**. See the article "Ultimate Strength of Prestressed Concrete Piles and Columns" by Arthur R. Anderson and Saad E. Moustafa, which appeared in the August 1970 issue of the *ACI Journal* for more information on the methods for evaluating slenderness effects.

The effective stiffness of the pile is evaluated using the moment and curvature for both the ACI and Secant methods rather than the approximate method usually used with the ACI method.

Design Points

The user has the option of entering up to six design points **[3]** to be plotted on the interaction diagram. The moment values entered for these points should not be magnified, since the effect of slenderness is considered directly in the interaction diagram.

OUTPUT

The output is reported on two separate tabs.

OUTPUT SUMMARY TAB (FIGURE 5)

The first output worksheet provides a summary of the majority of the Input along with computed values for area, moment of inertia, etc. **[1]** as well as the slenderness ratio **[3]**, prestress losses and effective stresses and forces in the strands at transfer and final conditions **[4 & 5]**. A tabulation of the design points is provided along with the maximum moment, including slenderness effects, for the specified axial loads **[7]**.

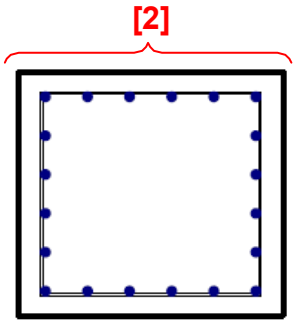
A cross-section of the pile is also shown with the strand pattern, mild reinforcement, and, if used, the void in the pile **[2]**. This cross-section may sometimes appear stretched

because of scaling features in Excel. The effective stress in the concrete **[6]** is provided to allow a comparison to the limit recommended in PCI BDM Chapter 20.

Figure 5

24 in. Solid Square Pile

20 - 0.5 in. Dia Strands with W3.4 Spiral



Gross Area, A	=	576.0	in^2	**[1]**
Moment of Inertia, I	=	27,648	in^4	
Radius of Gyration, r	=	6.93	in.	
Unsupported Length, ℓ	=	60	ft	(Input)
Effective Length Factor,k	=	0.80		(Input)
kℓ/r	=	83.1	**[3]**	
Applied Dead Load	=	20.0	kips	(Input)
Concrete Unit Weight, w_c	=	0.150	kcf	(Input)
Ambient Relative Humidity, H	=	75	%	(Input)
Concrete Ultimate Strain, ε_{cu}	=	0.003	in./in.	(Input)
Concrete Strength at Transfer, f'_{ci}	=	4.00	ksi	(Input)
Specified Concrete Strength f'_c	=	6.00	ksi	(Input)
Strand Modulus, E_{ps}	=	28,000	ksi	(Input)
Area of Strand, A_{ps}	=	0.153	in^2	(Input)
Strength of Strand, f_{pu}	=	270	ksi	(Input)

Prestress Loss and Effective Stresses:

Initial Strand Stress, f_{po}	=	202.5	ksi	(Input)
Initial Loss, Δf_{pIL}	=	5.5	ksi	**[4]**
Effective Stress in Strands after Transfer, f_{pi}	=	197.0	ksi	
Effective Prestress Force in Strands after Transfer, F_{pi}	=	602.8	kips	
Total Loss, Δf_{pTL}	=	25.0	ksi	**[5]**
Effective Stress in Strands after All Losses, f_{pe}	=	177.5	ksi	
Effective Prestress Force in Strands after All Losses, F_{pe}	=	543.3	kips	

Effective Prestress in Concrete:

Effective Prestress in Concrete Pile, f_{pc}	=	0.943	ksi	**[6]** = F_{pe}/A

Concrete Cover:

Concrete Cover to Spiral	=	2.00	in.	(Input)
Concrete Cover to Strands	=	2.21	in.	

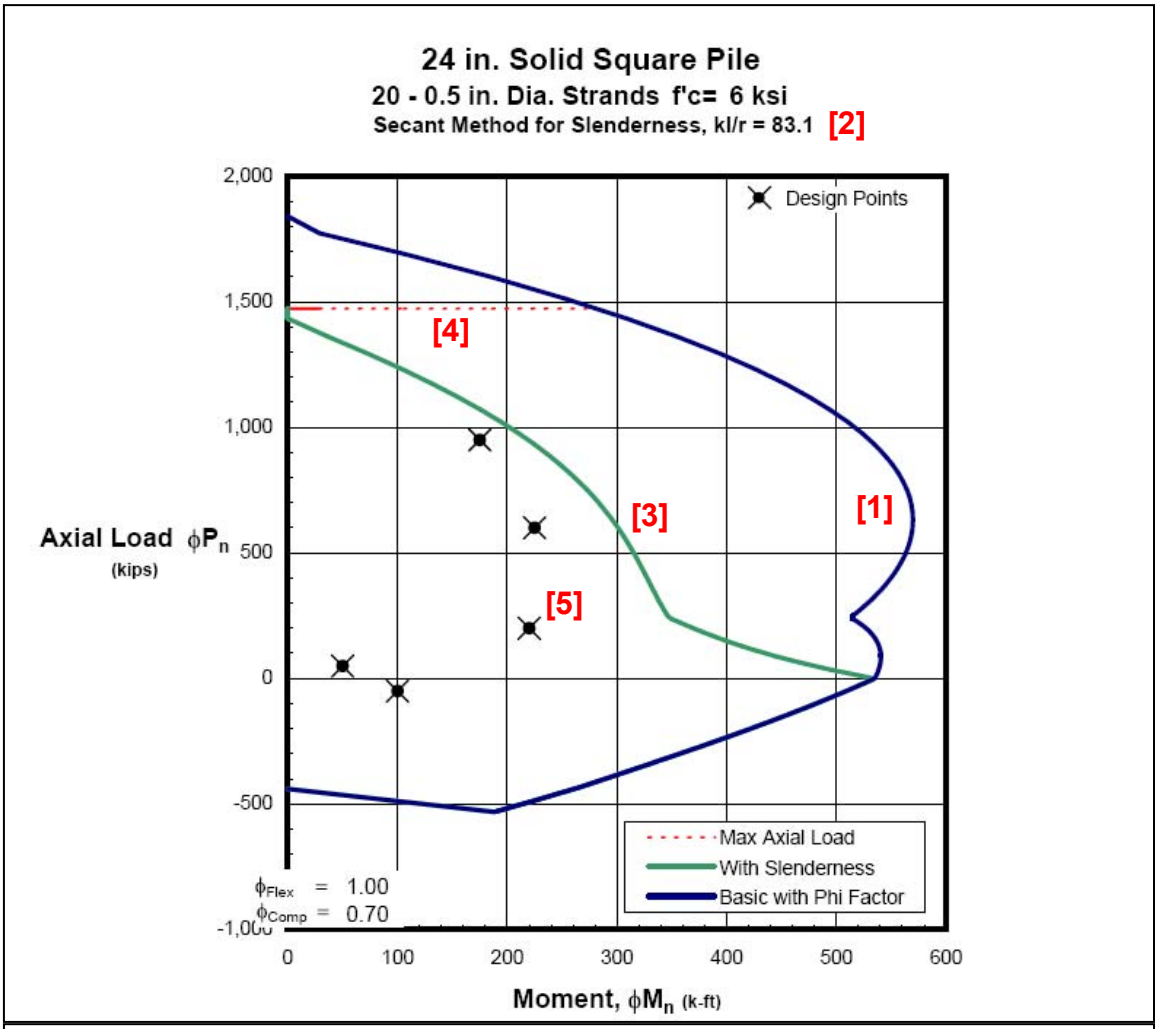
Design Points as Input:

	Axial Load (kips)	Moment (k-ft)	Max. Moment w/ Slenderness (k-ft)	
1	950	175	218.9	**[7]**
2	600	225	301.0	
3	200	220	369.6	
4	50	50	479.6	
5	-50	100	509.1	
6	0	0	532.9	

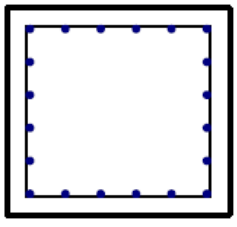
INTERACTION DIAGRAM TAB (FIGURE 6)

The second output worksheet displays the interaction diagrams produced by the spreadsheet.

Figure 6



Cross-Section



Key Points on Basic Interaction Diagram including ϕ Factors:

	Axial Load, ϕP_n (kips)	Moment, ϕM_n (k-ft)	
Pure Compression	1840.2	0.0	
Maximum Axial Load	1472.1	281.4	
Maximum Moment*	636.8	569.8	
ϕ Break Point	241.9	512.7	[6]
Pure Bending	0.0	535.1	
Maximum Tension	-531.5	188.4	
Pure Tension	-440.0	0.0	

* Based on point of maximum moment before ϕ factors are applied

The interaction diagram contains the following:

- Basic interaction curve without slenderness consideration (blue). **[1]**
- Basic pile design information, including the slenderness ratio and method of slenderness evaluation, is given in the title block of the diagram. **[2]**
- Interaction curve with slenderness considered (green). **[3]**
- The maximum axial load cutoff, as required by both AASHTO specifications (dashed red). **[4]**
- The design points entered are shown on the diagram. **[5]**
- The key design points on the basic interaction diagram, including ϕ factors, are shown below the interaction diagram. **[6]**

DESIGN ASSUMPTIONS

The strain compatibility approach is used to develop the points for the interaction diagram. Details of this method are presented in Section 8.2.2.5 of the PCI BDM.

- The stress-strain relationship for the prestressing strands is modeled using a modified Ramberg-Osgood function. This equation has been calibrated for typical 270 ksi low-relaxation strands. (See **Stress-Strain Curve Tab**)
- The equivalent rectangular stress block is used for the concrete stress-strain relationship. This method is typically used for strength design. Details are found in the Standard and LRFD Specifications.
- Slenderness effects are computed using one of two methods: the ACI approach or the Secant Method. See the PCI Journal article "Ultimate Strength of Prestressed Concrete Piles and Columns" by Arthur R. Anderson and Saad E. Moustafa for more information on this analysis.
- The contribution of the concrete is calculated using a "strip" method. The "strip" method divides the cross-section into small strips which are taken to have a height of Δ_h = (Pile Size)/100 and a width of b_{avg}, where b_{avg} is the average width of the top and bottom widths of the strip including any reductions required due to an inner void or chamfer. This allows circular, octagonal and square sections to be analyzed using one spreadsheet routine.

ADDITIONAL FEATURES

In addition to creating interaction diagrams, the piling spreadsheet assists the user in determining the spiral or tie requirement depending on the seismic classification for both the AASHTO and PCI methods (**Spiral Tab**). The methods follow the method presented in PCI Chapter 20.

The user can also check or compute lifting locations for prestressed piles (**Lifting Loops Tabs**). The user can select from typical lift locations as discussed in PCI Chapter 20, or create a custom lift location pattern.

CONCLUSION

The PCI Prestressed Piling Spreadsheet was developed as a tool to assist designers in determining which pile type/size is required for their particular situation. This spreadsheet provides versatility for design as well as user friendly output. The spreadsheet is based on Chapter 20 of the PCI Bridge Design Manual.