NETC 19-1

Curved Integral Abutment Bridge Design

NEW ENGLAND TRANSPORTATION CONSORTIUM

Introductions & Acknowledgements

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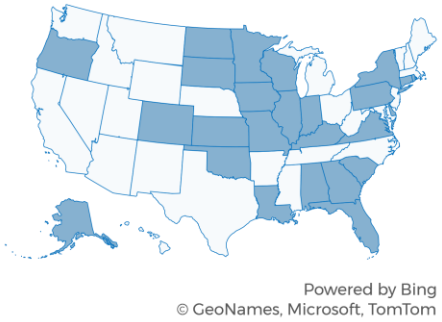
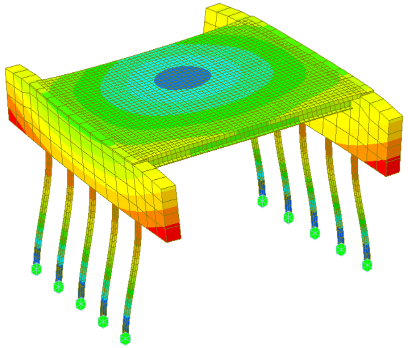
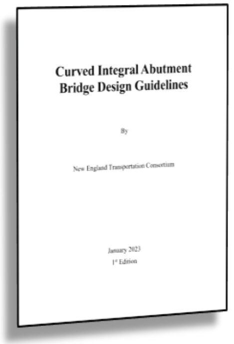
Outline







Task 1:
Literature Review and National Survey

Task 2:
Parametric Study

Task 3:
Design Guidelines

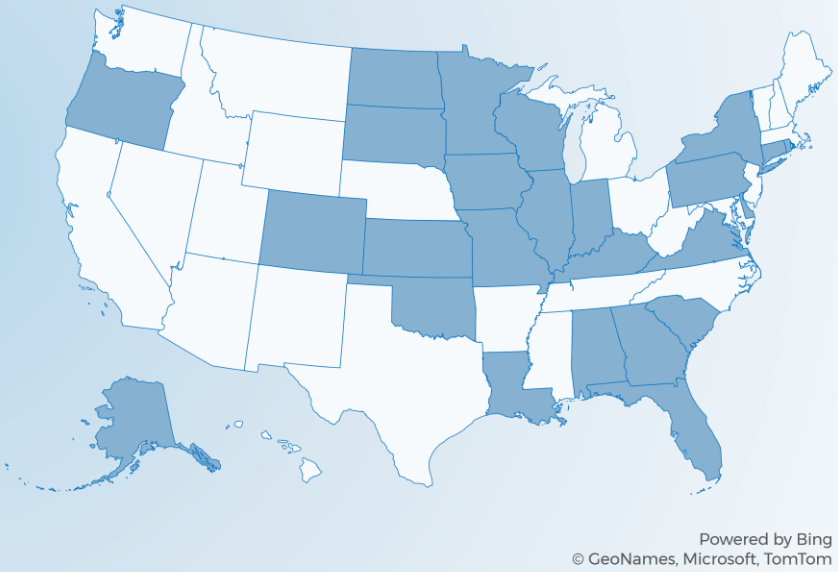
Questions

Study Questions – Curved Integral Abutments

- What parameters are key to establish a simplified design method?
- How do these parameters impact performance?
- What is a logical simplified design method for CIAB's?
- What information can be provided to assist designers when a refined analysis is recommended?

Task 1: Literature Review and Survey of States

- Review of:
  - *State and federal guidance*
  - *Published research*
  - *Existing structures*
- Survey of State Agencies:
  - *Current practices in their State*
  - *26 responses*
- Included in the report as support of the research



Conclusions from the Literature Review & Survey

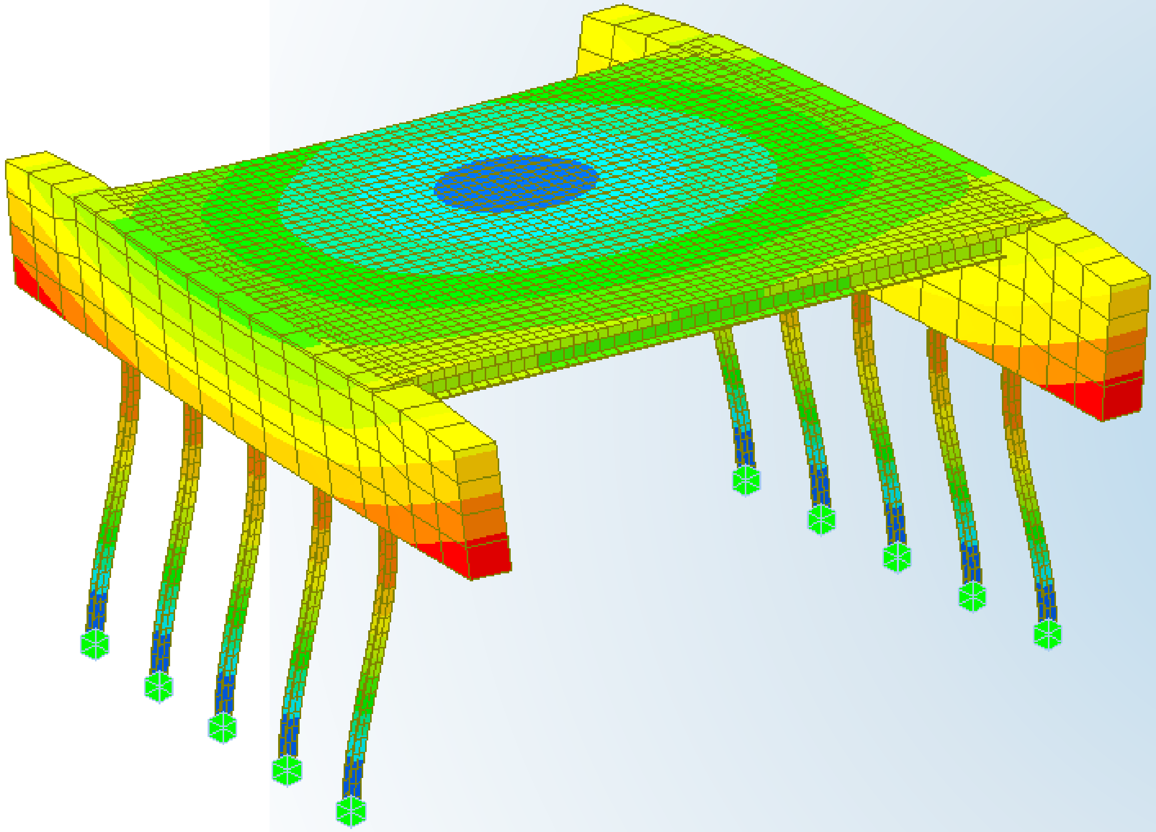
CIAB’s are being built

Concerns are similar to other curved structures and straight IAB’s in terms of deck cracking, diaphragm cracking, and approach settlement

Design guidance for CIAB’s is sparce and inconsistent

Recommendations vary substantially between states

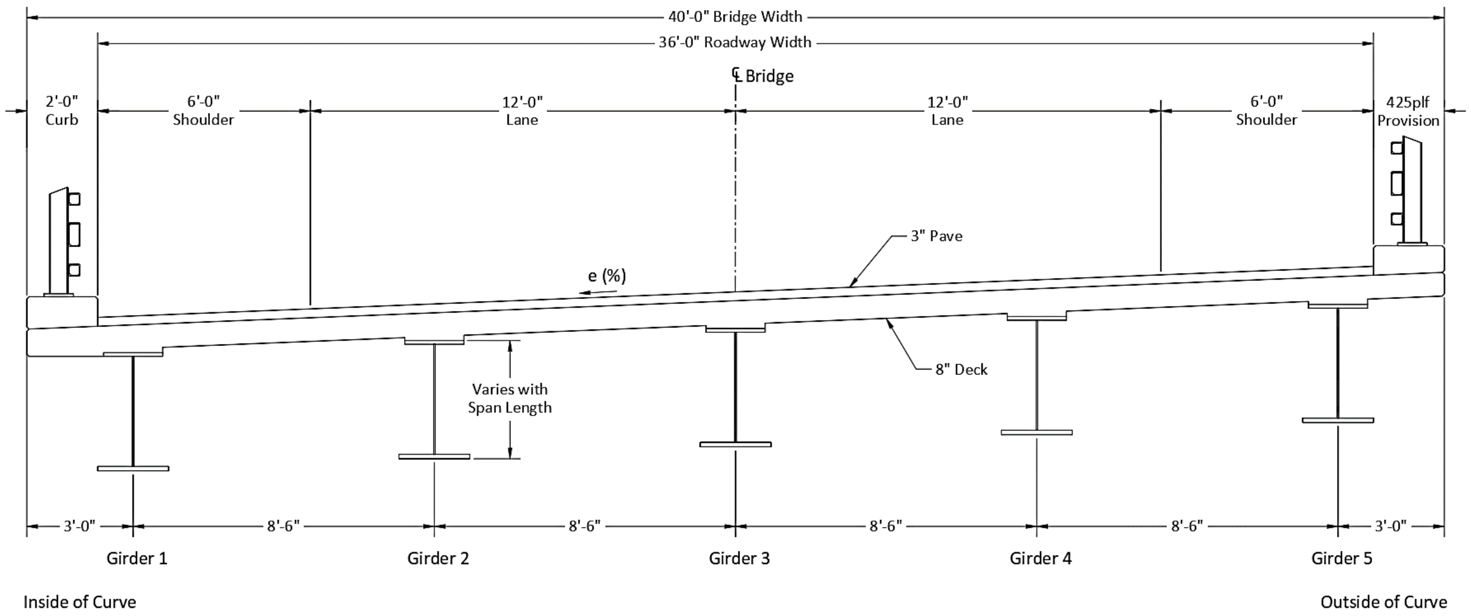
Modeling approach was defined



Task 2: Parametric Study

Structure Description

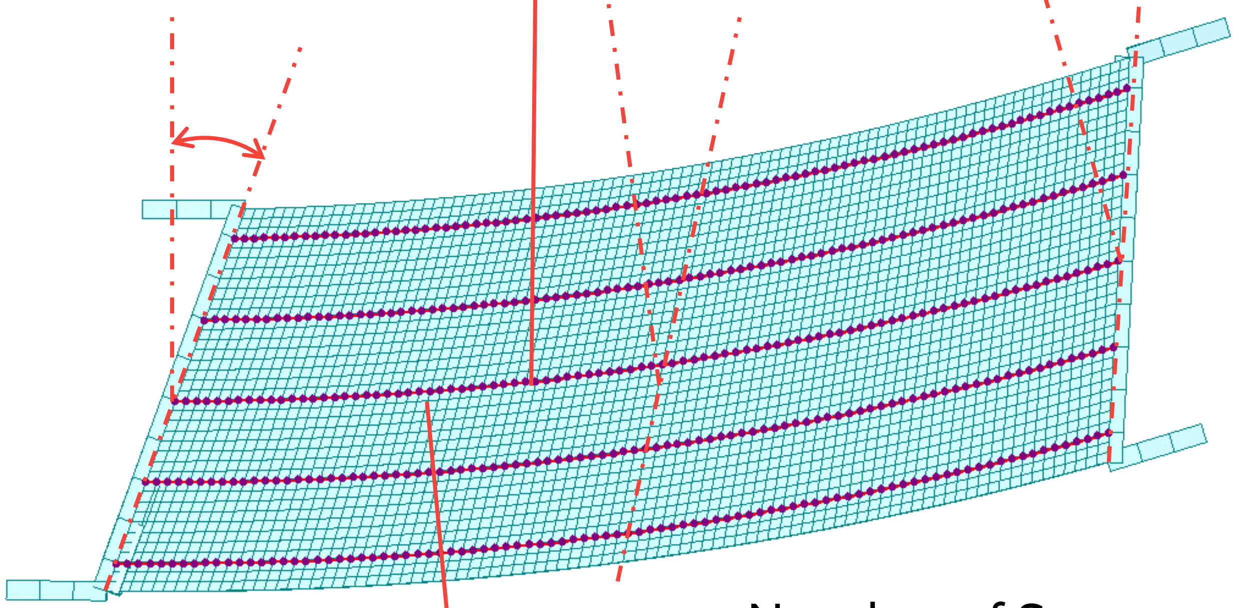
Item	Range of Applicability to Research Study
Superstructure Width	Two 12 ft. lanes, two 6 ft. shoulders, two 2 ft. barriers = 40 ft.
Superstructure	Curved Steel I girders composite with concrete deck – 5 total
Piles	Grade 50 Steel H Piles - 1 at each girder line
Abutments	Integral with superstructure – height varies with span length/girder depth
Wingwalls	10 ft. long cantilevered monolithic wing



Study Parameters – 585 Models

Skew Angle:
0, 10, & 20 degrees

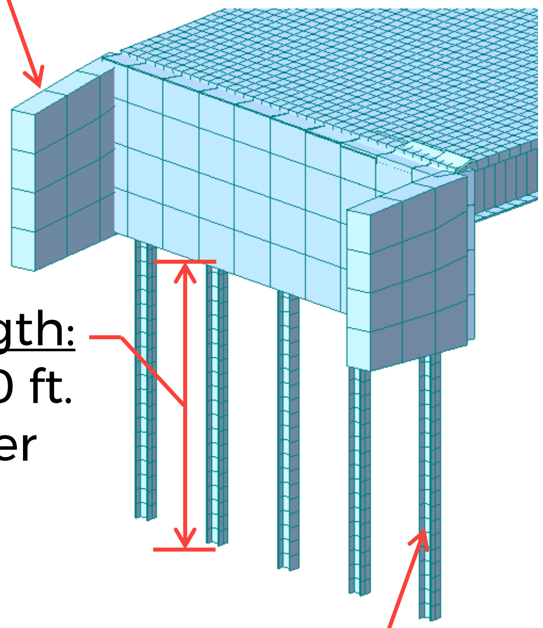
Curve Radius:
340 ft. – 2500 ft.



Bridge Length:
50 ft. – 300 ft.

Number of Spans:
1- & 2-spans

Wingwall Orientation:
In-Line & U-Wing



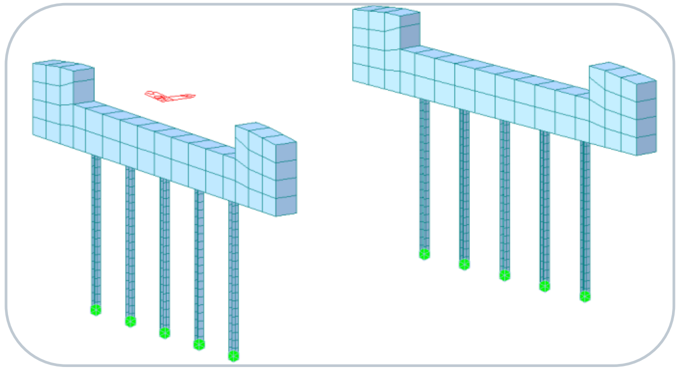
Pile Length:
10 ft. – 30 ft.
Cantilever

Pile Orientation:
Weak & Strong Axis

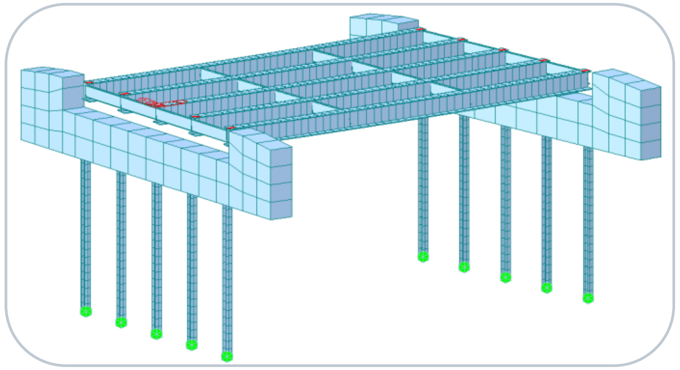
Modeling Approach

Component	Model Description
Geometry	Full 3D model capturing full geometry of the structure.
Deck	Plate elements rigidly linked to the girder elements for composite action.
Abutments	Plate elements.
Wingwalls	Plate elements.
Girders	Beam elements with torsional component rigidly linked to the deck elements for composite action.
Piles	Cantilevered approach where varying length accounts for varying soil conditions. Modeled as beam elements with fixed base boundary conditions and fixed at the top to the abutment elements.
Backfill	Compression-only soil springs tuned based on typical backfill properties for New England. Applied to back face of abutment and wingwalls
Live Load Placement	Model optimized live load placement across three design lanes with fractional wheel loads based on centrifugal effects.
Thermal Loading	Applied as rise and fall to superstructure elements.

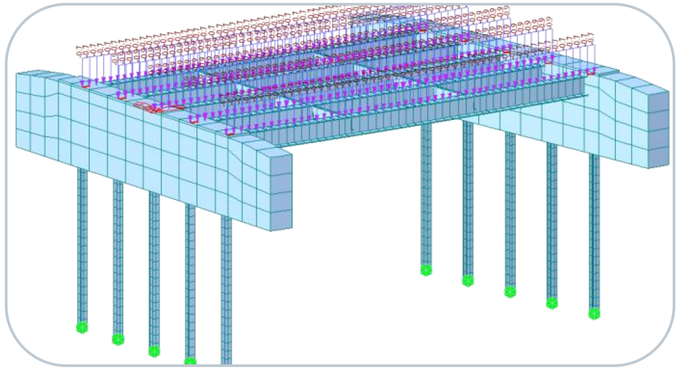
Construction Staging



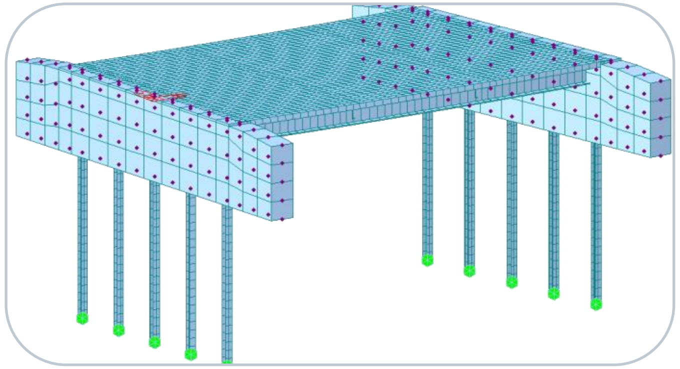
0 - Substructure Placement



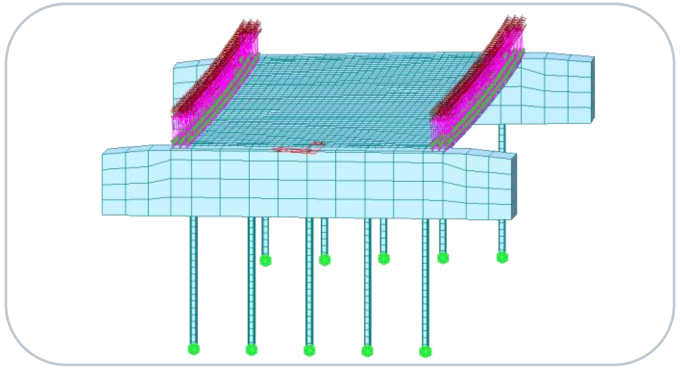
1 - Girder Placement



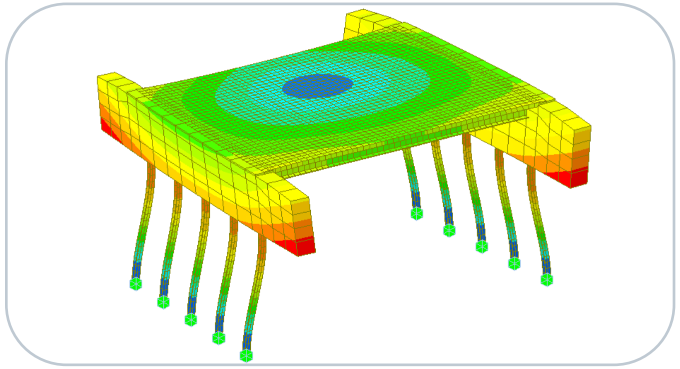
2a – Closure and Deck Pour



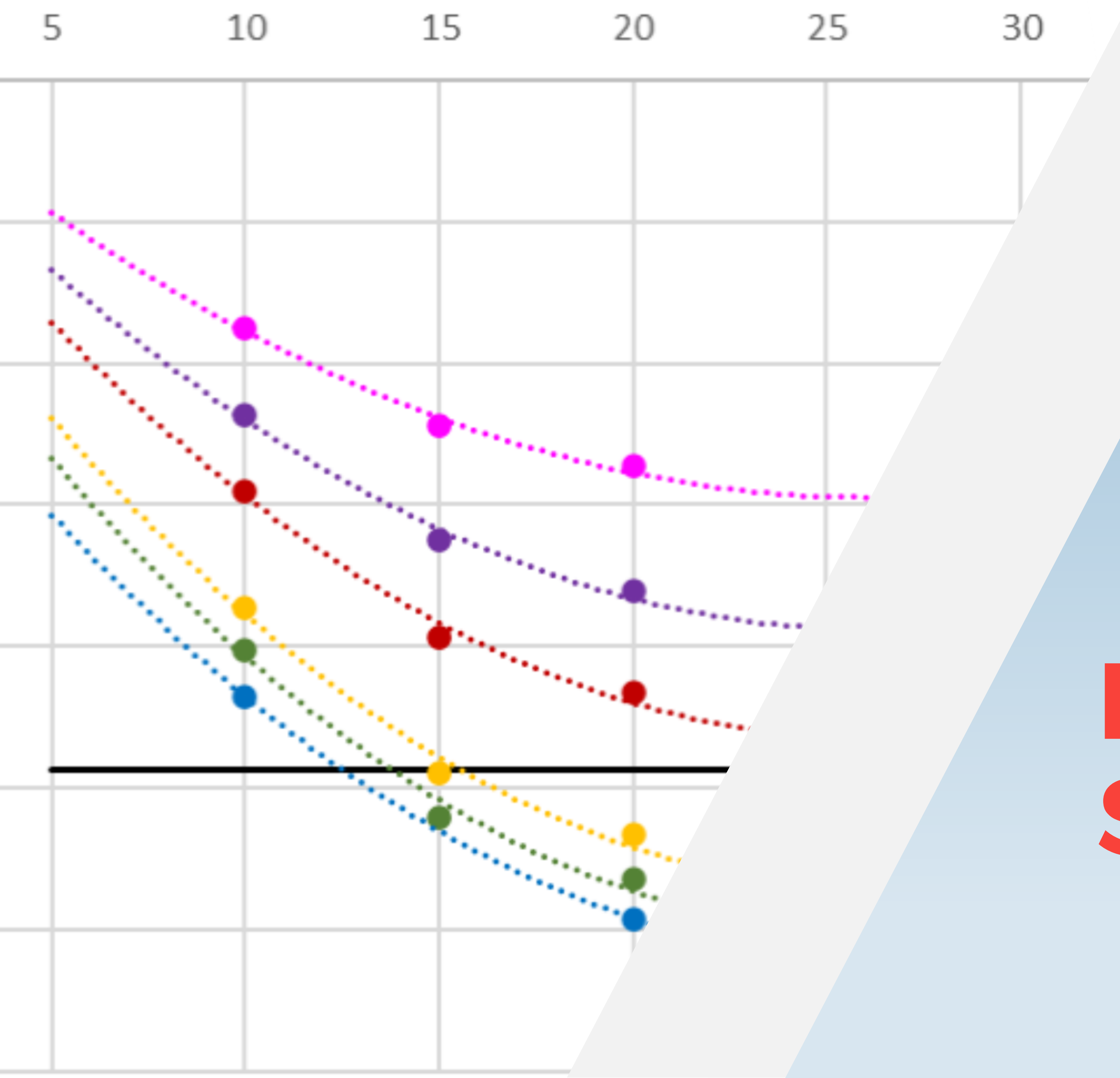
2b – Concrete Curing



3 – Remaining DC / DW



4 – Final Load Application



Parametric Study Results

Model Results of Interest

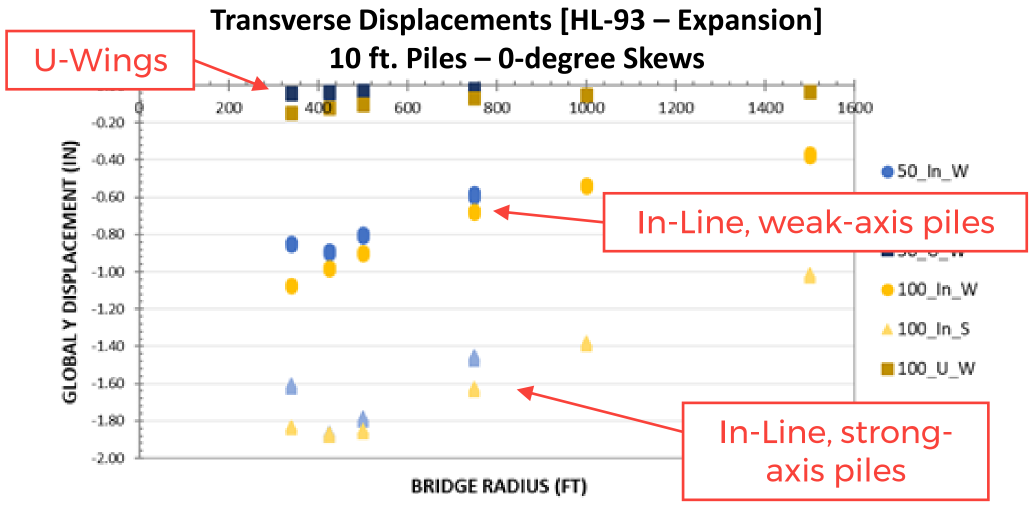
- Pile Head Displacements and Rotations
  - *Highly impactful to the design of a pile*
  - *Indicative of structure serviceability at approaches*
- Pile Forces and Reactions
  - *Identifies combinations of parameters that may produce unrealistic force effects*
- Girder End Forces
  - *Identifies parameters that may produce superstructure force effects that may require a refined analysis to capture*
- Deck End Stresses
  - *Identifies combinations of parameters that produce extreme deck stresses, particularly in high skew / curvature cases*

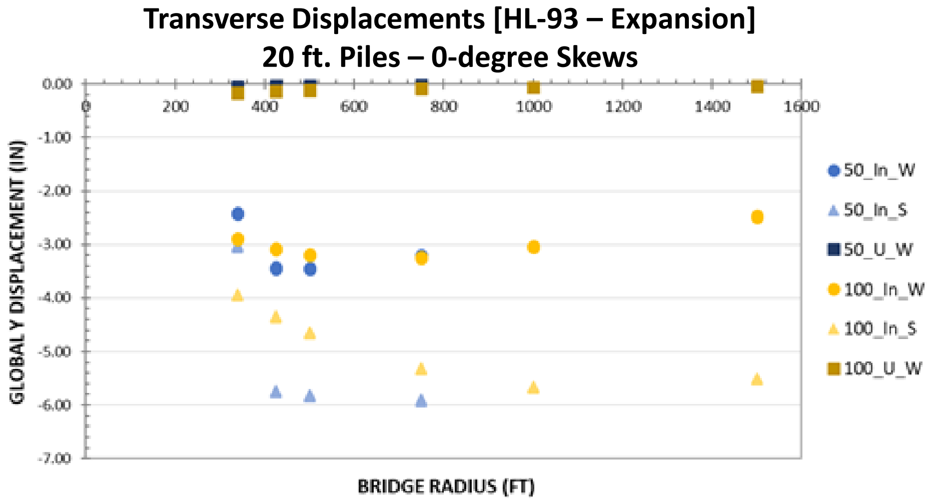
Impact of Parameters

- Higher Impact:
  - *These parameters shaped the criteria for the simplified methods*
    - Wingwall Orientation
    - Pile Orientation
- Lower Impact:
  - *These parameters resulted in specific guidance in both the simplified and refined design methods*
    - Curve Radius
    - Skew Angle
    - Pile Cantilever Length
    - Span Configuration
    - Bridge Length

Wingwall & Pile Orientation

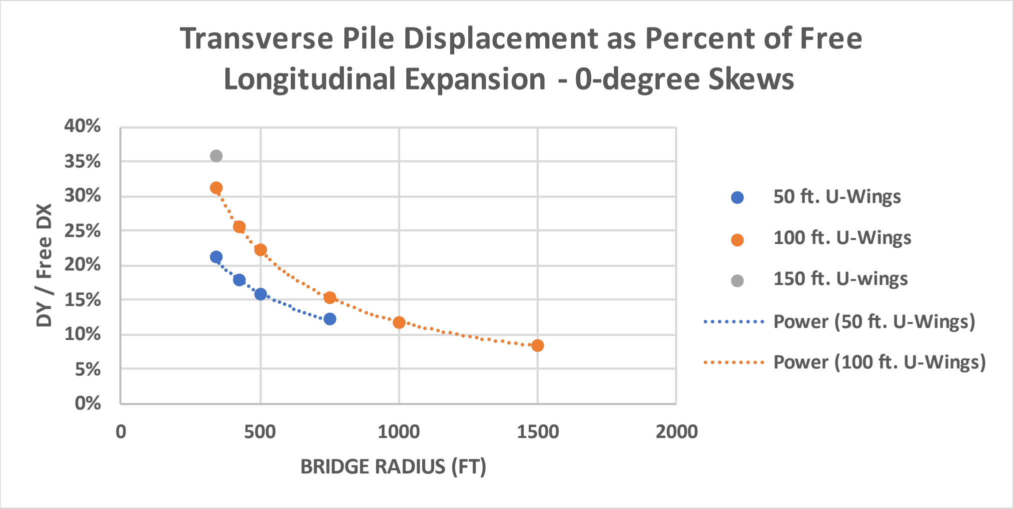
- Significant impact on the pile displacements
  - *U-wingwalls result in most favorable displacements*
  - *In-line wingwalls result in less favorable displacements*
  - *Strong axis piles result in more movement than weak axis piles*
- Attributed to U-wingwalls engaging backfill to resist movement
- In-line Wingwalls show a high sensitivity to pile length

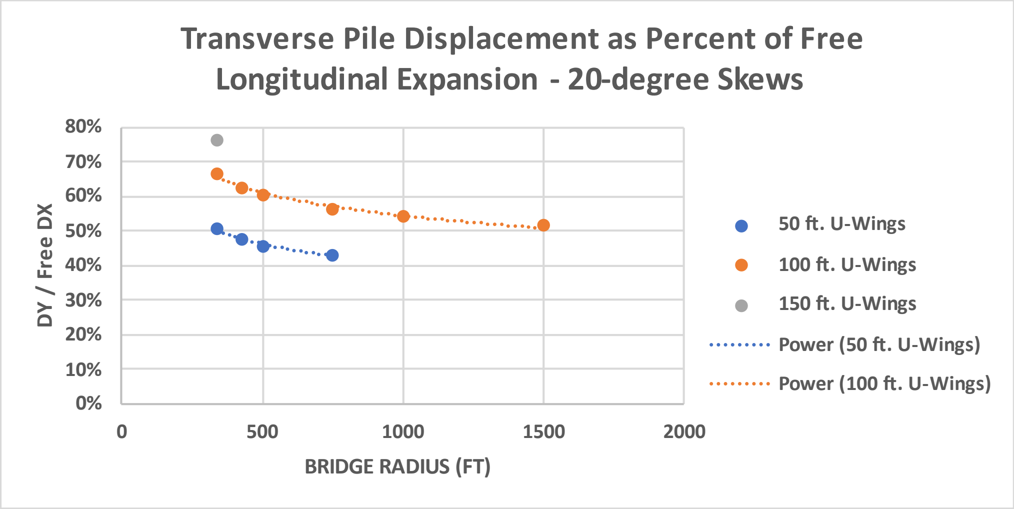




Behavior of U-Wingwalls

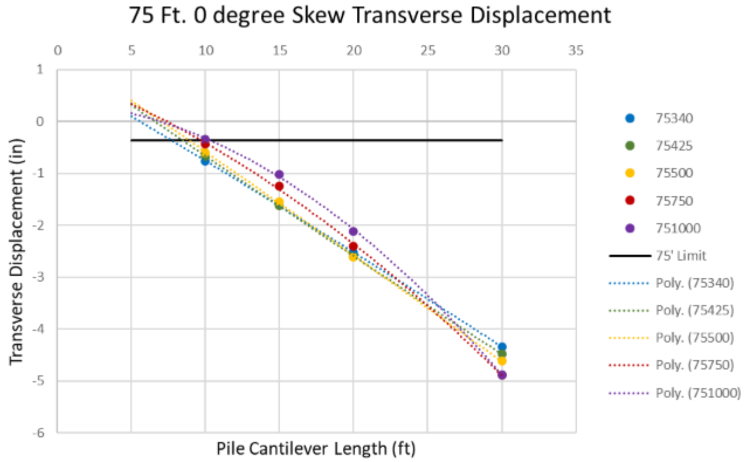
- The displacements of U-wingwalls can be predicted based on structure geometry (Bridge Length, Curve Radius, & Skew)
  - *Related to the expected longitudinal displacement due to thermal loads*
  - *Higher skews and tighter curves result in more transverse displacement*
  - *For shorter wingwalls, transverse displacement can be increased linearly*

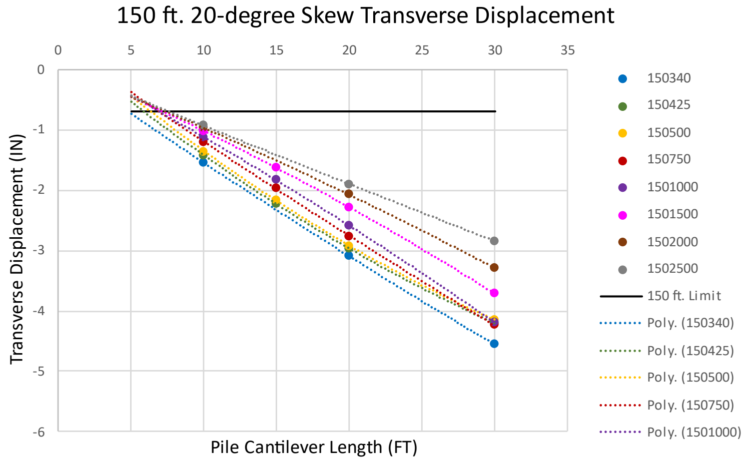


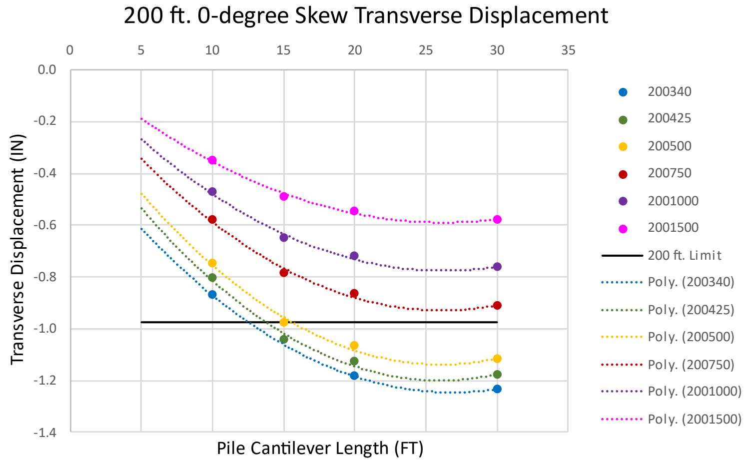


Behavior of In-Line Wingwalls

- In-line wingwalls are highly sensitive to pile length
  - *Representative of changing soil conditions around the pile*
  - *In order to design:*
    - Soil properties around the pile must be known for design
    - A full 3D model must be run to calculate the transverse displacements



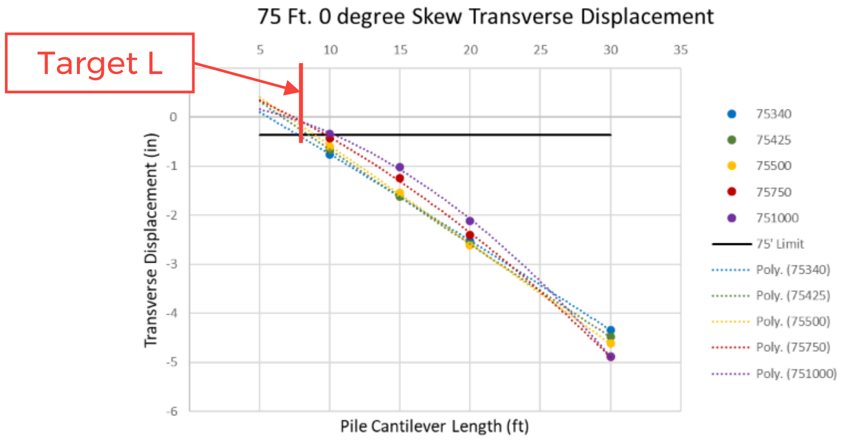




Behavior of In-Line Wingwalls

- The in-line wingwall results could be used to define a target substructure stiffness for acceptable design
  - *Creating a trendline for the Pile Length vs. Displacement results targets a required pile length for each combination of parameters*
  - *This length was input into the equation below to calculate the target stiffness value*
  - *Knowns:*
    - Pile Properties (E & I) for a given model
    - Required pile length (L based on displacement)

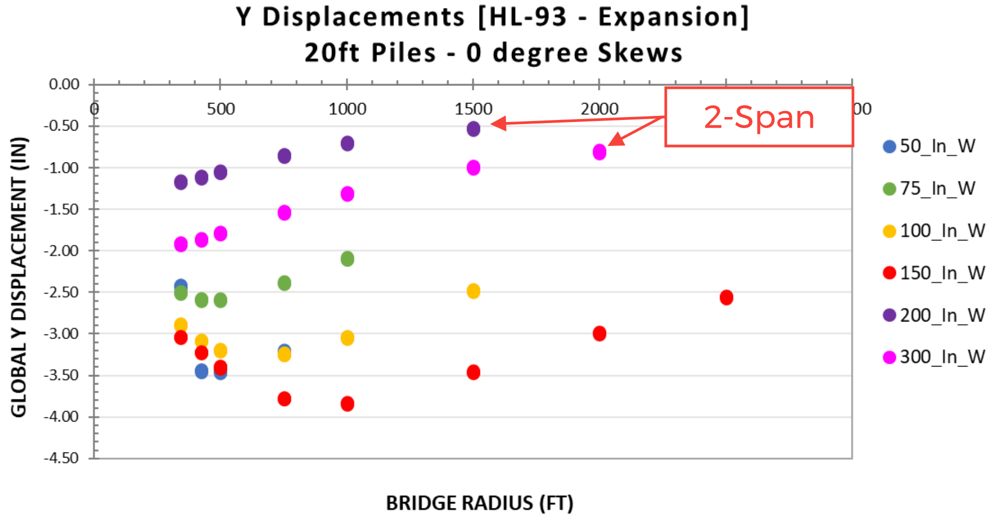
$$K\left(\frac{kip}{in}\right) = \frac{12 * E * I}{L^3}$$

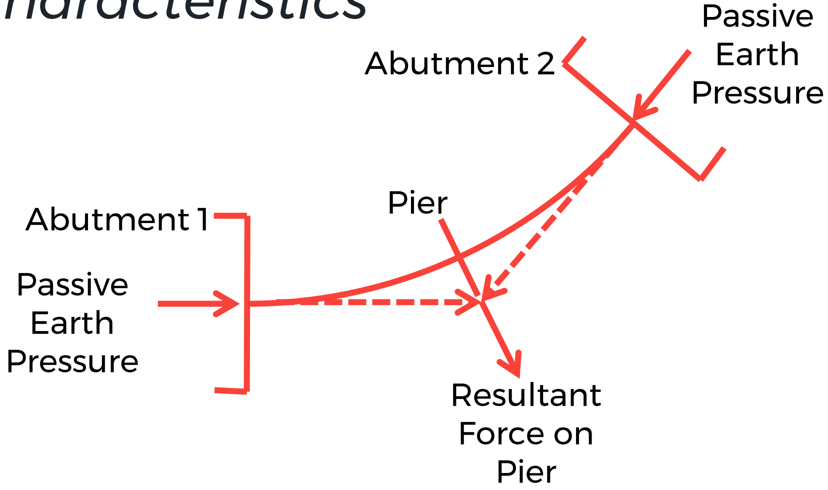


Target Transverse Stiffness (kip/in) for 0-degree Skews						
Radius (ft.)	Structure Length (ft)					
	50	75	100	150	200	300
340	597	1414	2527	4949	333	495
425	568	1108	1313	2013	282	450
500	515	1004	1157	1712	199	372
750	449	770	898	1263	82	179
1000	-	604	738	1047	82	114
1500	-	-	510	752	82	114
2000	-	-	-	618	-	114
2500	-	-	-	483	-	-

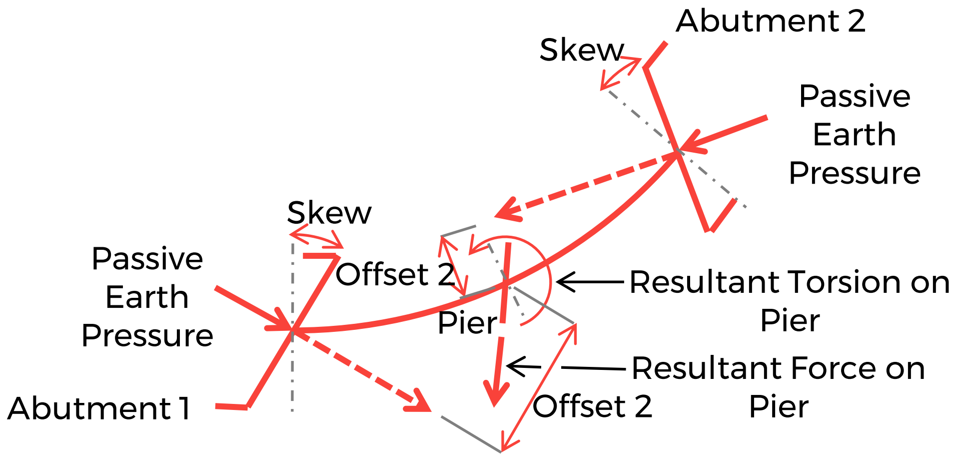
Effects of a Pier in Multi-Span CIAB's

- Models including a pier with fixed girder connectivity result in smaller transverse displacements
  - *Attributed to the stiffness of the pier restraining the transverse movement*
  - *This interaction is complex, and highly dependent on the pier characteristics*





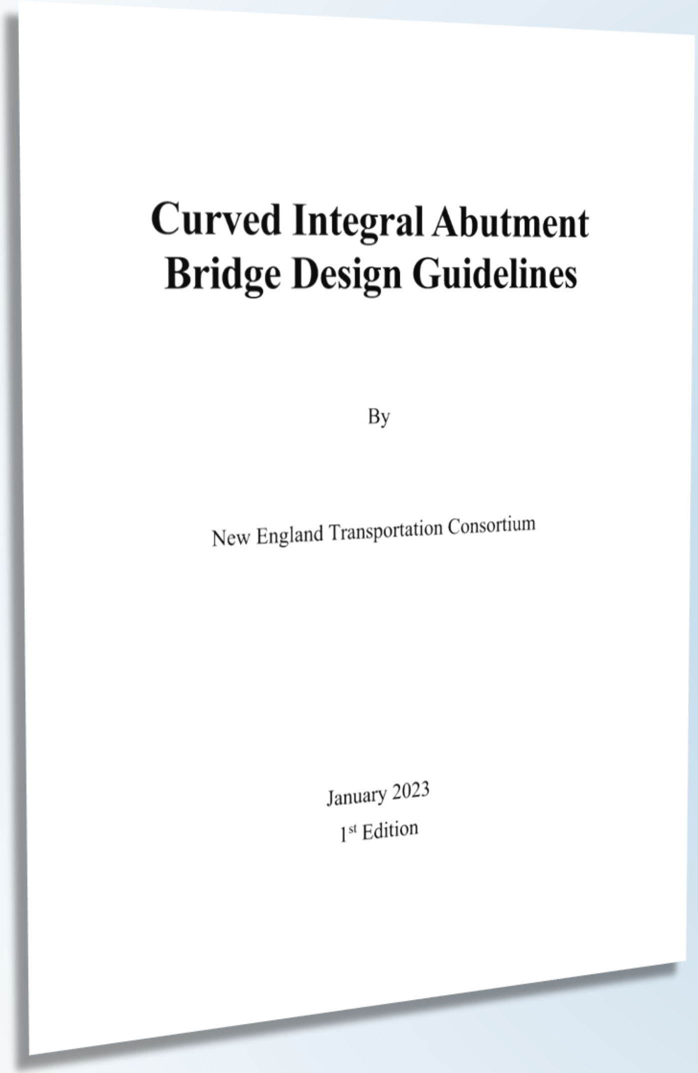
No Skew



Skewed

Conclusions from the Parametric Study

- Simplified analysis is possible for structures with U-wingwalls.
- Refined analysis is recommended for structures with in-line wingwalls and/or strong axis-oriented piles.
- Other study parameters (curve radius, skew angle, etc.) are impactful to the structure behavior, but can be accommodated through appropriate design guidance.
- The presence of a fixed pier can help reduce the force and displacement effects of the other structural components but will result in complex loading of the pier that should be included in its design.


Curved Integral Abutment Bridge Design Guidelines

By

New England Transportation Consortium

January 2023

1st Edition

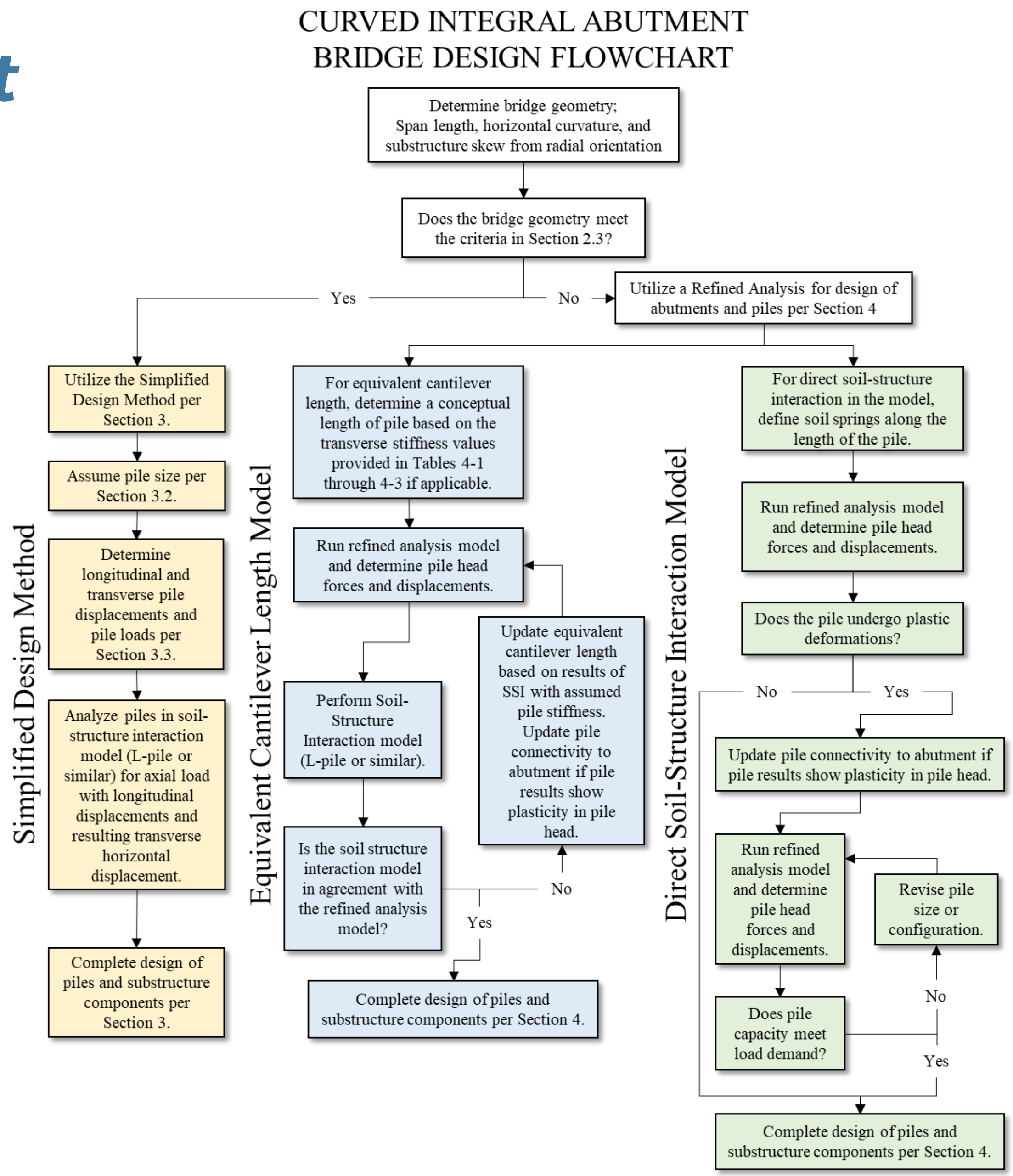
Task 3 – Design Guidelines

CIAB Design Guidelines
Outline

- Section 1: Curved Integral Abutment Bridges
- Section 2: Design Criteria
- Section 3: Simplified Design Method
- Section 4: Guidance for Refined Analysis

CIAB Design Guidelines
Section 2 - Design Flowchart

- Intent is to provide designer guidance on the design method they should use for designing the supporting piles.
- Simplified Design Method
- Refined Analysis
  - *Equivalent Cantilever Length Method*
  - *Direct Soil-Structure Interaction*



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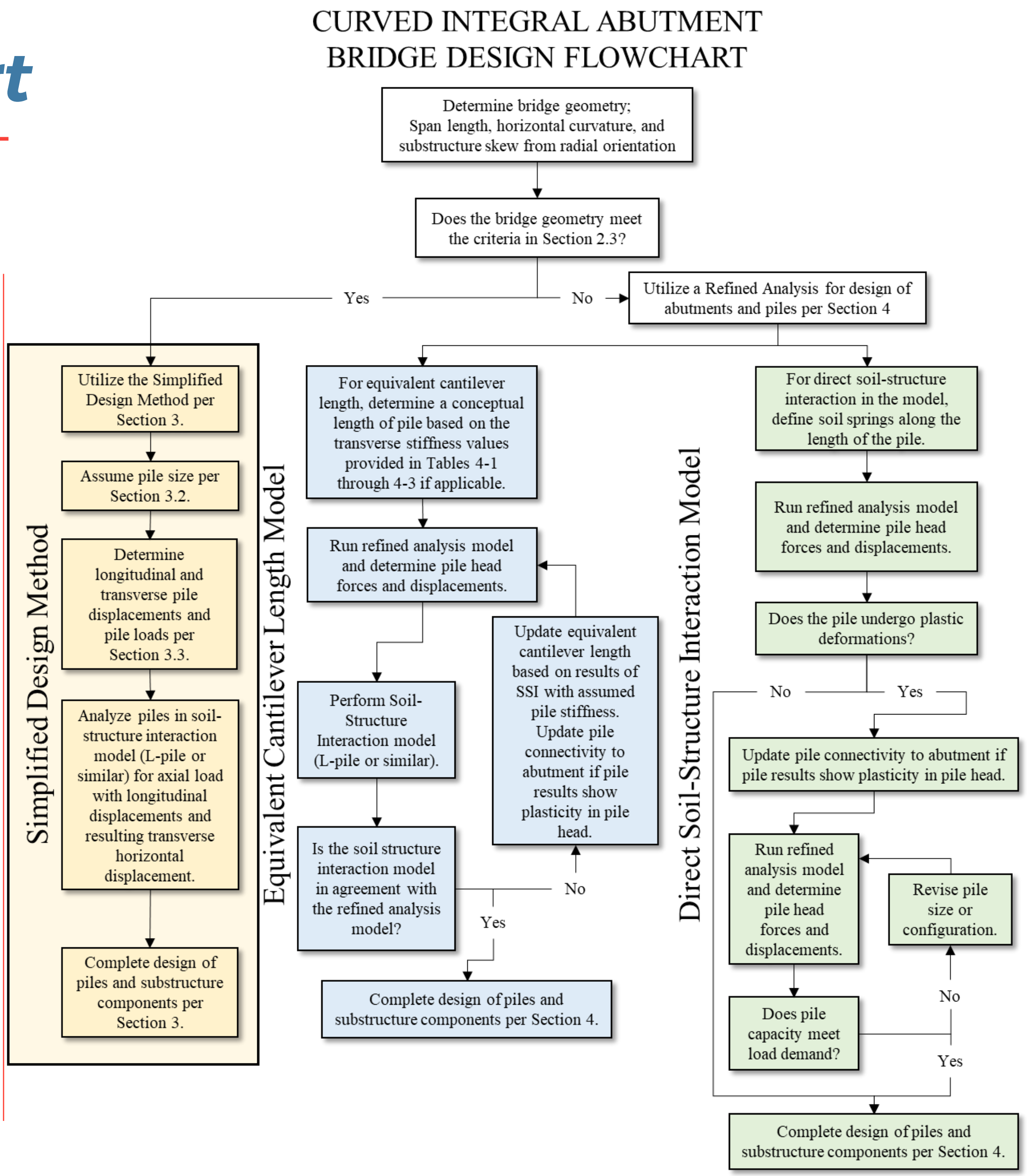

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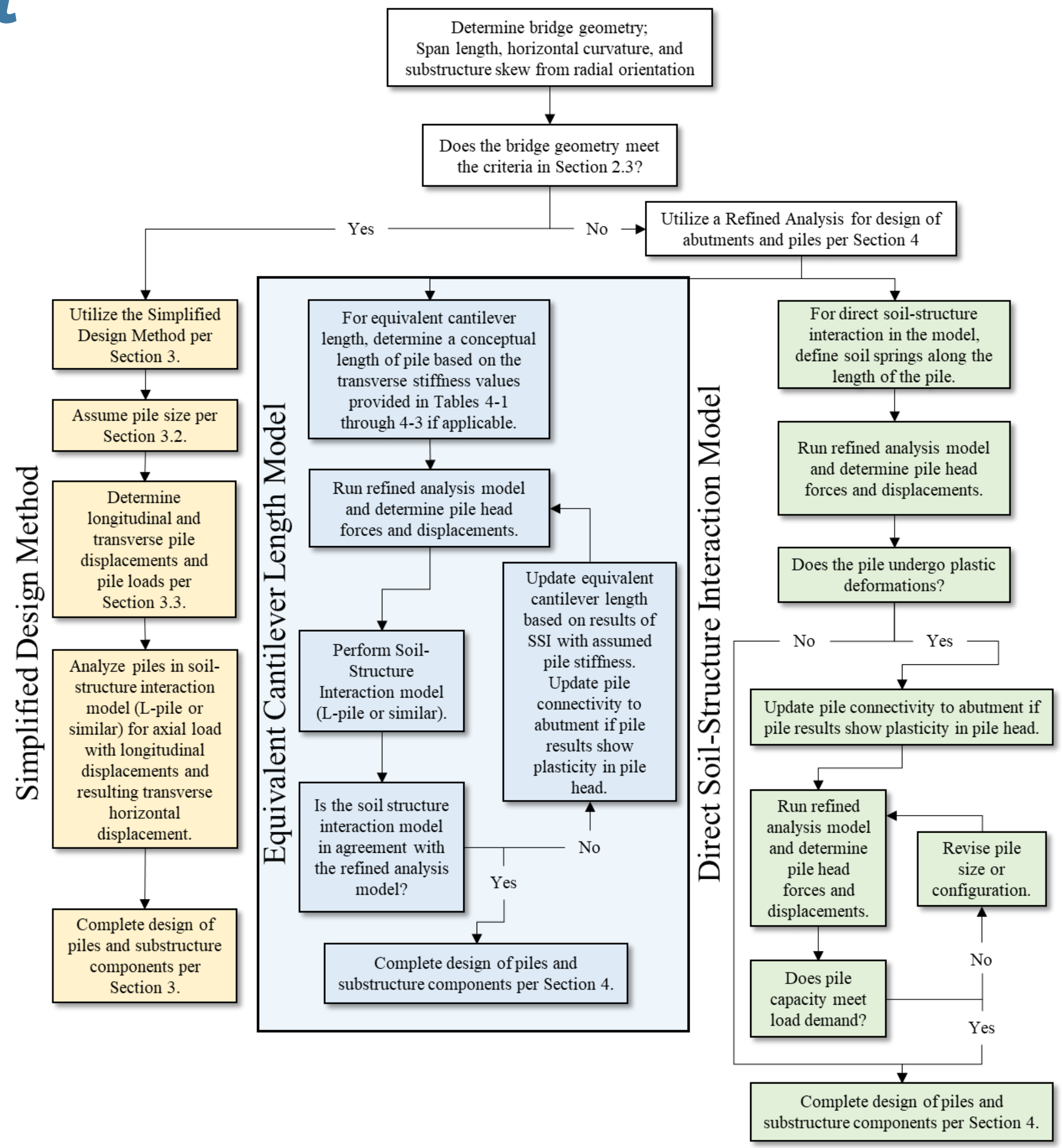
CURVED INTEGRAL ABUTMENT BRIDGE DESIGN FLOWCHART



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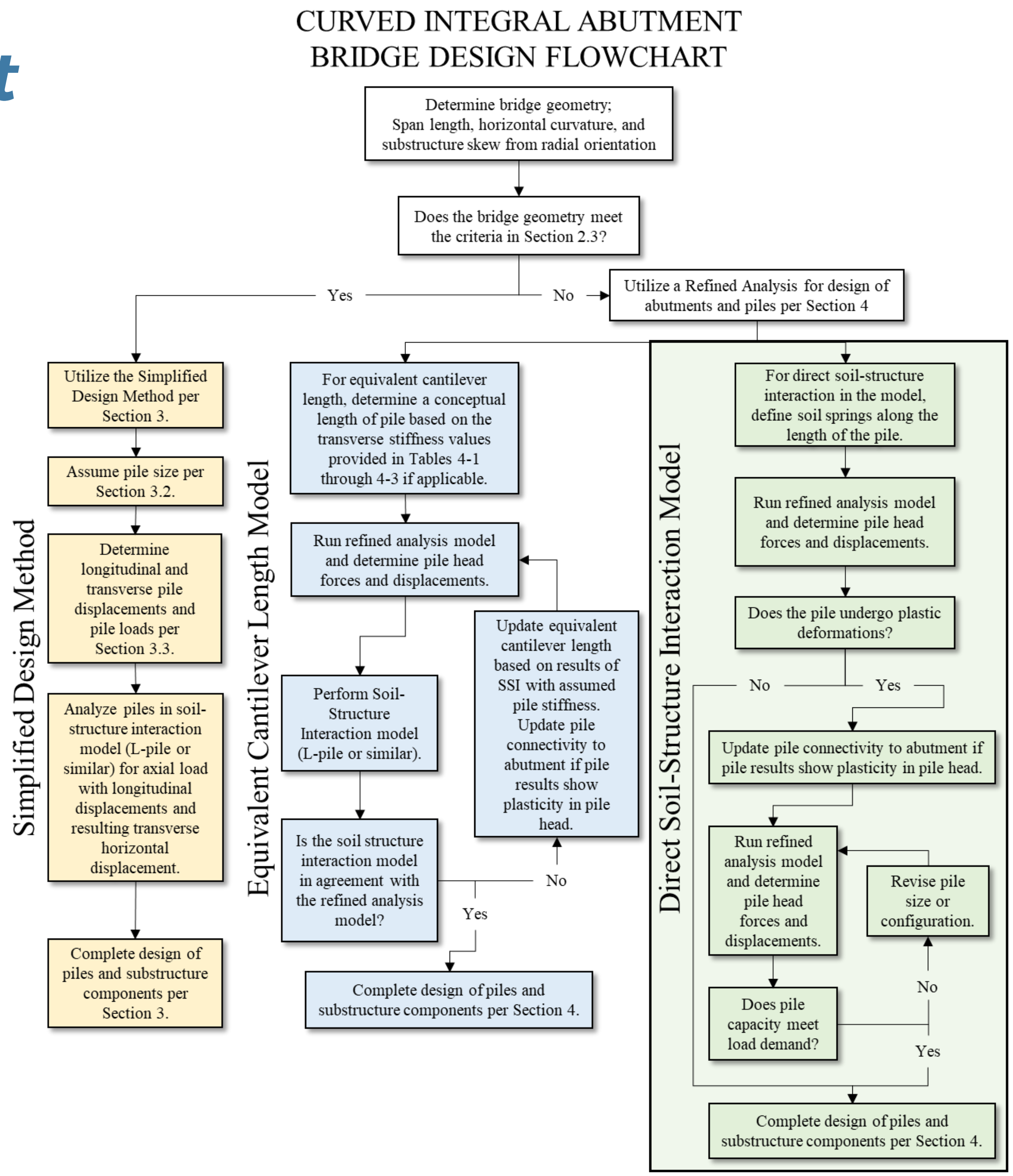
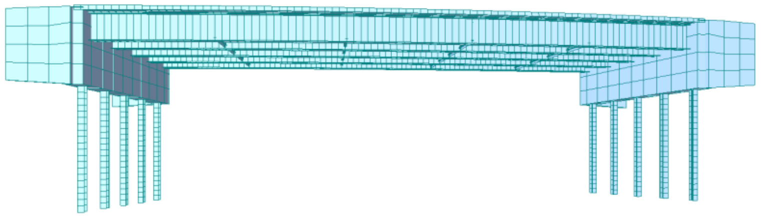
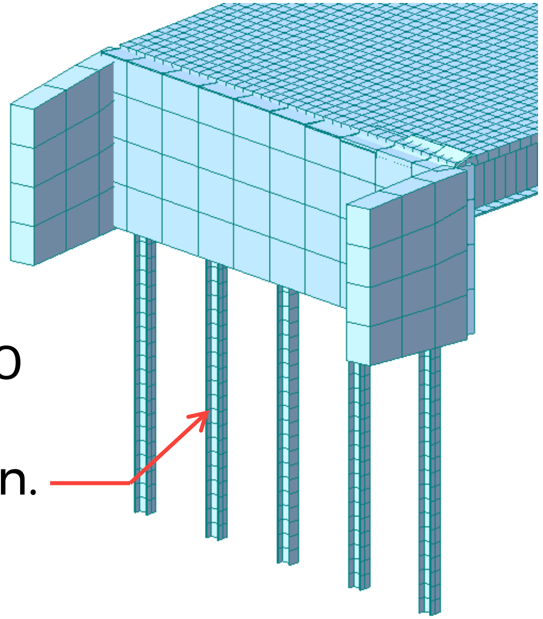


CIAB Design Guidelines

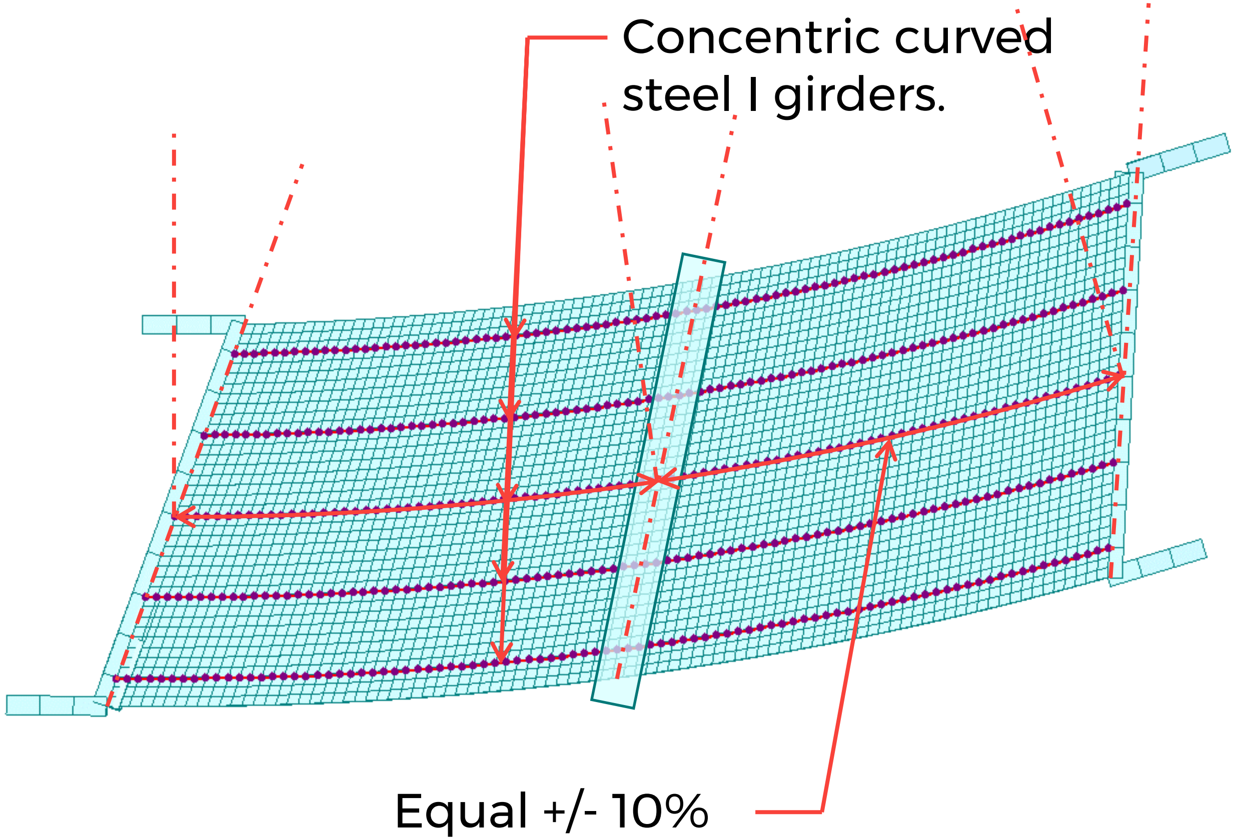
Simplified Design Method for CIAB's: Section 2 - General Design Criteria



Both abutments shall be integral connections with approach slab



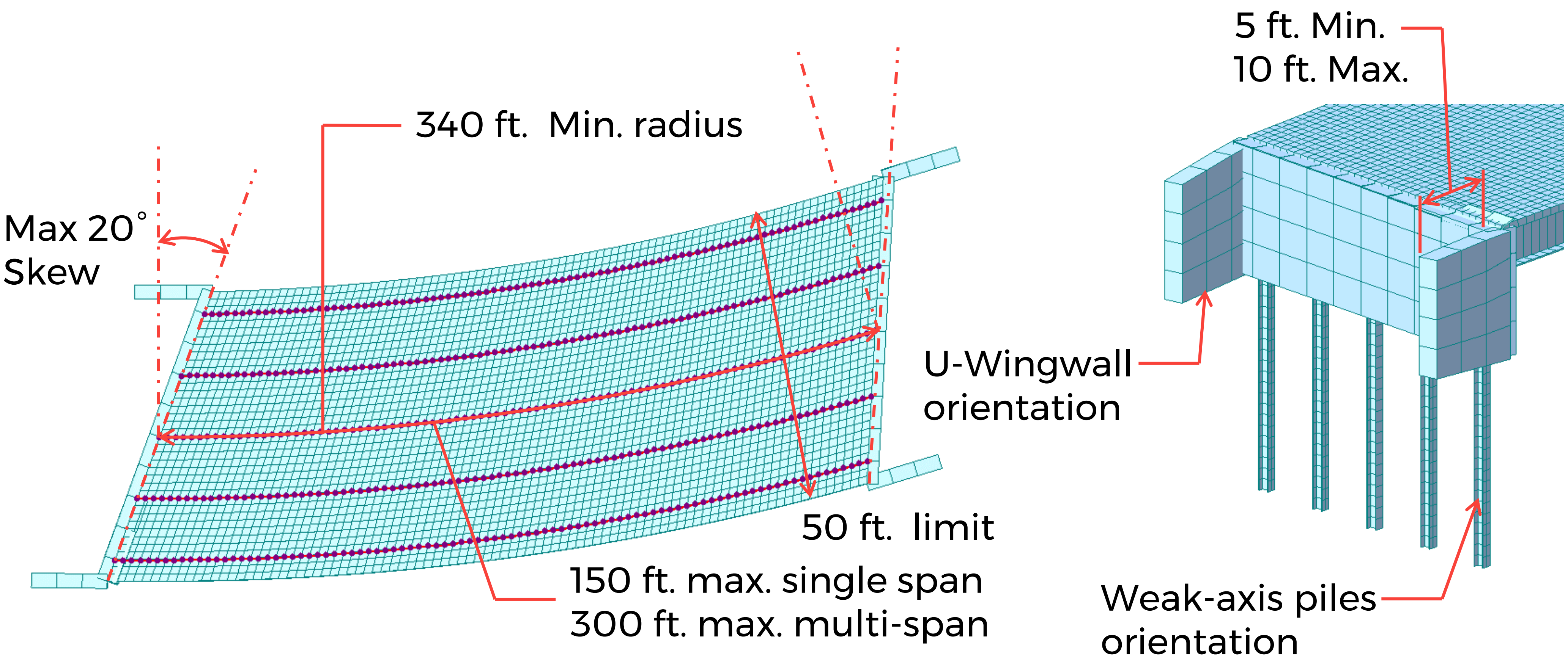
Grade 50 Steel HP10 Min.



Site shall not be subjected to extreme event loading (other than Seismic Design Category A / Seismic Zone 1 general criteria)

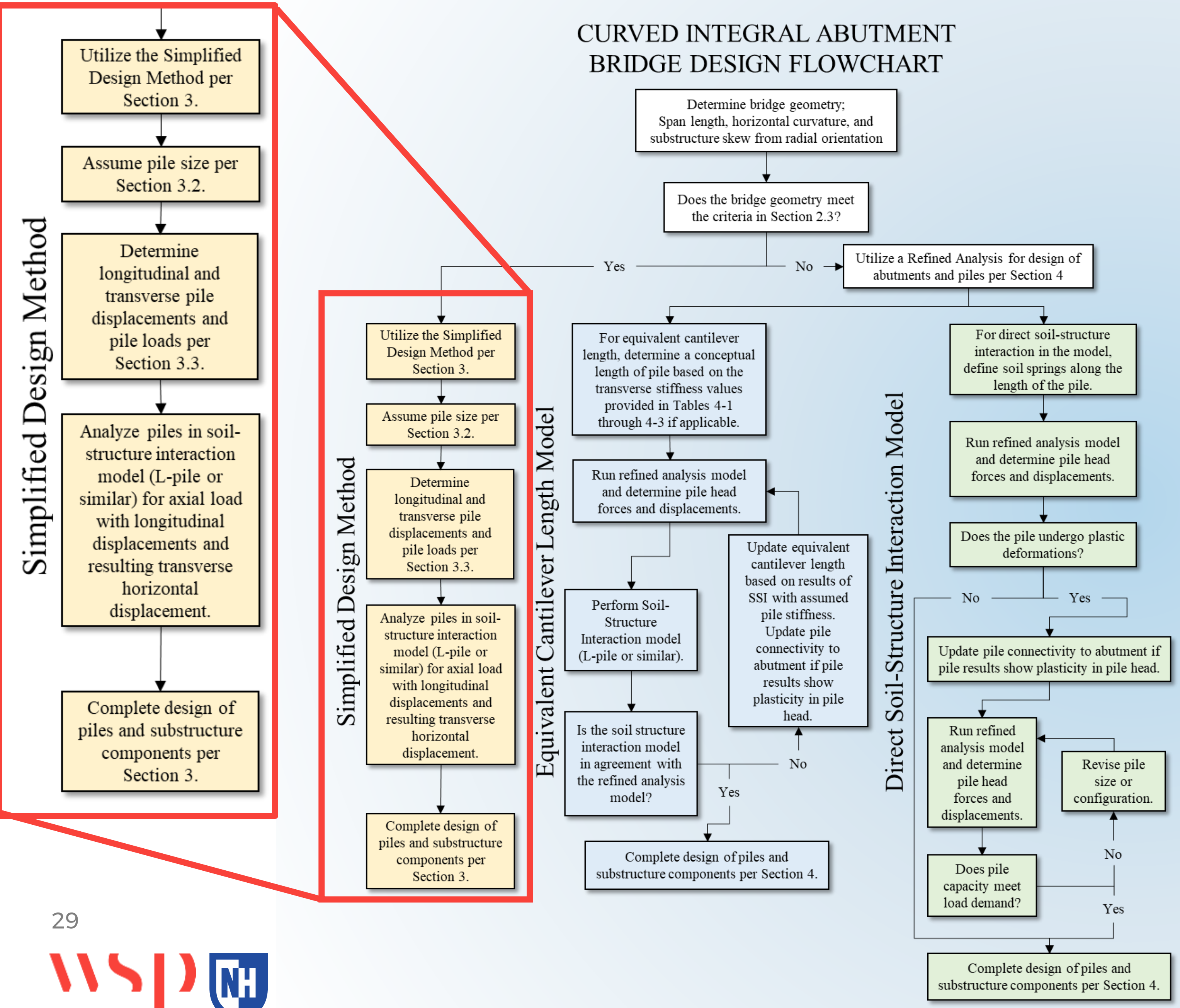
CIAB Design Guidelines

Simplified Design Method for CIAB's: Section 2 - Geometric Design Criteria

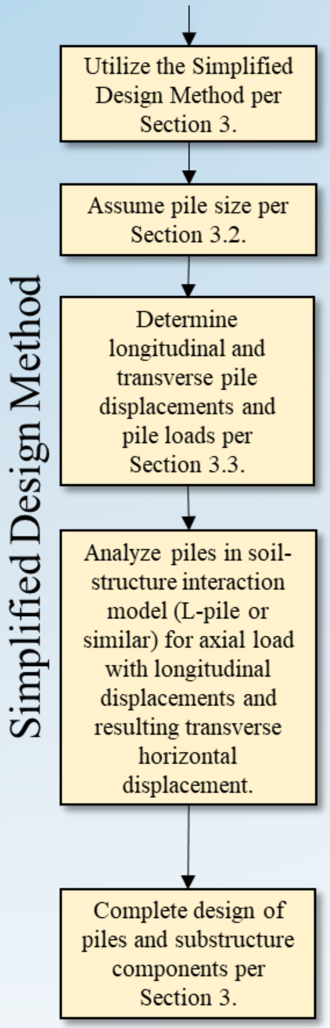


- Scour shall be considered when the abutments are located near a stream or river.
- The abutments should be of similar configuration and geometry with a difference between abutment heights at each end of the structure not exceeding 1 ft.

Simplified Design Method



CIAB Design Guidelines
Section 3 - Simplified Design Method



Meet the criteria in Section 2.

Utilize the Simplified Design Method Per Section 3.

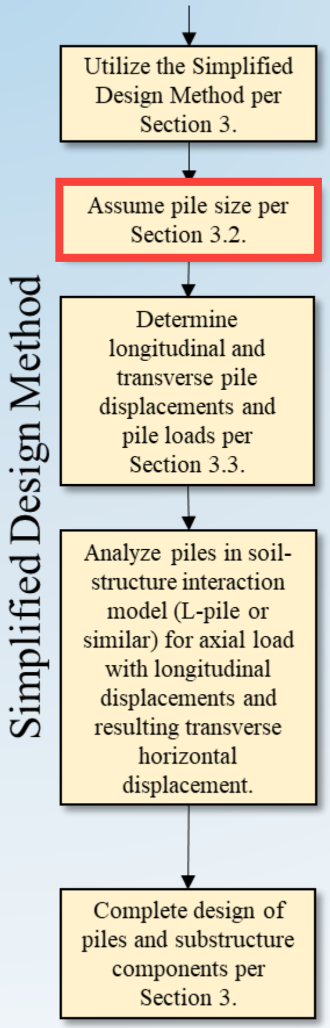
Assume pile size per Section 3.2.

Determine longitudinal and transverse pile displacements and pile loads per Section 3.3.

Analyze piles in soil-structure interaction (L-pile or similar) for axial load with longitudinal displacements and resulting transverse horizontal displacement.

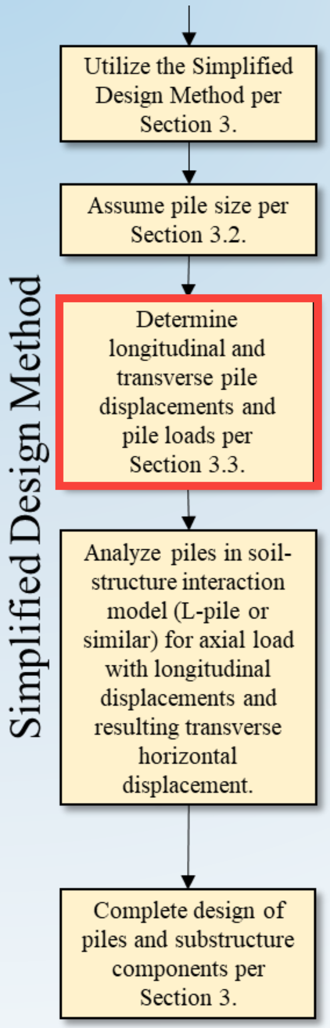
Complete design of pile and substructure components per Sections 3.3 – 3.6.

CIAB Design Guidelines
Section 3 - Simplified Design Method



- Section 3.2: Pile Selections
  - *Select pile size based on state guidance or preference*
  - *Otherwise, start with HP10 and satisfy requirements for AASHTO Section 6.9 for axial loads.*
  - *Initial pile selection based on factored axial loads less than 0.5*Fy*Ag*
  - *Weak-axis orientation of the pile*

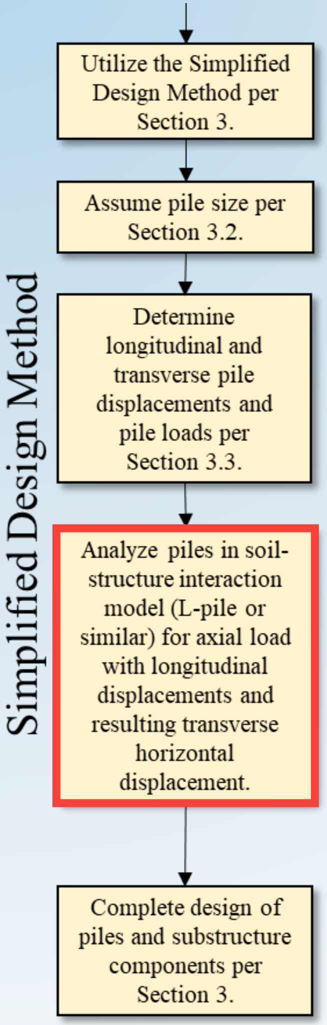
CIAB Design Guidelines
Section 3 - Simplified Design Method



- Section 3.3: Pile Head Displacements
  - *Apply thermal movements the piles based on free longitudinal displacements of the structure's arc length*
  - *Additionally, apply a transverse displacement to account for curvature and abutment skew effects*
- Transverse Displacements
  - Δ_L = *longitudinal displacement*
  - Δ_T = *transverse displacement*
  - *For 5 ft. long U-wingwalls increase* Δ_T *by 33%.*

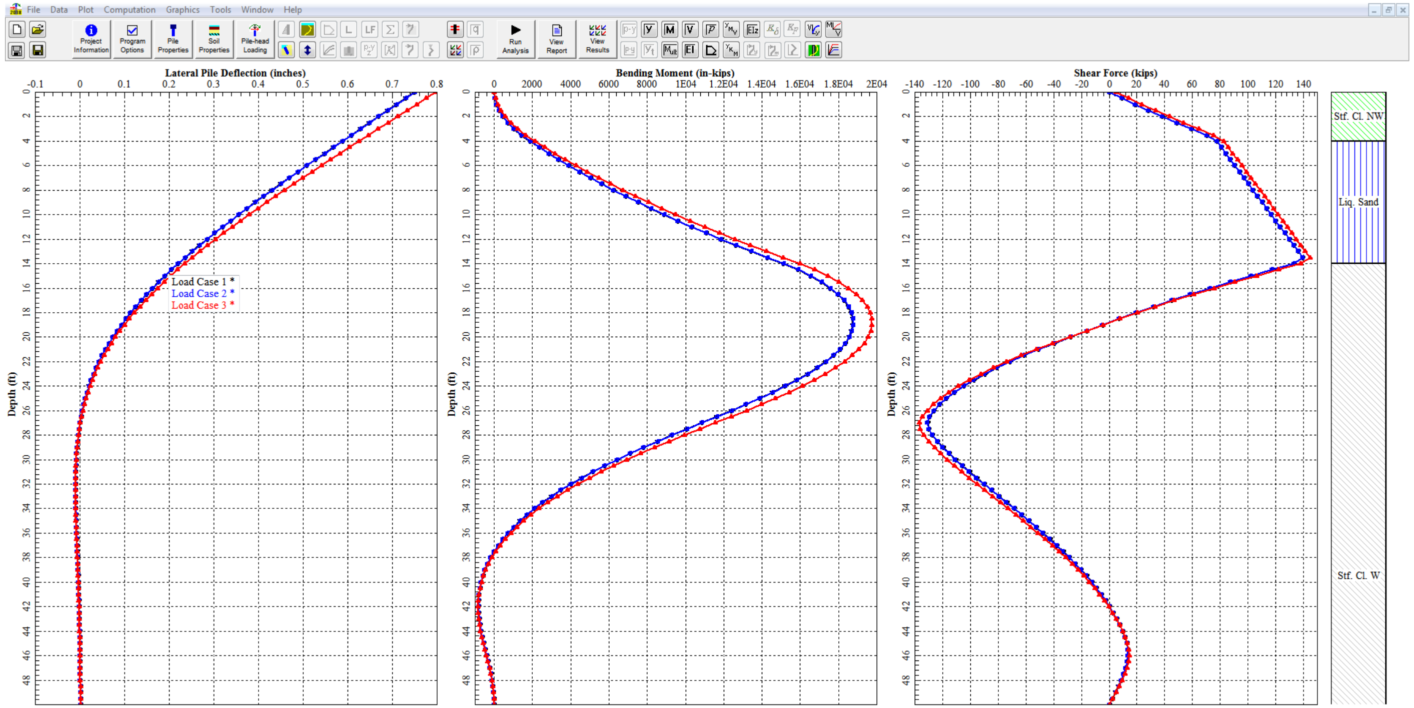
$$\Delta_T = C_T * \Delta_L$$

	Coefficient for the Portion of Longitudinal Displacement Applied in the Transverse Direction (C_T)	
Skew	Upper Limit (Radii approaching 340 ft)	Lower Limit (Radii approaching straight girder analysis)[12]
0 degrees	0.40	0.10
10 degrees	0.65	0.35
20 degrees	0.80	0.50



CIAB Design Guidelines
Section 3 - Simplified Design Method

— Analyze piles in Soil-Structure interaction model



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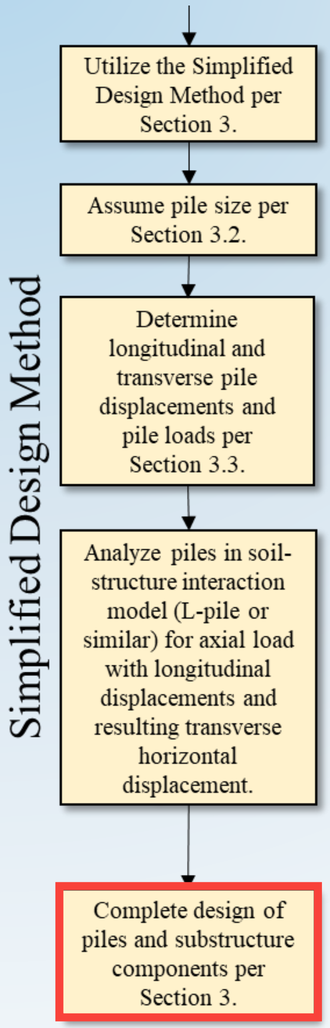
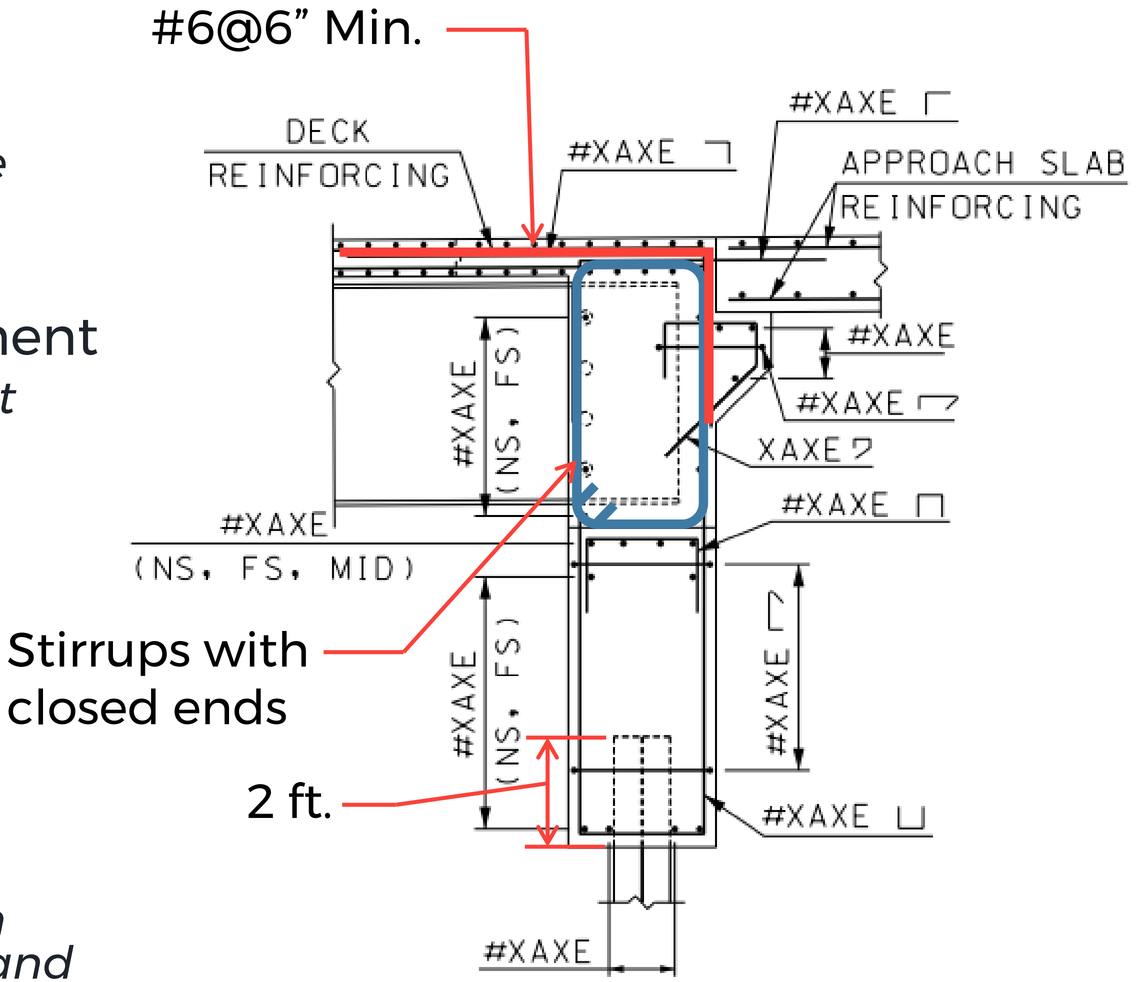
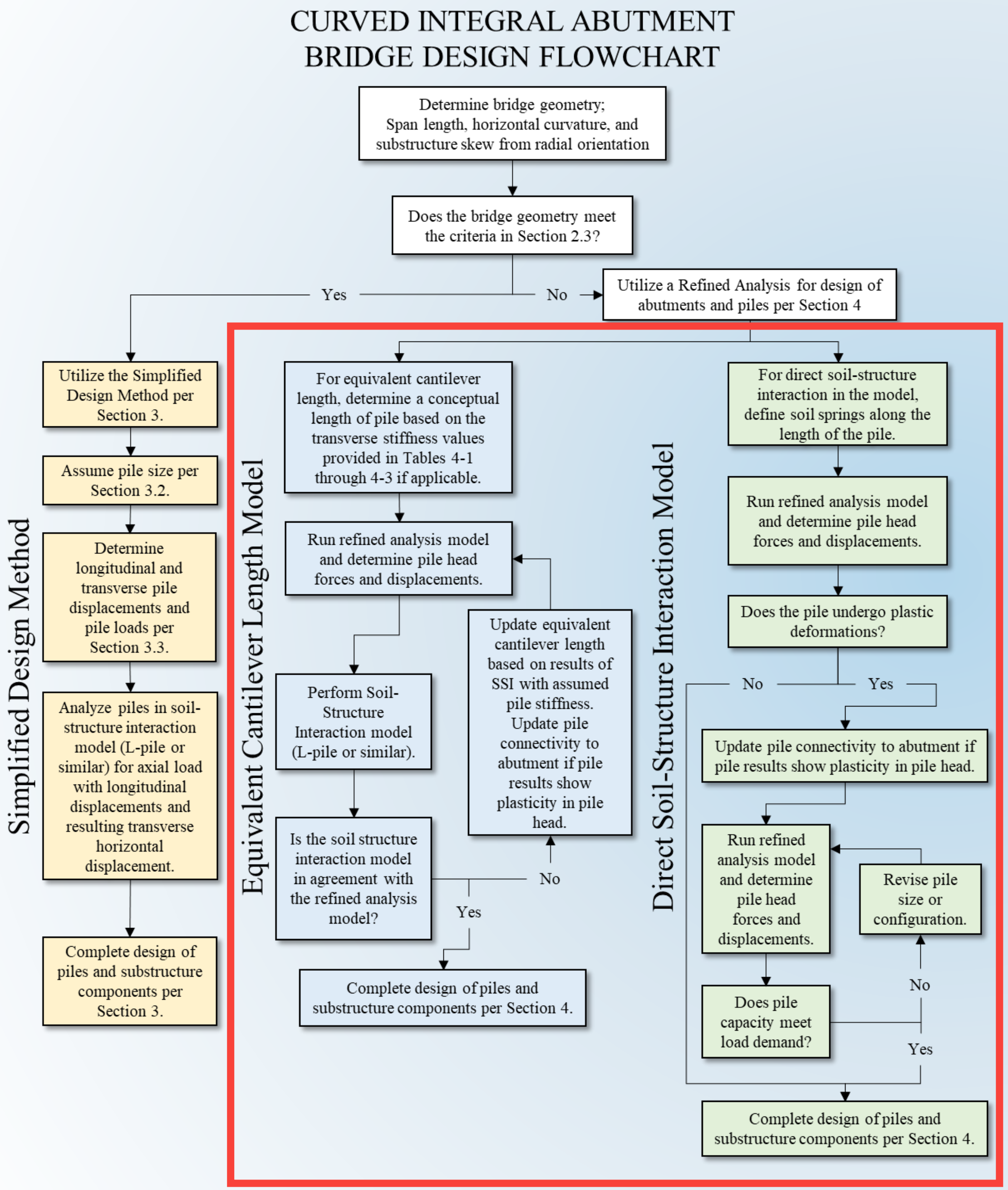


CIAB Design Guidelines
Section 3 - Simplified Design Method

- Section 3.3: Pile Design
  - *Determine pile size and required embedment based on soil-structure interaction*
  - *2 ft. embedment in pile cap*
- Section 3.4: Abutment Reinforcement
  - *Design typical for integral abutment bridges*
  - *Differential Beam end moments*
  - *Continuity Steel*
- Section 3.5: Wingwall Design
  - *Design for passive earth pressure to resist bridge displacements*
- Section 3.6: Pier Design for Multi-Span Structures
  - *Consider the effects of passive earth pressure applying a resulting force and torsion on the pier(s)*





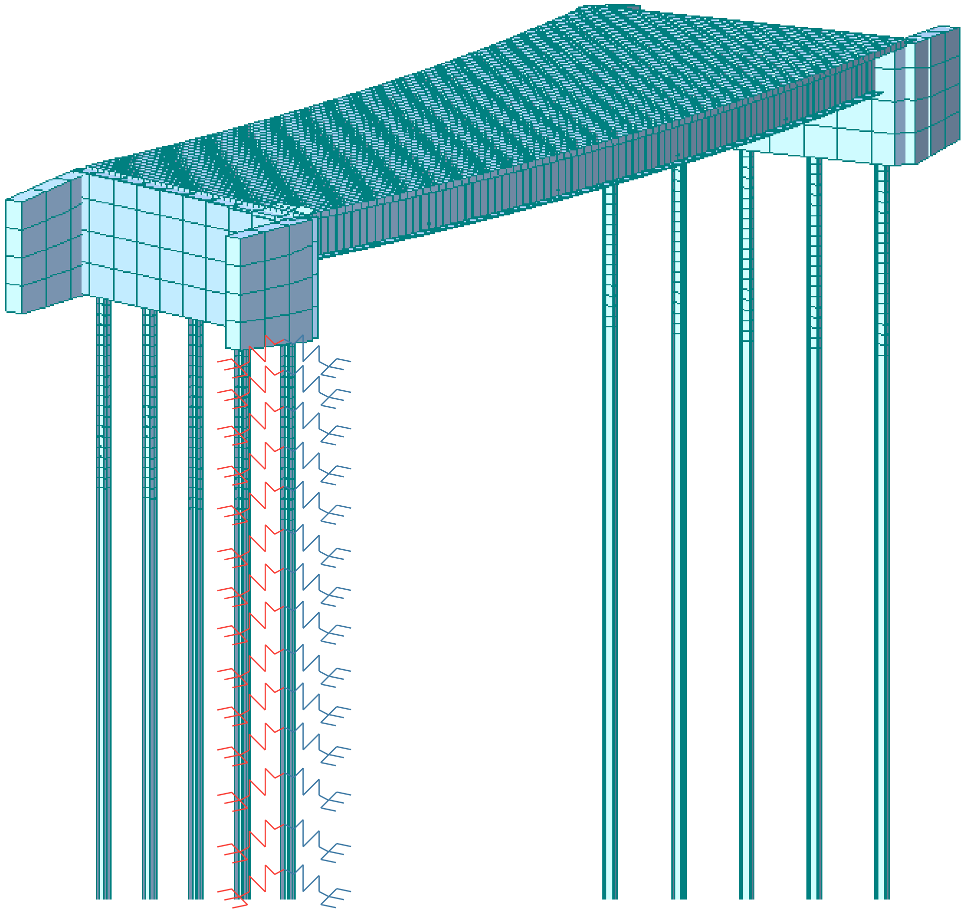
Refined Analysis

CIAB Design Guidelines
Section 4 - Refined Analysis Method

- Refined Analysis
  - *Utilize a program capable of including torsional effects if superstructure design is desired along with the pile design*
  - *Include highway geometry, all superstructure elements, all substructure components*
- Modeling Piles
  - *Direct soil-structure interaction*
    - Most accurate
    - Most complex and time consuming
    - Non-linear analysis
  - *Equivalent cantilever lengths*
    - Iterative
    - Stiffness dependent
    - Simplifies modeling
    - Linear analysis

CIAB Design Guidelines
Section 4 - Refined Analysis Method

- Direct Soil-Structure Interaction Model
  - *Soil-Structure system are modeled and analyzed in one step directly*
  - *Define soil springs along the length of the pile*
    - Transverse and longitudinal directions
  - *Run analysis to determine pile head displacements and loads*
  - *Does the pile undergo plastic deformation?*
    - Update pile connectivity to abutment and rerun analysis if plastic hinge is formed.
    - Check pile capacity vs demand
    - Revise pile size or configuration is necessary



CIAB Design Guidelines
Section 4 - Refined Analysis Method

- Equivalent Cantilever Length
  - *What pile length to assume for initial model run?*
  - *Three tables for transverse stiffness provided for 0°, 10°, and 20° skew cases*
  - *Provides designers a starting point to speed up the iterative design process*

$$K\left(\frac{kip}{in}\right) = \frac{n_{piles} * 12 * EI}{L^3}$$

Transverse Stiffness (kip/in) for 0-deg Skews						
Radius (ft)	Structure Length (ft)					
	50	75	100	150	200*	300*
340**	597	1414	2527	4949	333	495
425**	568	1108	1313	2013	282	450
500	515	1004	1157	1712	199	372
750	449	770	898	1263	82	179
1000	-	604	738	1047	82	114
1500	-	-	510	752	82	114
2000	-	-	-	618	-	114
2500	-	-	-	483	-	-

CIAB Design Guidelines
Section 4 - Refined Analysis Method

- Equivalent Cantilever Length Iterative Design Process
  - *Run analysis to determine pile head displacements and loads on piles.*
  - *Run Soil-Structure Interaction (SSI) model based on pile head displacements and loads.*
    - Determine depth to fixity (point of zero moment)
  - *Determine equivalent cantilever length and check if assumed pile length matches.*
  - *If necessary rerun analysis with updated pile lengths.*

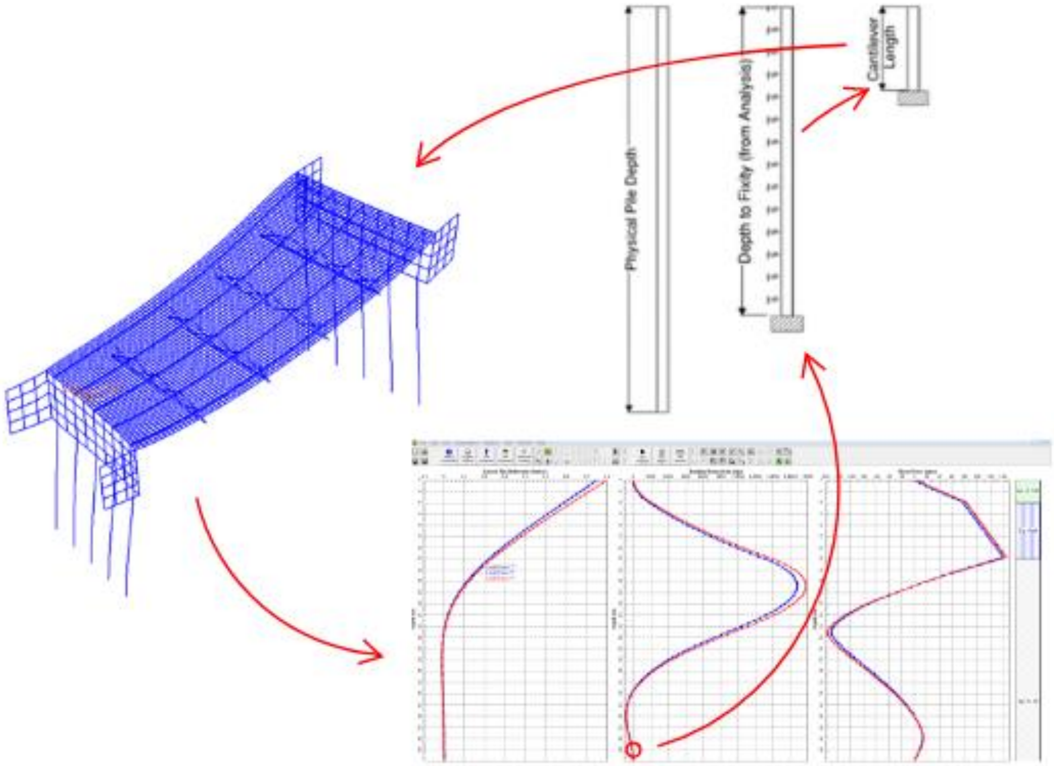


Image Source: Ensoft Inc, https://www.ensoftinc.com/products/lpile/#:~:text=LPILE%20is%20a%20special-purpose,using%20a%20finite%20difference%20approach.

CIAB Design Guidelines
Summary of Design Guideline

- Simplified Design Method
  - *No 3-D modeling required.*
  - *Design criteria in Section 2.3 should be met.*
  - *Similar approach to pile design for straight integral abutment bridges.*
  - *Determine pile head displacements based on thermal movements and lateral loads.*
  - *Determine forces in the pile subjected to AASHTO loading.*
  - *Lateral displacements included in the movement of the piles.*
  - *Multi-span pier force/torsion shall be considered for pier design.*
- Refined Analysis
  - *Two different modeling approaches for soil-structure interaction.*
  - *Provide guidance to designers on where to start for equivalent cantilever length.*
  - *Design of the piles is iterative.*

Study Questions – Curved Integral Abutments

What parameters are key to establish a simplified design method?

U-wingwalls and weak-axis pile orientation produce predictable performance.

How do these parameters impact performance?

Measurable impact on the performance but can be accommodated

What is a logical simplified design method for CIAB's?

Similar to straight integral abutments w/ additional lateral displacements applied to the piles.

What information can be provided to assist designers when a refined analysis is recommended?

Guidelines provide suggested process and stiffness tables for a starting point using the equivalent cantilever length model.

Thank you for your time!

Open Discussion / Questions

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