Curved Integral Abutment Bridge Design Guidelines

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16. Abstract
Straight integral abutment bridges have been used throughout the New England states to reduce bridge maintenance costs and extend the service life of structures. Extending integral abutment bridges to curved alignment applications offers bridge owners additional areas to reduce construction costs associated with the lengths of approaches and right-of-way acquisitions as compared to tangent alignments. The purpose of this research is to investigate the effects of various bridge parameters pertaining to the behavior of curved integral abutment bridges (CIAB's). The results are to be used to make recommendations for a simplified design method for CIAB's. The simplified design method is to be implemented in a design guideline to enhance the bridge design practice throughout the New England region. A finite element analysis parametric study was performed to investigate the behavior of CIAB's. The results of this study have been used to develop the *Curved Integral Abutment Bridge Design Guidelines* to supplement the bridge design guides for the region's state transportation agencies, and are intended to aid in the design of CIAB's that would be encountered under typical conditions in New England, including cold climate thermal ranges and low seismic hazards.

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PREFACE

This document has been developed by the New England Transportation Consortium (NETC) with the primary goal of providing guidance for curved integral abutment bridge structures. This guideline is intended to be used in conjunction with state and federal guidelines. Where the content of this guideline conflicts with the AASHTO LRFD Bridge Design Specifications or State Bridge Manuals, the more stringent guidance should control. The intent is that the requirements of the AASHTO LRFD Specifications will be met by using the recommendations in this guideline.

This guidance was developed by NETC for curved integral structures in the New England region. Therefore, load cases and considerations were based on conditions indicative of the northeast. Users are strongly encouraged to review state specific guidelines and site-specific conditions to ensure conformance with the parameters of the development of this guidance. For guidance on straight integral abutments, refer to state standards.

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The information presented within this document is a guideline that will not be applicable to all projects and is provided for information only. The information presented shall be used in conjunction with engineering principles and competent engineering judgement. In all cases, the Engineer must use professional judgment when applying information contained herein. Use of this information assumes all liability arising from such use.

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1 Curved Integral Abutment Bridges

1.1 Introduction

Integral abutment bridges (IAB) are single or multi-span structures where each abutment is monolithically connected to the superstructure system, supported by a single row of flexible piles. In conventional bridges, movement of the bridge due to loading and thermal expansion/contraction is accommodated by means of sliding or expansion bearings with joints at the ends of the bridge deck. On integral abutment bridges, the abutments are designed to displace as the bridge superstructure expands and contracts and to resist the resulting forces including the earth pressure.

Straight IAB's have been successfully utilized in multiple states to reduce life cycle costs and maintenance demands through the elimination of bearings at the substructure supports and expansion joints in bridge decks. Extension of integral abutment use to curved alignments offers an immediate opportunity to address the need to reduce bridge maintenance costs throughout the region.

The geometric complexity of curved structures can vary significantly depending on site specific conditions. Engineering judgment should be utilized to develop design criteria for components that are not covered by the design specifications of federal and state specific design standards.

NETC recently completed a research contract to study curved integral abutment bridges. The research involved a literature review and finite element study to determine the influence of various parameters on structural behavior. Updates from further research should be used to update and/or supplement these guidelines.

1.2 Implementation

These guidelines are intended to aid in the design of curved integral abutment structures that would be encountered under typical conditions in New England, including cold climate thermal ranges and low seismic hazards. These guidelines should be considered a supplement to existing state design manuals and not as standalone guidance. The document will direct designers to state design manuals for all load magnitudes and applications, state specific detailing requirements, and deck pour sequencing. Designers will also be directed to state guidelines for straight integral abutment bridges for the method of designing reinforcement in the abutment diaphragm and stem. Pile selection should follow state typical pile sizes where applicable. The intention with this approach is to allow the states flexibility in using the guidance to supplement their existing systems.

Individual states may elect to incorporate these guidelines in the following manner:

- Incorporate directly into existing structures manuals or integral abutment bridge design guidance as an appendix.
- Incorporate directly into existing structures manuals or integral abutment bridge design guidance by modifying the section numbers as appropriate to fit into the desired chapter of existing guidance.
- Refer to this guidance as a supplement to existing straight integral abutment design guidance when curved alignments are encountered on projects.
- Choose to not incorporate / not allow simplified procedures for curved integral structures.

This document should be supplemented by updates from further research. The scope of this study limited the number of parameters that could be feasibly included in the study. Further studies could refine or expand the guidance provided.

1.3 Limitations of this Document

This document is not intended to provide design requirements for superstructure components. The designer is required in all cases to perform all applicable checks for safety and stability during erection of components, regardless of the design method implemented for the substructure.

Engineering judgment for applicability and implementation of various design guidelines, including the information presented herein, shall accompany best practices for the analysis and design of various bridge components. All state and local standards shall be met for all bridge projects.

When refined analyses are recommended, the designer is encouraged to see the Manual for Refined Analysis in Bridge Design and Evaluation[1] and the AASHTO Guidelines for Steel Girder Bridge Analysis[2] for guidance on modeling techniques and requirements.

All bridges should be designed to accommodate the anticipated thermal movement range with the understanding that thermal movements in curved structures occur in both the longitudinal and transverse directions at any point in the bridge structure. Serviceability impacts relating to bridge rail transitions and pavement cracking should be considered. Movement should be accommodated using state specific detailing for approach slab connections, inclusion of sleeper slabs, and preferred joint methods when practical. In all cases, movements greater than 1½ in. are likely to be complex and may require additional detailing and joint considerations.

1.4 Superstructure Design Considerations

Design of superstructure components of curved integral abutments shall be in conformance with state and federal guidelines for curved structures, with effects of curvature, skew, rotations, and support restraint included in the analysis. Curved structures produce torsion that is restrained at the girder ends, which should be accounted for in the design of the girders and diaphragms. Superstructure components should be designed to account for additional normal flange stresses due to thermal loads and warping stresses. Thermal loads where fixity is established also contribute to flange lateral bending effects, particularly in the bottom flanges.

The design of primary and secondary deck reinforcement should be completed in accordance with state specific guidelines including bar size and spacing limitations, bar coatings, and cover requirements. Continuity reinforcement extending into the deck from the frame corners should be designed for the fixed end moments generated in the structure from superimposed dead loads (SDL) and transient loads, but should not exceed a spacing of 6 in. for control of cracking. Smaller bars at tighter spacings should be chosen over large bars at larger spacings for all deck end reinforcement where practical. The extension of the bars into the deck should extend a development length beyond the location of need, which should be

[1] (USDOT FHWA, 2019)
[2] (AASHTO/NSBA Steel Bridge Collaboration, 2014)

determined in accordance with deck stress limitations in the AASHTO LRFD Bridge Design Specifications.

Curved bridges consisting of straight beams with all beams parallel with each other should be designed as straight integral abutment bridges.

1.5 Definitions

Abutment – The support at each end of a bridge.

Abutment Stem – A large prismatic volume of reinforced concrete topping a line of embedded piles. This is typically the first placement of concrete in an integral abutment and supports the superstructure until the closure pour between the superstructure and abutment has cured. This may also be referred to as a pile cap topped by a backwall.

Closure Pour – Segment of the abutment that the girder ends are embedded into, sitting atop the pile cap. This segment can also be referred to as the diaphragm or backwall and is typically the second placement of concrete in an integral abutment.

Continuity Connection – A connection between the pile cap and deck that uses continuity reinforcement to fully transfer the forces and moments resulting from the frame action that is characteristic of an integral abutment system.

Continuity Reinforcement – Steel reinforcement required to resist the negative moments caused by frame action, which extends into the deck and reinforces the corner of the system frame. This may also be referred to as negative moment or deck end reinforcement.

Depth to Fixity – See Point of Fixity.

Effective Length – Modified unbraced length obtained by multiplying the unbraced length by the end restraint coefficient, K.

Flared Wingwalls – Wingwalls that extend from the abutment at an angle until the slope of the earth rising from the river or underpass meets the slope descending from the roadway.

Frame Action – Occurs when each end of a beam is fully embedded in its supports. Negative end moments from composite dead load and live load form along with positive mid-span moments.

In-Line Wingwalls – Short extensions off the abutment at either end that sit in line with the abutment or pile cap.

Integral Abutment – An abutment comprised of a pile cap with an embedded superstructure end, supported by a single line of piles.

Leveling Plate – A steel bearing plate that temporarily supports the end of a girder prior to completion of the closure pour, often supported by two large anchor bolts on either side of the girder to allow for elevation adjustments.

Lower Zone – The lower portion of the pile that is fully supported by earth along its length with negligible deflections.

Pile Head – The top of the pile as it becomes embedded into the pile cap.

Pile Orientation – The direction of a pile with respect to the girder web at the connection, oriented for either weak axis bending or strong axis bending.

Pile Tip – The lowest end of the pile. Typically sits on bedrock and may or may not include a special tip for driving or rock penetration.

Plastic Hinge – The onset of either full compressive or tensile yielding that occurs when an applied moment causes permanent deformation at a specific point. The boundary of these two failure zones is the neutral axis.

Point of Fixity – Depth required to achieve zero deflection and rotation in the pile under applied loads.

Pre-bore – Excavation of the top strata of rocky or otherwise rigid earth to control the soil condition surrounding the upper zone of the pile, allowing it to deflect as required.

Simplified Design Method – A design methodology presented in this guide that simplifies the design process for curved integral abutments by using general assumptions in the way the bridge will perform.

Simply Supported – A beam supported by a pin and roller in the vertical and lateral directions. Rotational degrees of freedom are released to allow rotation at the support.

Skew – The angle between the centerline of bearing and a transverse line oriented 90° to the tangent of the alignment where it crosses the centerline of bearing.

Strong Axis Bending – Bending of a section about the axis with the greatest flexural resistance. This equates to bending about an axis parallel to the flanges in I sections.

Total Allowable Movement – The maximum allowed longitudinal movement at the abutment caused by expansion or contraction from shrinkage, creep and temperature effects in the deck.

U-Wingwall – Wingwalls that extend backwards from the abutment on a line parallel to the roadway alignment. In abutments with no skew, the wingwalls are perpendicular to the back face of the abutment.

Unbraced Length – The length of a pile considered to be laterally unbraced.

Upper Zone – The top portion of the pile that experiences measurable deflections due to bending.

Weak Axis Bending – Bending of a section about the axis with the least flexural resistance. This equates to bending about an axis parallel to the web in I sections.

1.6 Notation

Additional notation not defined herein shall be as identified in the AASHTO LRFD Bridge Design Specifications.

A_s = cross sectional area of steel pile

C_T = correction factor for lateral displacement

F_y = yield strength of pile

K = effective length coefficient for column buckling

L_b = unbraced length

M_p = plastic moment capacity of a steel pile

$M_{p'}$ = moment that creates a plastic hinge at the pile head with an axial load applied

M_r = flexural resistance of the pile

M_u = factored applied moment

P_n = nominal structural pile resistance

P_r = factored structural pile resistance

P_u = factored applied axial load

R = radius of curvature of roadway alignment

Δ_L = expected unrestrained thermal displacement of the superstructure in the longitudinal direction

Δ_T = thermal displacement in the transverse direction

ϕ_c = resistance factor for compression in a pile

ϕ_f = resistance factor for flexure in a pile

ϕf_r = factored modulus of rupture of the concrete

2 Design Criteria

2.1 Use of Design Criteria

The research supporting this documentation has been completed for curved steel I sections only. Chorded bridges, steel tub girder bridges, concrete bridges of any type, etc. require refined analyses if intended to be used in a curved integral setting.

In addition, the research supporting this documentation has been completed for steel H piles only, oriented for strong or weak axis bending.[3] This document is not applicable for the use of micropiles, pipe piles, concrete-filled steel tubes (CFST's), or timber piles.

The simplified design method discussed in Section 3 is based on the criteria noted herein. For curved integral abutment bridges that do not meet the criteria required for simplified design, a refined analysis is recommended. It is important to note that bridges that do not meet the criteria noted in Section 2.2 are not disqualified from utilizing an integral abutment support system but should be analyzed fully as noted in Section 4 rather than by simplified methods.

Approach slabs and integral abutment standard end details should conform to state standards except for continuity reinforcement, which should consist of a minimum of #6 bars at 6 in. spacing with adequate development into the abutment and the deck. Smaller bars at tighter spacing should be chosen over large bars at larger spacing for all deck end reinforcement where practical. Extension of bars into the deck should provide reinforcement a minimum of the development length beyond the point where flexural stresses in the deck reach ϕf_r from frame behavior, or the development beyond the construction phase joint at the deck end, whichever is greater.

Criteria for meeting simplified design requirements were selected in part to decrease out of plane effects from curvature and variable soil conditions. In particular, the limitation to U-wingwalls orientation is meant to reduce the structure sensitivity to geometric parameters and soil characteristics. This configuration allows for predictable pile responses such that they may be designed independently from the superstructure. Both skewed structures and curved structures require additional considerations for reinforcement in the deck ends, which may be evaluated conservatively using a superstructure-only model with enveloped boundary conditions (pinned and fixed).

2.2 Site Considerations

Complex geometric conditions have been successfully accommodated by bridge structures throughout the United States. Skews and increasing curvature on steel bridges present complexities for design, analysis, fabrication, and erection that may increase costs. Skew angles should be eliminated or minimized to the extent possible through adjustments to the alignment, span length, or both. Compound and complex curvature, including spirals, and superelevation transitions should be limited to roadway approaches. If complex geometry on the bridge structure is unavoidable due to adjacent geometric site constraints, the appropriate refined and complex methods of analysis should be implemented. This guideline is intended to aid the designer in designing the majority of integral abutment bridge structures that would be encountered on a simple horizontal curve in New England.

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[3] (WSP USA Inc. and UNH, 2023)

Given the shorter abutment height required, integral abutment bridges tend to provide a larger hydraulic opening than required. The designer should coordinate the required clear span and bridge clearance with the site-specific hydraulic report. The stability of the structure should be ensured considering the anticipated scour has occurred, which may require driving the piles deeper than determined by design. This requirement is intended to ensure that failure will not occur in an extreme scour event.

In soil conditions where settlement is anticipated, the designer should consult with the geotechnical engineer to ensure that the piles are designed adequately for additional effects not typically included in the simplified method, such as downdrag. The simplified method may still be used with downdrag effects considered; however, engineering judgment should be utilized for larger anticipated settlements and refined analyses should be conducted if warranted. Generally, this guideline relates to piles driven through non-cohesive soils to bedrock. Design issues including skin friction, settlement, and downdrag have not been fully explored in this guideline. If these issues are a concern, review AASHTO LRFD Section 10 and consult with geotechnical and state engineers as appropriate to determine the applicability of the simplified method.

The research did not investigate bridges supported on short piles with pinned end supports, which may be caused by site conditions such as shallow bedrock where pile fixity cannot be achieved. Where high bedrock conditions are encountered, the designer should coordinate with the applicable state bridge engineer to determine whether pre-boring, blasting, or alternative bridge solutions should be considered to achieve pile fixity.

Site conditions that require a multi-span structure warrant additional analysis based on the structure parameters. Piers with bearings fixed for translation help to limit global translation of the structure but result in additional forces on the intermediate piers. A method for conservatively approximating these force effects is provided. This method may result in extreme over-conservatism in cases with small curve radii and skewed substructure components, particularly if the skews at the two ends are in opposite directions. Refined analysis is recommended in cases where a less conservative approach is desired.

2.3 Criteria for Use of the Simplified Design Method for Curved IAB's

The following criteria shall be met for use of the Simplified Design Method presented in Section 3.

2.3.1 General Criteria for Curved IAB's

- Both abutments shall be integral connections.
- Superstructure must consist of concentric curved steel I girders.
- Piles shall be Grade 50 steel H piles with a minimum flange width of 10 in.
- Multi-span bridges shall have equal span lengths +/- 10% for each individual span.
- Approach slabs shall be included to reduce impacts of approach settlement and live load surcharge on the abutment.[4]
- Site shall not be subjected to extreme event loading (other than Seismic Design Category A / Seismic Zone 1 general criteria).

[4] Approach slabs should be designed and detailed according to typical state standards but should be designed to accommodate the anticipated movement of the abutment.

2.3.2 Geometric Criteria for Curved IAB's

The curved integral abutment bridge shall consist of the following geometric requirements:

- The maximum total bridge length, as measured along the curve at the bridge centerline and between the centerlines of bearing at the abutments, shall be 150 ft. in a single span and 300 ft. for multi-span bridges.[5]
- Bridge width is limited to 50 ft.[6]
- The horizontal curve radius shall be 340 ft. or greater, measured at the center of the bridge.[5,7]
- The substructure components shall have a maximum skew of 20 degrees from the radial orientation. Substructure components are permitted to have different skew angles but must be skewed in the same direction.[5,8]
- Piles shall be orientated for weak axis bending with the pile webs perpendicular to the tangent line of the girders at the mid-width of the bridge at each abutment.[9]
- A minimum pile embedment length below the bottom of the abutment stem of 10 ft. is required.[10]
- Piles must achieve fixity.[11]
- Scour shall be considered when the abutments are located near a stream or river.[12]
- Wingwalls shall be monolithic cantilevered U-wingwalls with a minimum length of 5 ft. and a maximum length of 10 ft., as measured from the back face of the abutment.[5,13]
- Maximum abutment heights should be as indicated in state standards for integral abutments of straight bridges. If no standard exists, abutment height shall be limited to 12 ft. from finished roadway grade to bottom of cap to reduce passive earth pressure effects. The difference between abutment heights at each end of the structure should not exceed 1 ft.

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[5] The limits for this criterion are based on the parametric study that was performed.

[6] Larger width curved structures may produce complex thermal movements.

[7] A refined analysis is recommended for bridges with a radius less than 340 ft. to accurately account for pile head displacements.

[8] Bridges with unequal skews at the different substructure components were not investigated in the parametric study but can be adequately designed for using the simplified design method.

[9] The research concluded that weak-axis orientation of the piles resulted in significantly lower lateral displacements when compared to strong-axis orientation. Due to the nature of horizontally curved abutment bridges, lateral displacements occur at the abutments which must be restrained to prevent maintenance and serviceability issues. In weak-axis orientation, the strong axis of the piles helps resist these lateral displacements. Additionally, the research concluded that weak-axis orientation of the piles provides more flexibility under thermal expansion and contraction loading in the longitudinal direction as compared to the strong-axis orientation of the piles.

[10] The 10 ft. embedment depth is based on best practice for straight integral abutment bridges.

[11] Where high bedrock conditions are encountered the designer shall coordinate with the respective state bridge engineer to determine whether pre-boring, blasting, or alternative bridge solutions should be considered. Piles with pinned ends, such as in cases with shallow bedrock, shall be designed using refined analysis.

[12] Generally, abutment foundations near streams and rivers are protected by riprap or other means. Unprotected abutment foundations near stream or river channels, or based on state and local design requirements, that result in scour conditions, should be evaluated in the soil-structure interaction analysis. Larger pile sizes may be required for the unbraced length under the scour condition.

[13] The research concluded that U-wingwall orientation resulted in significantly lower transverse moments of the pile heads when compared to the inline orientation. The large soil mass contained between the U-wingwalls help to restrain the abutment movement and provide favorable displacements for maintenance and serviceability, independent of piles length, skew and radius. Flared wingwalls fall outside the parametric study that was performed. Any wingwall length beyond 10 ft. shall be designed as a freestanding retaining wall with an expansion joint between the freestanding wall and the cantilevered wing capable of accommodating the full abutment movement in the longitudinal and lateral directions, or as directed in state standards for straight integral abutment bridges.

- The abutments at each end of the bridge should have similar configuration and geometry.

Bridges falling outside the above parameters have characteristics that were either not investigated in the research or produced unacceptable results, deflections, or stresses. A structure that falls outside the criteria stated above may require more detailed analysis, such as the refined analysis outlined in Section 4. If approved by the bridge owner, the engineer of record may use engineering judgement to extend the limits for bridge length, bridge width, or radius of curvature for use with the Simplified Design Method. Extending these limits should be evaluated on a case-by-case basis to ensure that the effect on the behavior of the structure is limited.

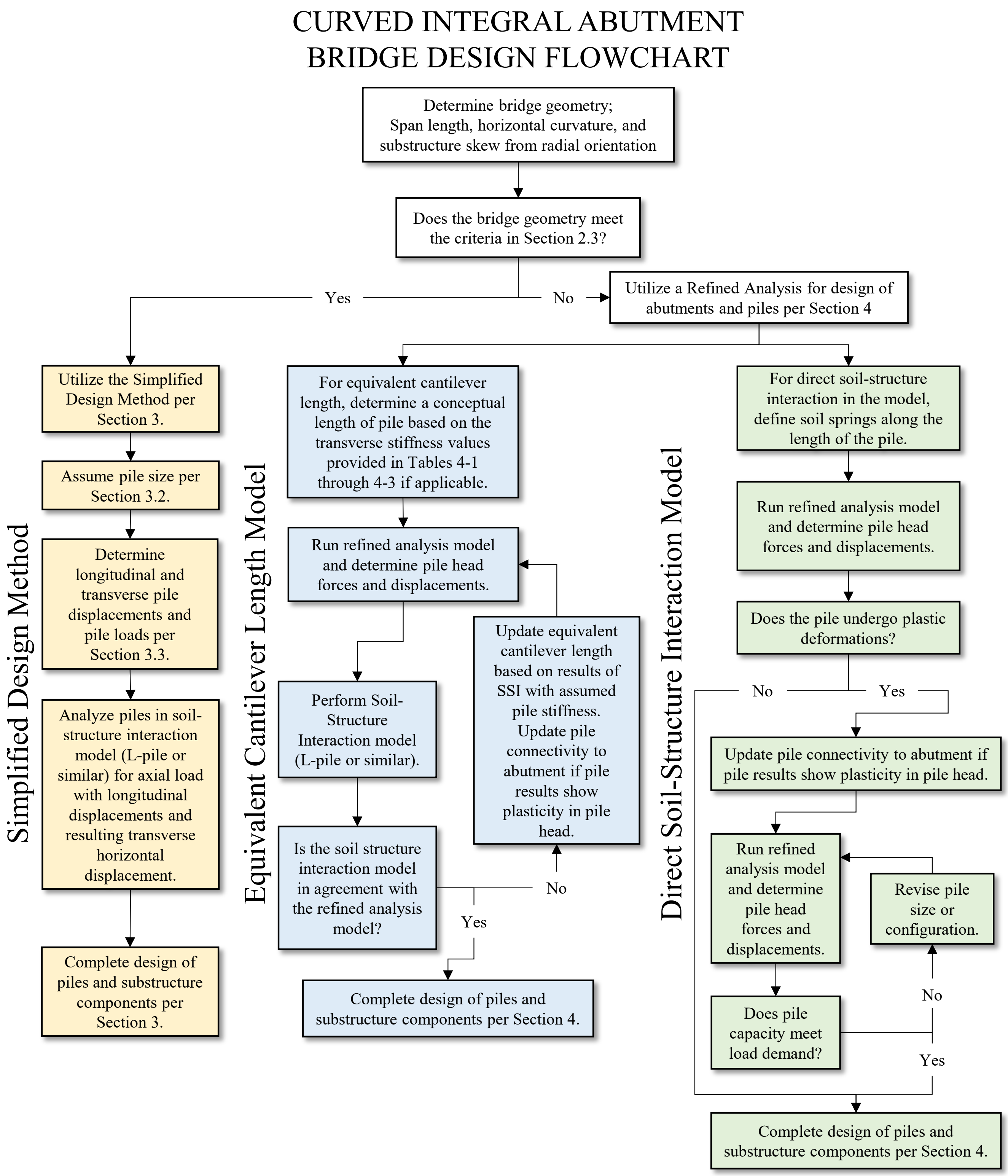
2.4 Loading Assumptions for Design Criteria

The following loading assumptions were considered in the development of these guidelines. Exceedance or variance from these loading conditions may require a refined analysis. Engineering judgment shall be implemented in all cases.

- Dead Load of Components, DC1 and DC2: Dead loads are applied in stages with noncomposite properties utilized for girder designs for self-weight and wet concrete, with long term composite section properties utilized for long term composite dead load. An 8 in. thick composite concrete deck is assumed with standard concrete barrier.
- Dead Load of Wearing Surface and Utilities, DW: Wearing surface weight assumed as 3 in. of asphalt applied equally to all girders. No provisions have been made for utilities. The designer should coordinate with the governing state agency for utilities penetrating through the abutment stem wall and ensure adequate detailing to accommodate movement of the abutment.
- Live Loads, LL: HL-93 Live Load and HL-93 modified Live Loads (125% increase) were considered
- Live Load Surcharge, LS: Live load surcharge need not be considered when approach slabs are present. Default to state guidance. If LS loads must be included in the design of the frame system, a refined analysis is recommended. If LS loads are applied to the abutment explicitly for the design of reinforcement in the abutment in accordance with state standards and an approach slab is present, the simplified design method may be used.
- Braking Forces, BR: Standard braking forces were considered with all lanes traveling in the same direction.
- Centrifugal Forces, CE: Centrifugal forces were determined according to the AASHTO LRFD Specifications Article 3.6.3 with the exceptions discussed below. In most cases the centrifugal force on an abutment for a horizontally curved bridge will be small and easily resisted by the abutment foundation. The number of lanes loaded for CE were tied to the number of lanes loaded for live load. Superelevation effects were included in the models.
- Thermal Loads, TU: Thermal contraction and expansion for steel structures in cold climates (Procedure A).
- The thermal load factor, γ_{TU}, shall be 1.0 for steel substructures in accordance with AASHTO LRFD Article C3.4.1. All other load factors and combinations shall be in accordance with AASHTO LRFD Tables 3.4.1-1 and 3.4.1-2.

2.5 Design Flowchart

The following flowchart may be used by the designer to assist in determining the order of design for the curved integral abutment bridge:



3 Simplified Design Method

3.1 Assumptions

The following is intended to provide guidance on the design of integral abutment pile supports for curved bridges. It is not intended to be all inclusive. The designer is responsible for ensuring that any code updates and local guidance are incorporated in their design. Bridges designed by this process may be more conservative than those designed following a more detailed or refined analysis method.

The following assumptions are made for the simplified design of curved integral abutment structures:

- All loads are applied as simply supported for the design of positive moments and with fixed ends for negative bridge end moments in the superstructure.
- The plastic moment of the pile section is impacted by the applied axial load, in that the moment required to cause a plastic hinge (M_p') will decrease as axial loads increase. Once a hinge is formed, allowable axial loads transmitted to the piles will be as determined by the interaction equation in AASHTO LRFD 6.9.2.2 using M_p' as the limit to the applied moment.
- Thermal movement is distributed equally to both abutments.

Dynamic load allowance should be considered in calculating the axial force of the piles.

3.2 Pile Selection

Each state has preferences for pile size usage on straight integral abutment bridges, which are based on many factors including availability, design preferences, researched pile sizes and other factors. As such, it is recommended that pile sizes be limited to those specified by state guidance for straight integral abutment bridges, if possible. If no guidance is given, pile sizes shall be HP10 or larger and shall satisfy the requirements of AASHTO LRFD Section 6.9 for axial loads. If the preferred pile sizes of the state are not adequate for the methods presented in Section 3.3, a larger pile size should be chosen. An initial pile selection can be based on factored axial loads less than $0.5*F_y*A_s$.

3.3 Pile Design

Piles shall be designed for structural resistance to the applied loads and expected displacements. This will generally be governed by the strength limit state requirements. Piles shall also be checked for geotechnical pile driving capacity. Service limit states are uncommon for pile supported integral foundations, however, serviceability checks should be incorporated as required on a site-specific basis, if issues such as settlement are expected to occur.

The criteria for the use of simplified design methods were developed with the intention of limiting the lateral effects typically seen in curved structures. If all criteria described in Section 2 for the simplified method are met, the designer may elect to utilize the state specific procedures for the design of piles on straight integral abutment design guidelines, with the exception of the following:

- Thermal movements in a curved structure will occur on a resultant line that does not correspond orthogonally with the weak or strong axis pile orientations. Lateral thermal movements shall be estimated from bridge geometry with prescribed displacements in each orthogonal direction applied to the pile head. Biaxial bending should be considered with the interaction equations of AASHTO LRFD Section 6.9.2.2 with the out of plane moment resulting from lateral movement used to limit the moment required to generate a plastic hinge (M_p').

If no procedures exist, or if the designer is directed by the governing state officials, the following steps for pile design may be used (See Figure 3-1 and Figure 3-2).

- Determine the applied vertical loads and resultant displacements from thermal loads, including downdrag should it be deemed necessary.
    - Longitudinal displacement is equal to the expected unrestrained expansion and contraction magnitude for the structure length and applied thermal range.
    - Transverse displacement is defined by Table 3-1, based on the bridge curve radius and abutment skew angle.
- All lanes should be assumed loaded for live load, and all dead and live loads are equally distributed to the piles with the design truck positioned to produce maximum reaction at the abutment. Dynamic load allowances and multiple presence factors should be included.
- Select an initial pile size based on factored axial loads less than $0.5*F_y*A_s$.
- Determine the structural pile resistance in accordance with AASHTO LRFD Section 6.9.4.1 and the flexural resistance applicable to both pile axes. The weak axis pile orientation will be governed by AASHTO LRFD Section 6.12.2.2.
- Apply vertical loads and thermal displacements in L-Pile or equivalent soil structure interaction program to determine the pile depth to fixity and internal moments.
- Apply the appropriate resistance factors for the upper and lower pile zones and calculate the factored pile resistance and moment capacity.
- Upper Zone, Top Segment:
    - Determine if the applied moment on the pile as a result of the applied displacements and vertical loading will cause the pile head to reach plastic deformations by using the interaction equation for combined axial and flexural load effects within a pile.
        - If the plastic moment M_p’ is not reached, no further analysis is required.
        - If M_p’ is reached, then a plastic hinge will form which will allow pile head rotations under a constant moment (M_p’). This will change the unbraced length of the pile as the pile head becomes a pinned connection. Repeat the L-Pile or equivalent analysis using the axial loads, displacements, and M_p’. This will change the depth to fixity of the pile. Recalculate the pile axial capacity using these revised conditions together with the strong axis moment demand calculated from lateral movement and an effective length factor of K = 2.1.
        - Check local buckling of the pile flange and web.
- Upper Zone, Second Segment:
    - From the final analysis run of the top segment of the upper zone, determine the unbraced length and maximum moment of the second segment. Using an effective length factor K = 1 for pinned-pinned behavior, determine the flexural resistance of the second segment and ensure AASHTO LRFD interaction equations are satisfied.
- Lower Zone:
    - Check axial capacity against the nominal yield resistance ($P_o = F_yA_s$) multiplied by the appropriate resistance factor ($\phi_c = 0.5$ when pile tips are required or $\phi_c = 0.6$ if pile tips are not required, or as recommended in the geotechnical report).
- Check that the shear capacity of the pile is adequate to resist the maximum shear load effect.
- Check the Geotechnical resistance and pile driving resistance.
- Review the final design.

The upper zone consists of the top of the pile to the point of fixity of the pile. The lower zone is the point of fixity to the pile tip. Fixity occurs at the second point of 0 deflection on the L-Pile deflection curve.

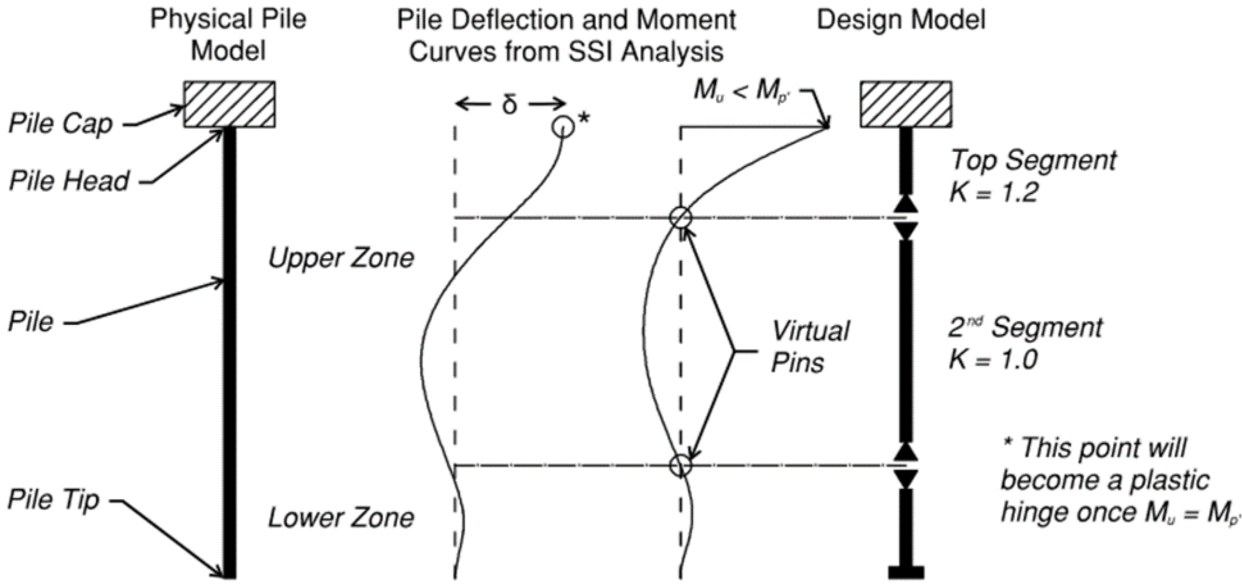


Figure 3-1:Pile Design Model When $M_u < M_p$'

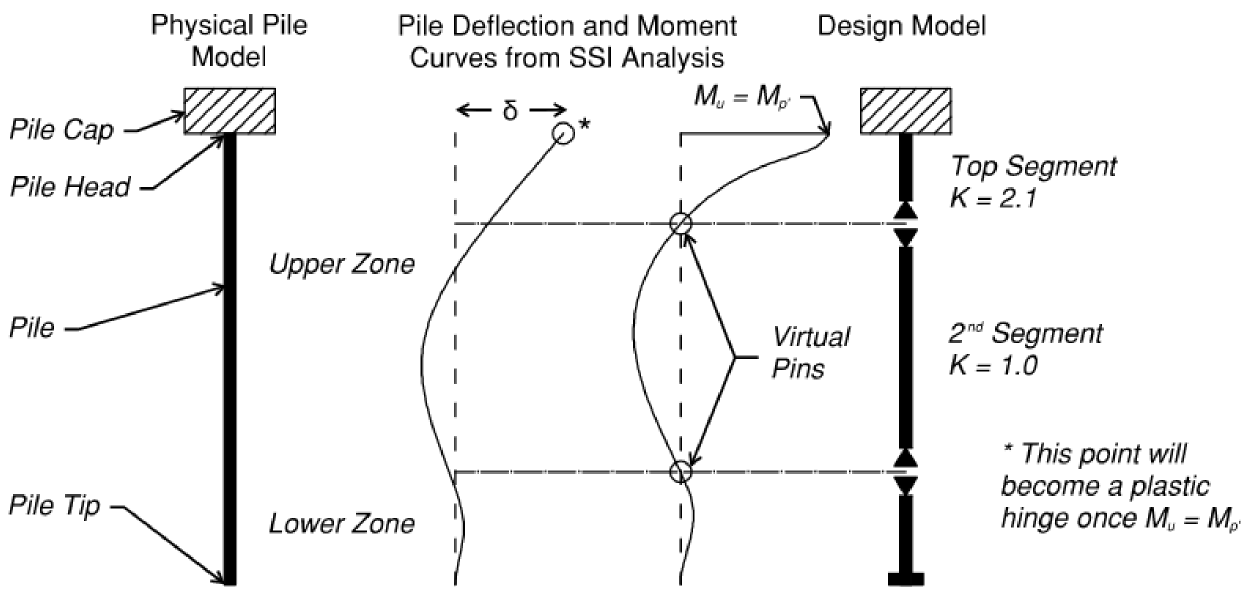


Figure 3-2: Pile Design Model When $M_u = M_p$'

Lateral displacement of the piles shall be considered in addition to the free longitudinal displacement for the design of the piles. The lateral displacement shall be determined by the engineer, or the following conservative assumptions may be considered.

Equation 3-1 may be used to conservatively estimate the transverse pile head displacements (Δ_T) for the simplified design method. The coefficient for the portion of longitudinal displacement applied in the transverse direction (C_T) is as defined in Table 3-1 for bridges with 10 ft. long U-wingwalls. For a given radius and skew combination, there is a resulting transverse displacement (Δ_T) proportionate to the expected unrestrained thermal displacement of the superstructure in the longitudinal direction (Δ_L). This method results in the controlling pile load case for structures meeting the criteria for simplified design. The values in Table 3-1 may be linearly interpolated for radii and skew falling within the simplified design criteria.

Equation 3-1: Transverse Displacement for Simplified Design Method

$$\Delta_T = C_T * \Delta_L$$

Table 3-1: Recommended Lateral Displacement for Simplified Design Method.

Coefficient for the Portion of Longitudinal Displacement Applied in the Transverse Direction (C_T) for 10 ft. Long U-wingwalls

Skew	Upper Limit (Radii approaching 340 ft)	Lower Limit (Radii approaching straight girder analysis)[14]
0 degrees	0.40	0.10
10 degrees	0.65	0.35
20 degrees	0.80	0.50

Increase Δ_T by 33% for cases where the minimum U-wingwalls length of 5 ft. are utilized. This may be applied proportionally for wingwall lengths between 5 ft. and 10 ft.

3.4 Abutment Reinforcement

Guidance and approaches for the design of reinforcement in the diaphragms and stems of straight integral abutment bridges vary significantly by state. The intention of this design guideline is to allow the reinforcement requirements by standard state procedures for straight integral abutments to be applicable to curved integral abutment structures. If no state specific requirements are provided, the following guidance may be used.

The largest force on the pile cap will be the passive earth pressure of the backfill material placed behind the abutment. Additional forces from vertical loads and moments induced by live load and superimposed dead loads will also be present. The abutment stem / pile cap (region below the construction joint) horizontal bars on the front and back faces should be designed to resist the combined moment from passive earth pressure and the composite dead and live loads. For front face positive moment reinforcement, the stem may be assumed to be a simply supported beam supported between two piles. For

[14] Where "straight" is defined as L_{as} / R < 0.06 Radians per AASHTO Article 4.6.1.2.4b where the effects of curvature may be ignored.

back face negative moment reinforcement, the stem may be assumed to be a continuous beam supported by the piles. Bars in the top and bottom of the stem should be designed to support stem self-weight and all dead load reactions from the superstructure self-weight (including wet concrete) assuming the stem is a continuous beam supported by the piles. Where the pile spacing to stem height ratio meets the requirements of concrete design for D-Regions or deep beam analysis, a strut and tie analysis should be considered, per AASHTO LRFD 5.8, for additional reinforcement in the abutment stem. Horizontal bars in the diaphragms should be designed to resist passive earth pressure, assuming the diaphragm acts as a continuous beam between the girders, which can be considered as supports.

The vertical bars in the abutment shall be designed for the bending of the abutment acting as a cantilever below the beam seat elevation. The back face vertical bars shall be designed to resist passive soil pressures and lateral pile forces and moments for thermal expansion. The front face vertical bars shall be designed to resist the lateral pile forces and moments only for thermal contraction.

Differential beam end moments, due to the curvature of the bridge and skew of the substructure, shall be considered in the torsional design of the end diaphragm. The designer shall consider supplemental reinforcement such as utilizing stirrups with closed ends to resist these torsional forces.

Additional reinforcement shall be included for temperature and shrinkage reinforcement to prevent surface cracking of the concrete.

Piles should be embedded a minimum of 2 ft. - 0 in. into the pile cap and should have a minimum of 6 in. cover to all sides of the abutment after considering the allowable tolerances for pile driving.

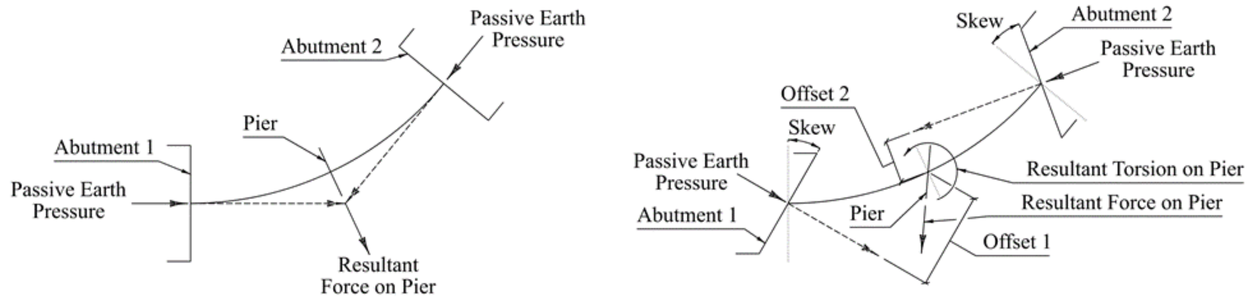
3.5 Wingwall Design

Wingwalls shall be monolithic with the abutment stem and should be designed to resist passive pressure forces as the wing engages the soil mass with bridge movement. U-wingwalls will engage the soil to resist kick out forces produced from curvature and in-line wingwalls engage the soil mass for expansive forces. As such, both configurations require design for passive earth pressure effects on curved integral abutment structures. The back face horizontal bars should be adequately designed and developed to resist these forces. Wingwalls shall be cantilevered from the abutment (without footings or pile supports) with top bars designed for self-weight of the wall and any other vertical loads the wall may experience. If bridge barrier is mounted to the wingwalls, the wingwall back face horizontal steel should also be designed adequately for vehicular collisions under the Extreme Event II Limit State. Wingwalls required to be longer than 10 ft. due to site specific requirements shall be designed as independent freestanding cantilevered retaining walls, separated from the monolithic wing by an appropriately sized expansion joint.

3.6 Pier Design for Multi-Span Structures

When multi-span structures are considered for design, the effects of the curved integral abutment behavior shall be included in the design of the piers. On curved integral abutment bridge structures, the tendency for the structure as a whole to laterally displace and rotate due to the non-concentric soil pressure forces against the abutments must be considered in the design of the bearings and piers.

The resultant force on the pier shall be determined based on 100% of the passive earth pressure acting on the abutments. On curved integral abutment bridge structures with skewed substructure components, the resultant torsion on the pier shall be determined based on the eccentric offsets of the passive earth pressure to the centroid of the pier, as shown in Figure 3-3.



No Skew **Skewed**

Figure 3-3: Resultant Forces on the Pier for No Skew (left) and Skewed (right) Substructure Components.

The resulting forces from this recommendation are highly conservative and in cases where the bridge has tight curvature, this design load for shear at the pier may be cost prohibitive. For cases with tight curvature, a refined analysis may be considered to determine a more accurate pier forces.

4 Guidance for Refined Analysis

4.1 General Approaches to Refined Analysis

Refined 3D analysis requires significantly more effort and expertise to develop than 2D analyses but provides more extensive data. Additionally, 3D analysis allows for the investigation of transverse direction bridge movements which is a critical component for curved structures and their supports. Best practices should be utilized for modeling, with preference given to state specific preferred analysis programs and modeling guidelines where appropriate.

The designer shall apply engineering judgment to all bridge designs and may choose to employ a refined analysis approach or a detailed design even when simplified design criteria are met. All site-specific parameters should be considered. Examples of cases where detailed designs may be performed include:

- Evaluation of construction load cases
- Alternative pile selections
- Alternative superstructure types
- Long spans
- Unequal span lengths in a multi-span structure
- Wingwalls that do not provide lateral restraint
- Skewed conditions with curvature
- Piles that are too short to develop fixity (shallow bedrock conditions)
- Severe scour conditions
- Tall abutment stems

4.2 Refined Analysis Approach for Curved Integral Models

The following aims to provide guidance to the designers for the development of refined analysis models for curved integral abutment structures. The information provided is not exhaustive and is intended to be guidance only. The engineer is responsible for the accuracy and approach to all modeling efforts and should validate that the approach is satisfactory for the site-specific application.

4.2.1 General

Transverse and longitudinal elevation changes including profile grade, superelevation, and crowns should be included in the analysis model. Elevation changes and superelevation will impact structure responses.

The inclusion of concrete barriers as shell elements with a stiff or rigid connection to the deck provides longitudinal stiffness against superstructure flexure, and these should only be included as elements when a higher degree of accuracy is sought. Inclusion of concrete barriers in bridge ratings or for analysis of the deck during vehicular collision with a barrier are potential reasons for inclusion. For most situations, including all designs, barriers are recommended for inclusion as a line load or pressure load at the location of application as opposed to structural elements.

4.2.2 Boundary Conditions

Boundary Conditions at the piers, abutments, and girder ends should be modeled as closely as possible to the intended bridge design and construction sequence, accounting for translational and rotational restraints, releases, and stiffnesses. The change in boundary conditions between the superstructure and substructure should be accounted for in the construction stage model from a simply supported end condition prior to deck cure, and a composite moment connection for all loads applied after the deck cure is complete.

Site-specific soil structure interaction should be included for the structure under design. All backfill springs should be nonlinear and must disengage for movement away from the backfill. Piles may be modeled with direct soil-structure interaction or may be modeled in conjunction with a soil structure interaction check (such as L-Pile) with the equivalent cantilever method. Direct soil-structure interaction is preferred but is not always practical. Designers should coordinate with geotechnical engineers to determine the appropriate spring stiffnesses for pile springs to account for site specific conditions. Piles should be designed with consideration for biaxial bending effects which are prevalent in curved structures due to transverse bridge movements and superstructure rotations.

Piles modeled using the equivalent cantilever method may use the stiffness values presented in Table 4-1, Table 4-2, and Table 4-3 as a basis for design. These values provide an initial transverse stiffness value for the pile group to begin an iterative design process, and are tabulated based on skew angle, bridge length, and bridge radius. A stiffness value is provided such that the designer may select a pile size and calculate a resulting cantilever length based on the pile section and material properties. The designer may use this cantilever length in a refined analysis model to obtain preliminary design loads and displacements for the analysis of the piles. Equation 4-1 may be used to convert the pile stiffness value to an equivalent cantilever length. The equation is based off the deflection equation for a beam fully fixed at one end (cantilever base) and fixed for rotation, free for translation at the other end (pile connection to abutment).

Equation 4-1: Stiffness of Equivalent Cantilever Pile

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

These values are limited to structures satisfying the criteria of Sections 2.3.1 and 2.3.2, with the exception of wingwall orientation, but may be useful for the design of structures with similar parameters. The stiffness tables developed in this section provide a logical starting point for the iterative design process. The designer may interpolate these values for bridge lengths, curve radii, and skew angles not included in these tables. A model can be developed using equivalent cantilever pile lengths based on a chosen pile section and the stiffness provided in the tables. The resulting loads and displacements from the model are then input to a pile analysis program to provide design values based on the site soil conditions. The equivalent cantilever lengths used in the model may then be revised based on those developed from the pile analysis for continued refinement of the design model.

The target stiffness values presented in Table 4-1 through Table 4-3 can be used to determine the equivalent cantilever length, as shown in an example with the following attributes:

- Structure length of 100 ft.
- Radius of curvature of 425 ft.
- Skew of 10-degrees
- 6 (six) HP12x84 piles per abutment oriented in weak-axis bending longitudinally

Using Table 4-2, the target transverse stiffness corresponding to the 425 ft. radius and the 100 ft. structure length is determined to be 2,011 kip/in. The steel piles have a strong axis moment of inertia of 650 $in.^4$ and a modulus of elasticity of 29,000 ksi. Rearranging Equation 4-1 to solve for L, as shown in Equation 4-2, the equivalent cantilever length to be used in the refined analysis model is determined to be 7.31 ft.

Equation 4-2: Calculating equivalent cantilever length for example.

$$L = \sqrt[3]{\frac{n_{piles} * 12 * EI}{K}} = \sqrt[3]{\frac{6 * 12 * 29000\ ksi * 650\ in^4}{2011\ \frac{kip}{in}}} = 7.31\ ft$$

Abutment backwall spring stiffnesses will be dependent on the backfill used behind the abutment stem and diaphragm. Granular backfill for bridges is generally consistent between New England states for gradation and compaction requirements. Some states specify soil stiffness spring parameters for integral abutment bridges. In these cases, state bridge standards for modeling soil stiffness should be followed. For all other cases, the Lehane[15] method for spring stiffnesses is recommended. Caltrans spring stiffnesses may also be implemented and are generally conservative as they utilize an assumed full passive pressure engagement.

[15] (Lehane, 2011)

Table 4-1: Transverse Stiffness Values for Bridges with 0-degree Skew Angles

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	-	-

Table 4-2: Transverse Stiffness Values for Bridges with 10-degree Skew Angles

Transverse Stiffness (kip/in) for 10-degree Skews						
Radius (ft)	Structure Length (ft)					
	50	75	100	150	200*	300*
340**	727	1789	2587	5701	2713	2053
425**	665	1536	2011	4286	2238	1900
500**	628	1356	1779	3499	2058	1805
750	606	1158	1540	2554	1616	1690
1000	-	981	1484	2390	1378	1554
1500	-	-	1299	2251	1132	1364
2000	-	-	-	2065	-	1332
2500	-	-	-	1900	-	-

Table 4-3: Transverse Stiffness Values for Bridges with 20-degree Skew Angles

Transverse Stiffness (kip/in) for 20-degree Skews						
Radius (ft)	Structure Length (ft)					
	50	75	100	150	200*	300*
340**	836	1897	3267	6762	3306	2716
425**	751	1829	2667	5134	3195	2668
500**	688	1754	2552	4160	2772	2527
750	646	1511	2418	3425	1986	2408
1000	-	1179	2221	3050	1671	2141
1500	-	-	2010	2657	1382	1813
2000	-	-	-	2315	-	1653
2500	-	-	-	2108	-	-

**200 ft. and 300 ft. cases assume a pier located at midspan with bearings fixed for translation and free for rotation. These values rely on the additional stiffness provided by this configuration and are not applicable to other pier boundary conditions.*

***Cases of high curvature, skew, and bridge length combinations may result in unattainable values for stiffness based on site soil conditions. They are provided here for reference to the designer.*

4.2.3 Material Properties

Bridge structure materials are assumed to behave in a linear elastic, homogeneous, and isotropic manner. All steel material properties should conform to the designated steel grade for each applicable element. All concrete materials should conform to state specific requirements for concrete classes to be used in abutment stems, wingwalls, and decks. The corresponding elastic modulus should be applied to the appropriate elements within the model. Time dependent effects may be included but are not as critical for the design of steel superstructure bridges. Time dependent effects should be included for any concrete superstructure type.

4.2.4 Member and Element Designations

Cross frames and diaphragms are primary members in curved girder structures and can carry significant loads as they resist differential deflection of adjacent girders and may form secondary load paths. Diaphragms are also critical during erection of curved and skewed structures and the anticipated construction sequence should be considered in the analysis. Additionally, stiffness from cross frames and diaphragms has shown to have an impact on prediction of non-composite dead load deflections[16]. Cross frames and diaphragms shall be designed in accordance with the current AASHTO Bridge Design Specifications and state standards.

Refined analysis models should implement best practices for the modeling of cross frame / diaphragm stiffness at the appropriate phases of bridge construction, with cross frames generally modeled as truss type members and diaphragms and cross frame chords as beam members with vertical and lateral stiffness at the girder connection.

4.2.5 Application of Loads

All analyses should consider the staged effects of non-composite, long term composite, and short-term composite behavior on applied loadings, as well as changes in boundary conditions as the girders are placed and end diaphragms are poured. All non-composite loads should assume that the girder ends are free to rotate, and all composite loadings should assume a rigid closure pour connection that will distribute loads through frame action to the supports. Deck pour sequences should be considered as appropriate for the anticipated pour sequences for the project.

Loads magnitudes, application, and combinations shall conform to AASHTO and state standards active at the time of design and shall include centrifugal effects (CE). Designers should coordinate with the roadway engineers to ensure that forces are calculated for the appropriate design radius of curvature, superelevation, and design speeds. The number of lanes loaded for CE should be tied to the number of lanes loaded for live load. Superelevation decreases centrifugal effects and may be included in the analysis model at the discretion of the engineer.

Thermal rise and fall should be applied to all exposed components in accordance with the governing state standard. If no standard exists, Procedure A for the appropriate climate shall be implemented in accordance with AASHTO LRFD Article 3.

4.2.6 Torsional Effects in the Superstructure

The method and requirements for design of curved girders shall be in accordance with applicable AASHTO and state standards. Torsion in curved structures is the result of gravity loads applied along the length of the girder offset from a chord line drawn between the supports of the girder in the span. Due to this offset, a resultant torsional reaction is required at the beam ends. As the radius straightens, the offset

[16] (AASHTO/NSBA Steel Bridge Collaboration, 2014) 3.11

between the chord and the arc decreases, and torsional effects decrease in kind. In an integral bridge structure, full fixity is achieved at the beam ends for all superimposed dead loads and transient loads.

Torsion in steel girders causes both normal and shear stresses as a result of St. Venant's torsional effects and warping. Given the open cross-sectional geometry, I-shaped girders have a relatively low St. Venant torsional stiffness (GJ), and therefore carry torsion primarily by warping. Warping causes both shear stresses and normal stresses. The shear stresses resulting from warping should be additive to flexural related shear responses and St. Venant's Shear effects. The normal stresses resulting from warping should be considered in conjunction with major axis bending stress, axial stress, and additional lateral bending stresses caused by out of plane loading, such as wind pressure and cantilever formwork brackets.

Refined analyses utilizing full plate elements for girder webs and flanges will capture warping effects at the expense of modeling economy, however in complex cases such analysis is warranted. For less complex structures, 2D grillage approaches to the superstructure floor with the deck as plate elements should be utilized only if the beam elements within the software program consider the warping stiffness parameter, EC_w, within the beam theory application and output. The degree to which this effect has measurable impact is dependent on a number of parameters unique to every bridge site, and often the overall torsional stiffness of the cross section will be dominated by differential major axis bending of adjacent girders as opposed to the torsional stiffness of a given single I shape[17].

[17] (AASHTO/NSBA Steel Bridge Collaboration, 2014)

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