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Criteria and Practices of Various States for the Design of Jointless and Integral Abutment Bridges

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Abstract: *The design of integral abutment bridges is not explicitly addressed in the U.S. bridge design specifications. Despite the lack of a specific national design standard for such bridges, their usage has grown steadily since several states began experimenting with this type of structure in the 1980s. The primary objective of the work reported here was to understand and compare the current (2017) design criteria and parameters that are being utilized by various states for the design of jointless and integral abutment bridges. In this paper, the required information was sought by obtaining all publicly-available "bridge design manuals" that are commonly (but not universally) published by state departments of transportation. Furthermore, when such information was not available online, direct contacts were made to obtain the necessary information. Data on each state's integral abutment preferences, pile types, pile orientation and embedment, skew angle, maximum permissible length, etc. are provided and compared.*

1 INTRODUCTION

The design of integral abutment bridges is not explicitly addressed in the U.S. Bridge Design Specifications published by the American Association of State Highway and Transportation Officials (AASHTO) [1]. Despite the lack of a specific national design standard for such bridges, their usage has grown steadily since several states began experimenting with this type of structure in the 1980s. One of the primary motivations behind this development has been to address the significant durability issues associated with failing expansion joints on conventional jointed bridges. Early pioneering efforts by states such as Tennessee established the practical feasibility of such designs. However, design practices for jointless bridges have become non-uniform and primarily empirical across various states. A research study sponsored by the U.S. Federal Highway Administration provided detailed design recommendations for jointless and integral abutment bridges [1 through 6]. However, the differing design and application criteria/procedures are expected to remain until a uniform set of design specifications is adopted by AASHTO.

The primary objective of the work reported here was to understand and compare the current (2017) design criteria and parameters that are being utilized by various states for the design of jointless and integral abutment bridges. In this paper, the necessary information was sought by obtaining all “bridge design manuals” that are commonly (but not universally) published online by various state departments of transportation (DOTs) in the United States. However, some states do not have an online bridge design manual. In such cases, those states were approached by email and the necessary information was obtained. This approach is believed to provide a reasonable basis to learn from and compare various state practices. In the following sections of this paper, all information related to jointless and integral abutment bridges that were extracted from the bridge design manuals or through direct contacts are summarized and compared.

2 DEFINITIONS

Some states have provided definitions for integral bridges or integral/semi-integral abutments. The following is a listing of those definitions:

New Jersey
New Jersey DOT defines integral abutment bridges as “single or multiple span continuous bridge structures that have their superstructure cast integrally with their substructure.” It is further explained that the concept is “based on the theory that due to the flexibility of the piling, thermal stresses are transferred to the substructure by way of a rigid connection between the superstructure and substructure… A positive connection with the ends of the beams or girders is provided by rigidly connecting the beams or girders and by encasing them in reinforced concrete. This provides for full transfer of temperature variation and live load rotational displacement to the abutment piling.”

Massachusetts and Vermont
Massachusetts DOT and Vermont DOT define integral abutment bridges as “single span or multiple span continuous deck type structures with each abutment monolithically connected to the superstructure and supported by a single row of flexible vertical piles.”

Ohio

Ohio DOT explains that integral construction "involves attaching the superstructure and substructure (abutment) together. The longitudinal movements are accommodated by the flexibility of the abutments (capped pile abutment on single row of piles regardless of pile type)."

Connecticut

Integral abutments are defined as "abutments that are cast integrally with the superstructure." Fully integral abutments are defined as abutments that are "integral from the superstructure through to the piles." Semi-integral abutments are defined as abutments that are "integral from the superstructure through a portion of the abutment stem. Typically, a joint will be detailed in the abutment stem."

Delaware

According to Delaware DOT's Bridge Design Manual, integral abutments are a "class of abutments where the superstructure is integrally connected to the abutment and the abutment foundation. Typically, the foundation is a deep foundation capable of permitting necessary horizontal movements. Fixity is accomplished by attaching the superstructure to the substructure, or monolithically pouring the superstructure slab with the abutments."

Semi-integral abutments are defined as a "class of abutments where the superstructure is integrally connected to the abutment. The semi-integral abutment approach includes a joint that allows for unrestrained rotation of the superstructure and thermal movements." It further adds: "The superstructure for semi-integral abutments is generally supported on bearings similar to conventional abutment detailing, thereby allowing longitudinal translation relative to the stationary abutment. The beam ends are encased in a full-height concrete diaphragm. A semi-integral differs from an integral abutment in that the concrete diaphragm remains separate from the abutment stem. Therefore, the foundation design of the abutment is similar to conventional reinforced concrete abutments, and can be supported by either a shallow or deep foundation."

New York

The bridge Manual for the New York State DOT (NYSDOT) states, "in an integral abutment structure, a rigid connection is made between the primary support members of the superstructure and a pile supported substructure by encapsulating the support members into the abutment concrete… An integral abutment does not have a footing, as the abutment is supported on a single row of piles extending out of the abutment stem. The piles are allowed to rotate and horizontally deflect as the abutment stem moves due to thermal expansion of the superstructure."

Rhode Island

According to the Rhode Island DOT's Bridge Design Manual, integral abutments are abutments which are supported on single row of flexible H-piles and which are rigidly connected to the superstructure."

Montana
Montana DOT defines integral abutment as a "flexible abutment without a joint between the backwall and pile cap (in cross section, the backwall and pile cap may, in fact, appear as a monolithic rectangle with no apparent cap." The semi-integral abutment is defined as a "flexible abutment with a pin joint between the backwall and cap to facilitate construction and subsequent maintenance."

Vermont
Vermont DOT defines integral abutment as "an abutment comprised of a pile cap with an embedded superstructure, supported by a single line of piles."

3 DESIGN PARAMETERS

3.1 Consideration of integral abutment bridges

Data from bridge manuals and direct contacts (Table 1 and Figure 1) show that roughly 70% of the State DOTs specifically mention and discuss integral or semi-integral abutment bridges in their bridge manuals. No state explicitly disallows the use of such bridges in their bridge manuals.

Table 1. Proportion of all states (and D.C.) that specifically consider integral or semi-integral abutment bridges.

	States (and DC)	**Percentage (%)**
Not mentioned	14	27.5%
YES	37	72.5%
Total	**51**	**100.00%**

3.2 Preference for integral design

Approximately 65% of all states expressly prefer using integral abutment bridges over traditional bridges (Table 2 and Figure 2). One state (Arizona) prefers semi-integral bridges. Some of the reasons provided for the use of integral bridges are listed below:

- Greater structural redundancy
- Effectiveness in accommodating horizontal movements and seismic forces.
- Superior long-term performance
- Stiffer longitudinal response at abutments

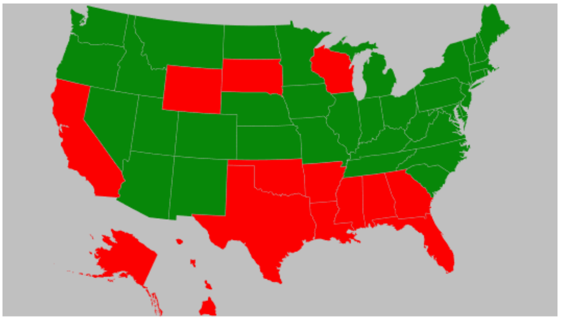

Figure 1. Graphical representation of states specifically considering integral/semi-integral bridges (green)

Table 2. State preference (integral over traditional design?)

	States and DC	**Percentage (%)**
Not mentioned	17	33.3%
Yes	33	64.7%
No	1*	2.0%
Total	**51**	**100.00%**

*Semi-integral is preferred (Arizona)

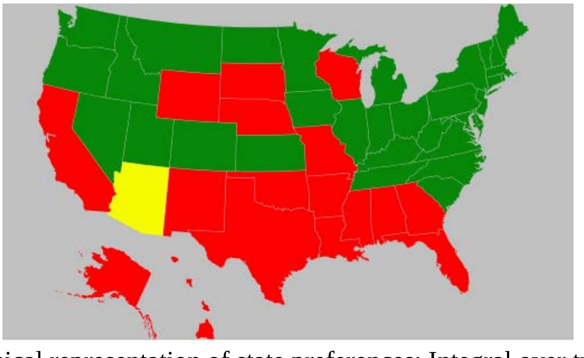

Figure 2. Graphical representation of state preferences: Integral over traditional? Yes (green), No (semi-integral preferred) (yellow), Not mentioned (red)

3.3 Maximum permissible length

Table 3 and Figure 3 show the maximum permissible lengths of steel and concrete integral abutment bridges as indicated by various states in their bridge manuals. The average maximum lengths allowed by states for steel and concrete bridges are 353.3 ft (107.5 m) and 482.7 ft (147 m), respectively. The corresponding standard deviations for steel and concrete bridges are 106 ft (32.3 m) and 154.5 ft (47.1 m), respectively.

Table 3. Maximum permissible length of steel and concrete integral abutment bridges

State	Max. Length-Steel		Max. Length-Conc.	
	ft	m	ft	m
Colorado	640	195	790	241
DC	460	140	460	140
Delaware	400	122	400	122
Idaho	350	107	650	198
Illinois	310	94	410	125
Indiana	500	152	500	152
Iowa	400	122	575	175
Kansas	300	91	500	152
Maine	200	61	330	101
Massachusetts	350	107	600	183
Michigan	300	91	400	122
Minnesota	300	91	300	91
Montana	200	61	200	61
Nevada	150	46	250	76
New Hampshire	300	91	600	183
New Jersey	450	137	450	137
North Carolina	300	91	400	122
North Dakota	400	122	400	122
Ohio	400	122	400	122
Pennsylvania	390	119	590	180
Rhode Island	350	107	600	183
South Carolina	240	73	300	91
Tennessee	500	152	800	243
Vermont	395	120	695	212
Virginia	300	91	500	152
Washington	300	91	450	137

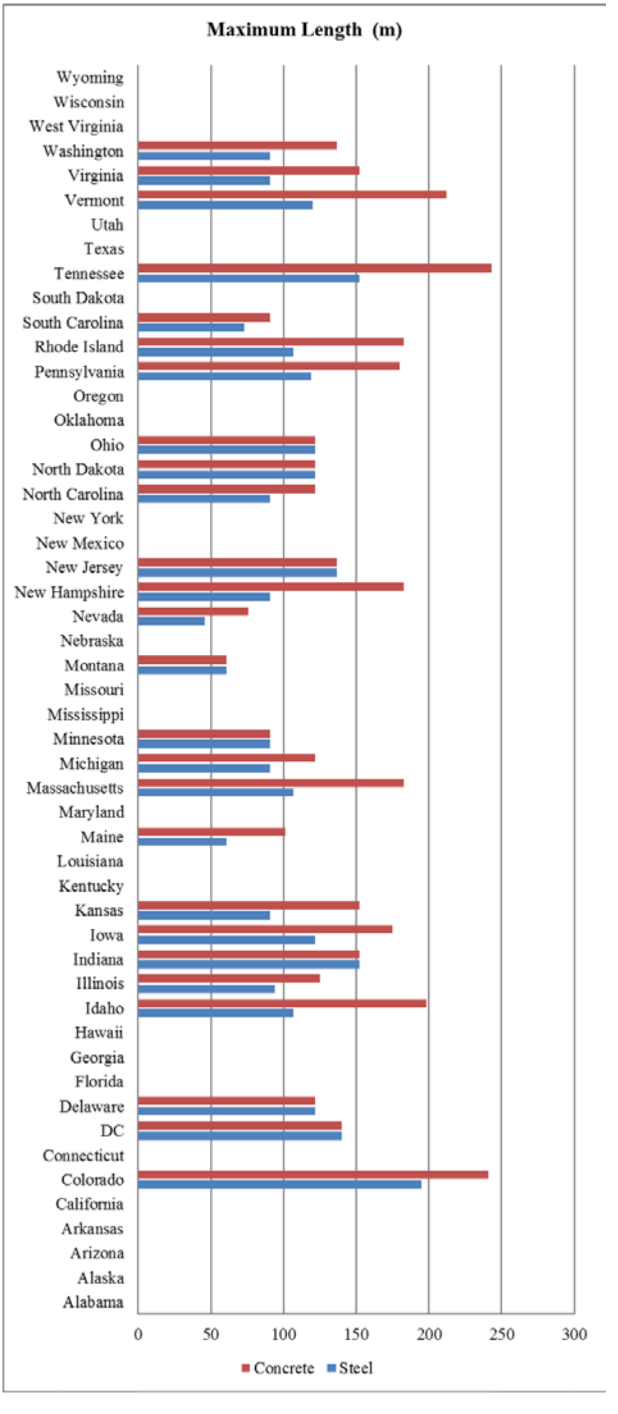

Figure 3. Maximum permissible length of steel and concrete integral abutment bridges.

3.4 Maximum skew angle

An integral bridge's skew angles influence the soil pressure behind abutment walls and the lateral movement of the bridge [2]. As shown in Table 4 and Figure 4, most of the states that consider integral bridges are limiting the bridge skew angle, typically to 30 degrees.

Table 4. Maximum skew angle reported by states that consider integral abutment bridges.

Skew angle (degrees)	States	Percentage of states that consider integral abutment bridges (%)
20	4	10.8%
25	2	5.4%
30	14	37.8%
45	6	16.3%
Not mentioned	11	29.7%
Total	**37**	**100%**

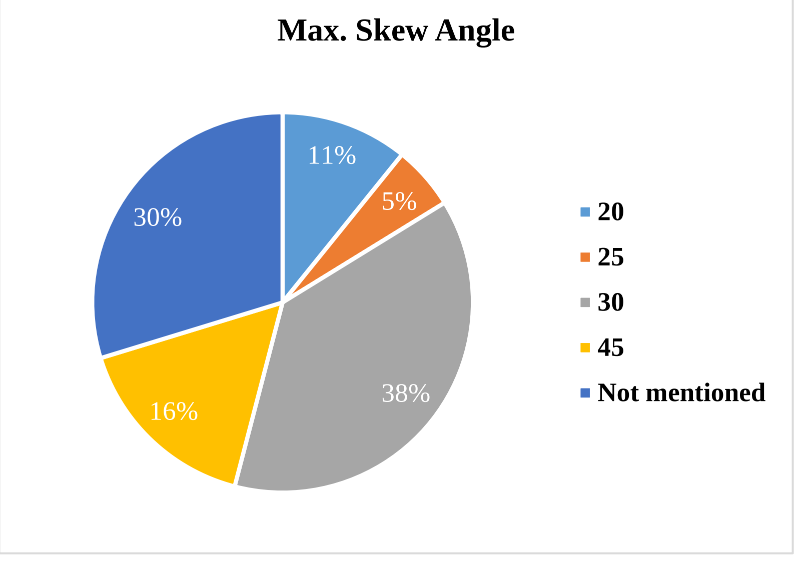

Figure 4. Maximum skew angles reported by states that consider integral abutment bridges.

3.5 Pile types, orientation and embedment length

The following data show pile types, orientation and embedment length in integral abutment bridges for states that consider integral abutment bridges. Data on pile types are shown in Table 5 and Figure 5. If a state were allowing multiple pile types, their number would be reflected in all such categories. The steel H-pile is by the far the most specified pile type in integral abutment bridges.

Table 5. Pile types for integral abutment bridges.

Pile Type	States
HP-Steel	30
Steel Pipe	9
PS Concrete	4
CFSP (concrete filled steel pipe)	5
Not mentioned	10

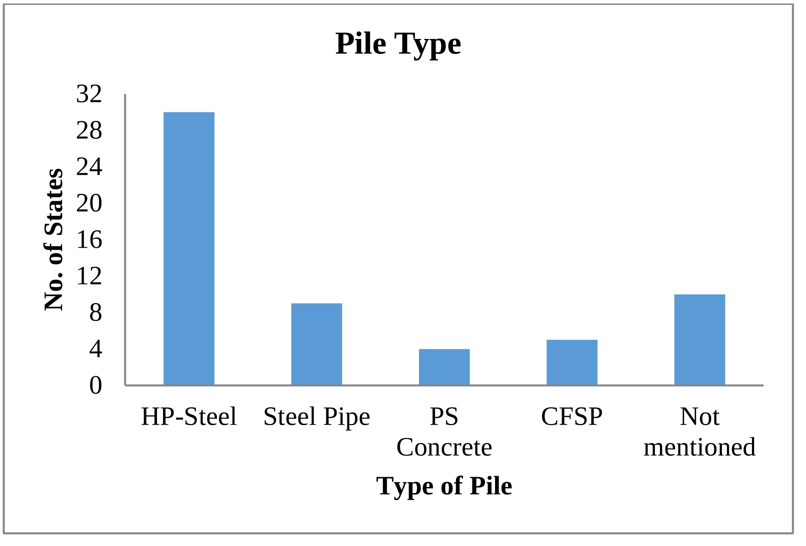

Figure 5. Pile types for integral abutment bridges.

Fifty-seven percent of state DOTs that consider integral abutment bridges prefer to orient the pile such that bending of the pile (due to longitudinal thermal movements) would occur about the weak axis. Only 14% prefer to orient the pile such that the bending is about the strong axis (Table 6 and Figure 6). New York selects the pile axis orientation based on bridge length.

New York

- If bridge's length is less than 245 feet, orient the pile to bend along the weak axis.
- If bridge's length is more than 245 feet, orient the pile to bend along the strong axis.

Table 6. Pile orientation in integral abutment bridges.

Orientation (bending axis)	States	Percentage of states considering integral abutment bridges (%)
Weak	21	56.8%
Strong	5	13.5%
Designer Choice	5	13.5%
Not mentioned	6	16.2%
Total	**37**	**100.0%**

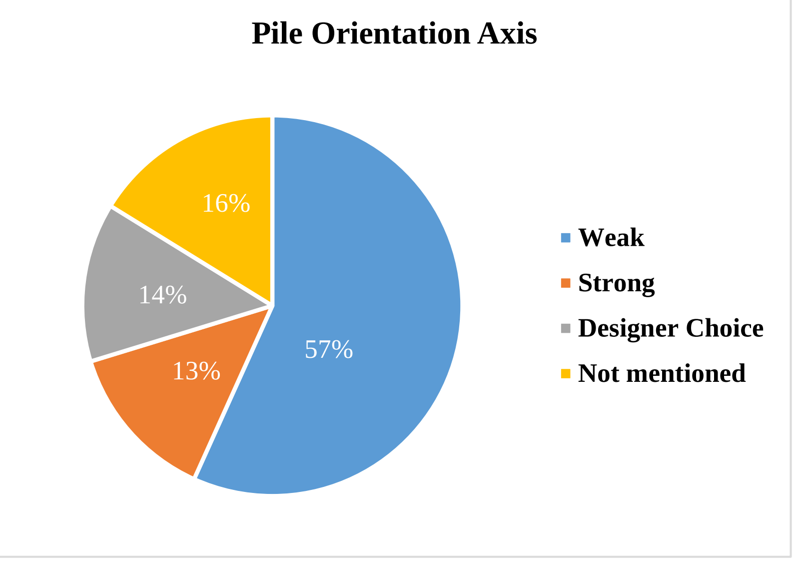

Figure 6. Pile orientation (bending axis) in integral abutment bridges.

Table 7 and Figure 7 show state preferences regarding lengths of pile embedment into the abutment pile caps in integral abutment bridges. The most common embedment length is 18 to 24 inches (0.46 m to 0.61 m).

Table 7. Minimum embedment length of pile into pile cap

Embedment Length	States	Percentage of states considering integral abutment bridges (%)
11-12 in (0.28 – 0.30 m)	7	18.9%
18-24 in (0.46 – 0.61 m)	18	48.7%
30-36 in (0.76 – 0.91 m)	3	8.1%
Not mentioned	9	24.3%
Total	37	100.0%

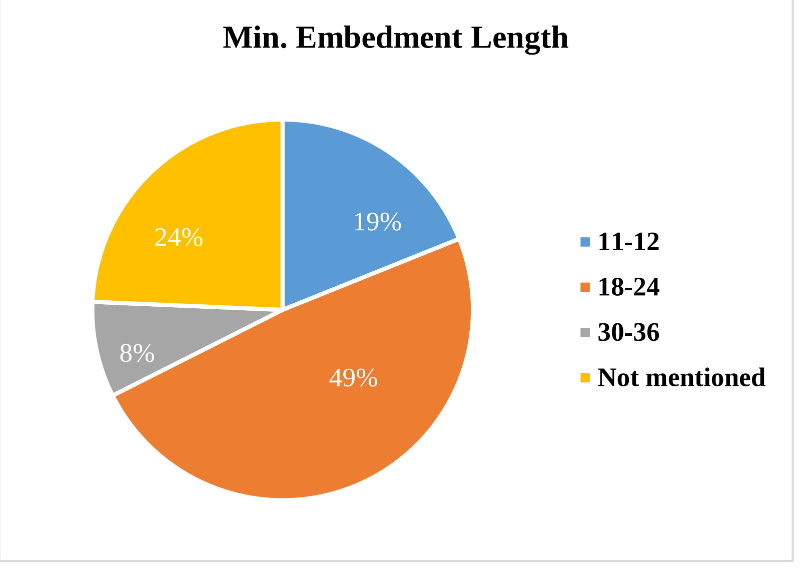

Figure 7. Minimum embedment length of pile into pile cap.

4 THERMAL MOVEMENTS

Calculation of thermal movements is an important consideration in integral abutment bridges. The AASHTO Bridge Design Specifications [1] provide guidance on the effective seasonal bridge temperatures and daily temperature gradients. A few states provide additional guidance related to calculations of movements. Those are discussed below:

Iowa

Iowa DOT recommends using setting factors of 1.50 for precast prestressed concrete bridges and 1.33 for continuous welded plate girder bridges. These factors are used to increase the calculated thermal movement. The setting factors provide for abutment construction temperatures ranging from 25 to 75 ºF (-4 to 24 ºC).

Maine

According to the Maine DOT Bridge Manual, the total seasonal thermal movement is assumed to be 1.25 in per 100 feet (104 mm per 100 m) of bridge length for steel structures, and 0.75 in per 100 feet (62 mm per 100 m) of bridge length for concrete structures.

Massachusetts

Thermal movements are calculated using the following equation provided in the Massachusetts Bridge Design Manual:

$$\delta_T = L\alpha\Delta T \tag{1}$$

Where:

L = Total length of member under consideration from point of assumed zero movement to point where movement is calculated;
α = Coefficient of thermal expansion of member material (0.00000645 /ºF for structural steel, 0.0000055 /ºF for concrete);
ΔT = 70°F temperature rise and 100°F temperature fall (structural steel);
ΔT = 35°F temperature rise and 45°F temperature fall (concrete).
"The thermal movement range for structural steel members was developed by assuming a 50°F ambient construction temperature to determine the temperature rise and a 70°F ambient construction temperature to determine the temperature fall."

5 PILE DESIGN

5.1 Point of fixity

Calculating the point of fixity of piles in integral abutment bridges is important for estimating pile/soil stiffness, movements and stresses.

Delaware

Delaware DOT recommends that soil/structure interaction software be used to estimate the point of fixity of pile based on the p-y curve method. The point of fixity is defined as the "uppermost depth where the calculated lateral deflection crosses the vertical axis (zero deflection)." It is further stated that, "for the pile to be fixed, lateral deflection has to be zero at least two different depths. Short piles with no fixity developed will typically exhibit rotation about a pivot point at a depth of zero deflection. The designer may need to examine several loading conditions to establish a consistent point of fixity for structural design."

Maine

The Bridge Manual for the Maine DOT states: "The practical depth to pile fixity is defined as the depth along the pile to the point of zero lateral deflection."

Rhode Island

Rhode Island DOT defines the theoretical point of fixity as "the depth at which the pile is firmly held by the soil (typically the second point of zero lateral deflection)"

Massachusetts

The Massachusetts DOT requires that integral abutment bridges have a 3D computer model of the bridge with soil springs. The HP-Piles should be modeled as beam elements. The equivalent length, L_e, is defined as "the length of pile from the base of the abutment to the point of fixity." The equivalent length is considered equal to "the length of a free standing column with fixed/fixed support conditions translated through a pile head horizontal displacement δ_T." The equivalent length must be calculated using the following equation:

$$L_e = A(\frac{EI}{d}) + B(\delta_T) + C \tag{2}$$

In the above equation, EI/d is the ratio of flexural rigidity of pile to the depth of pile section in the plane of bending. The coefficients in the above equation were determined based on a parametric study using different soil profiles. According to the Massachusetts DOT Bridge Manual, "the calculation of L_e shall be made using the average of the temperature rise and temperature fall." If the piles are driven, the embedment length must exceed the required length of fixity, L_f.

Table 8. Coefficients to determine equivalent pile length (from Massachusetts DOT Bridge Manual).

	Equation Coefficients for L_e			Fixity Ratio
L_e=A(EI/d)+B(δ_T)+C	A	B	C	L_f/L_e
	in/(in-kip)	in/in	in	
Dry crushed stone over wet or dry sand	3.28E-05	11.9	89.1	2.2
Wet crushed stone over wet sand	3.59E-05	13.9	98.8	2.2
Dry crushed stone over wet stiff clay	3.06E-05	15.4	81.9	1.8
Dry crushed stone over wet soft clay	4.80E-05	21.1	76.4	2.5
Wet crushed stone over wet stiff clay	2.99E-05	18.1	87.9	1.8
Wet crushed stone over wet soft clay	5.26E-05	25.8	86	2.2

5.2 Ductility check

Considering that the piles may sustain significant inelastic deformations, ductility checks should be performed. The following statements appear in the bridge manuals for Idaho and Rhode Island.

Idaho

According to the Idaho DOT Bridge Manual, Piles must be ductile enough to accommodate "both thermal movements and dead load and live load rotations of the superstructure." The following equations are suggested for ductility checks of the piles:

For Steel H-pile:

$$2\left[\frac{\Delta}{L} - \frac{M_pL}{6EI}\right] + \theta_w \leq \frac{3C_iM_pL}{4EI} \qquad C_i = \frac{19}{6} - 5.68\sqrt{\frac{f_y}{E}\frac{b_f}{2t_f}}, \qquad 0 < C_i < 1.0 \tag{3}$$

For hollow and concrete-filled pipe piles:

$$2\left[\frac{\Delta}{L} - \frac{M_pL}{6EI}\right] + \theta_w \leq \frac{C_iM_pL}{2.08EI} \qquad C_i = 3.5 - 1.25\sqrt{\frac{f_y}{E}\frac{D}{t}}, \qquad 0 < C_i < 1.0 \tag{4}$$

"Where:

- Δ= one half the factored thermal movement range at the abutment (in)
- L= twice the length from the bottom of the abutment to the first point of zero moment in the pile determined taking into account the effect of the soil on pile behavior and assuming a lateral deflection of Δ (in)

- M_p= plastic moment of the H-pile about the axis of bending or the plastic moment of the steel pipe pile without considering the concrete filling (kip-in)
- E= modulus of elasticity of the steel (ksi)
- I= moment of inertia about the axis of bending, the moment of inertia of the hollow pipe, or the moment of inertia of the concrete-filled pipe considering both the concrete and steel (in4)
- θ_w= maximum range of the factored angle of rotation of the superstructure at the abutment calculated assuming the structure is simply supported on the abutment (continuity of the superstructure over piers may be considered on multi-span bridges). This rotation is the sum of the rotations due to live loads plus all dead loads applied after making the rigid connection between the superstructure and the abutment assuming the loads are equally distributed to all girders (RAD)
- C_i= a ductility reduction factor for piles
- b_f= width of H-pile flange (in)
- t_f= thickness of H-pile flange (in)
- D= outer diameter of pipe pile (in)
- t= thickness of pipe pile (in)"

Rhode Island

The State of Rhode Island suggests using the procedures discussed in a 1989 Transportation Research Record publication (No. 1223) by Abendroth and Greimann entitled "Rational Design Approach for Integral Abutment Bridge Piles."

6 EARTH PRESSURE

Estimation of earth pressure distributions behind the abutment is another important consideration for the design of integral abutment bridges. The following specific guidelines were provided in bridge manuals from Idaho, Minnesota, and Rhode Island.

Idaho

According to the Idaho DOT's Bridge Manual, "the soil pressure distribution may be assumed as the passive pressure for the top third of the abutment with the pressure varying linearly down to the at-rest pressure at the base of the abutment …. This distribution is appropriate for concrete bridges up to 320 feet in length and steel bridges up to 120 feet in length. A more in-depth analysis of soil pressure distribution should be made for longer structures." Figure 7 shows Idaho DOT's proposed soil pressure distribution under expansion and contraction conditions.

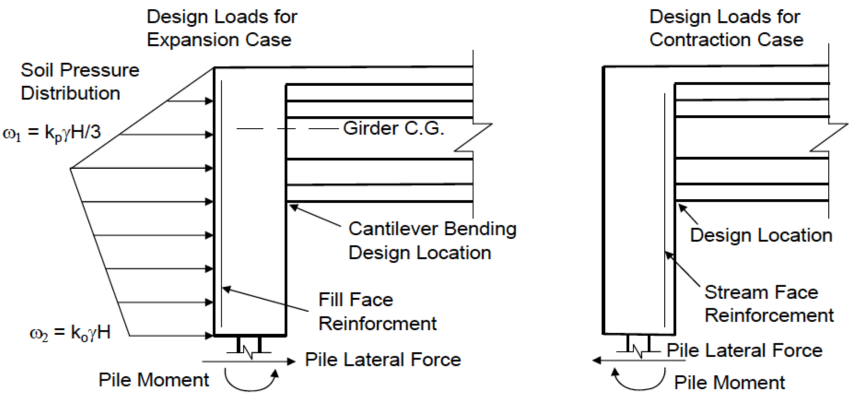

Figure 7. Soil pressure distribution in both expansion and contraction due to thermal movement (from Idaho DOT bridge manual).

Massachusetts

"The magnitude of lateral earth pressure developed by the backfill is dependent on the relative wall displacement, δ_T/H, and may be considered to develop between full passive and at-rest earth pressure." For integral abutments, the coefficient of horizontal earth pressure (K) is estimated using the following equation when using compacted gravel backfill:

$$K = 0.43 + 5.7\left[1 - e^{-190\left(\frac{\delta_T}{H}\right)}\right] \tag{5}$$

Rhode Island

According to the Rhode Island DOT, the lateral earth pressure is a function of the type of soil and amount of anticipated backfill movement (Δ) relative to the wall height (H). The pressure is dependent on the soil/pile interaction and is somewhere between the at-rest and full passive earth pressure. The Rhode Island manual refers to Table 9 below from the AASHTO Design Specifications [1].

8 SUMMARY AND CONCLUSIONS

A review and comparison of integral abutment bridge design criteria and procedures from all fifty U.S. states and the District of Columbia (DC) was performed. All available (online) bridge manuals from different states were obtained. Direct contacts were also made with individual state departments of transportation that did not have bridge manuals available online. Various parameters of interest related to integral and semi-integral abutment bridges were extracted and compared. These parameters included definition of terms, maximum permissible bridge lengths, maximum skew angle, pile types, pile orientation, pile embedment lengths, thermal movement requirements, abutment soil pressures, etc. In general, there are widely differing criteria and procedures that are adopted by various states. However, most states are designing integral abutment bridges and are gaining experience with them. It is anticipated that as research is performed, experience is gained, and information is shared among different states, consensus would emerge on a national set of design standards for integral abutment bridges.

Table 9. Approximate Values of Relative Movements Required to Reach Active or Passive Earth Pressure Conditions (Table C3.11.1-1 of the AASHTO LRFD Bridge Design Specifications [1]).

Type of Backfill	Values of Δ/H	
	Active	Passive
Dense sand	0.001	0.01
Medium dense sand	0.002	0.02
Loose sand	0.004	0.04
Compacted silt	0.002	0.02
Compacted lean clay	0.01	0.05
Compacted fat clay	0.01	0.05

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