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ABSTRACT

Current bridge design procedures used by bridge engineers to design integral abutment bridges built with cantilever wing walls start with girder design, continue with superstructure design, abutment and pile design, and end with the design of the cantilever wing walls. The design procedure does not cycle back to include the effects of cantilever wing wall forces on the other bridge elements previously designed. This paper investigates the stresses induced in the piles of integral abutments from those wing wall forces by means of parametric studies using as parameters the bridge length, length of wing walls, presence or absence of predrilled holes, temperature loads in both rising and falling temperatures, and various types of soil behind the abutments and wing walls. In all cases, the soil around the piles consisted of very stiff clay. The parametric studies were conducted by means of three-dimensional nonlinear finite element models that included both soil-structure and soil-pile interaction. The results indicate an increase in the magnitude of pile stresses as a result of those unaccounted wing wall forces and that the most critical combination occurs during temperature contraction when no predrilled holes are used and dense sand is behind the abutments and the wing walls.

Keywords: Integral abutment bridges, jointless bridges, soil-structure interaction, soil-pile interaction, thermal loads, wing walls.

Introduction

Integral abutment bridges are girder bridges with no expansion joints in the bridge deck and no bearings at the abutments (Figure 1). Their behavior was studied over the years by many researchers (Jorgenson, 1983; Yang et al., 1985; Greimann et al., 1986, 1987a, 1988; Amde et al., 1988a, 1988b, 1997; Lawver et al., 2000; Paraschos and Amde, 2010). Integral abutment bridges offer several advantages over conventional bridges (Figure 2) including construction and maintenance costs (Paraschos and Amde 2011). They have been used for decades in the United States (Burke 1990; Kunin and Alampalli 1999) and as a result of their excellent performance the current policy of the majority of states is to build integral abutment bridges whenever possible. In fact, AASHTO/NSBA (2011) states that full integral abutments on piles is the most efficient design in most situations and every effort should be made to achieve full integral construction.

Figure 1. *Integral Abutment Bridge*

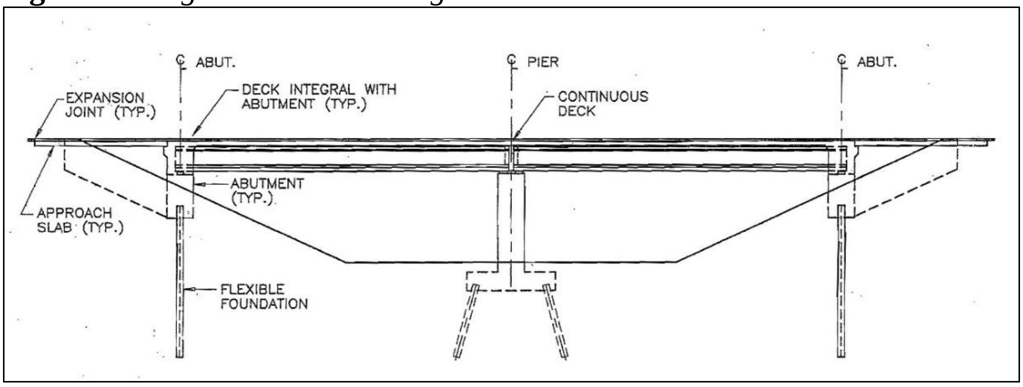
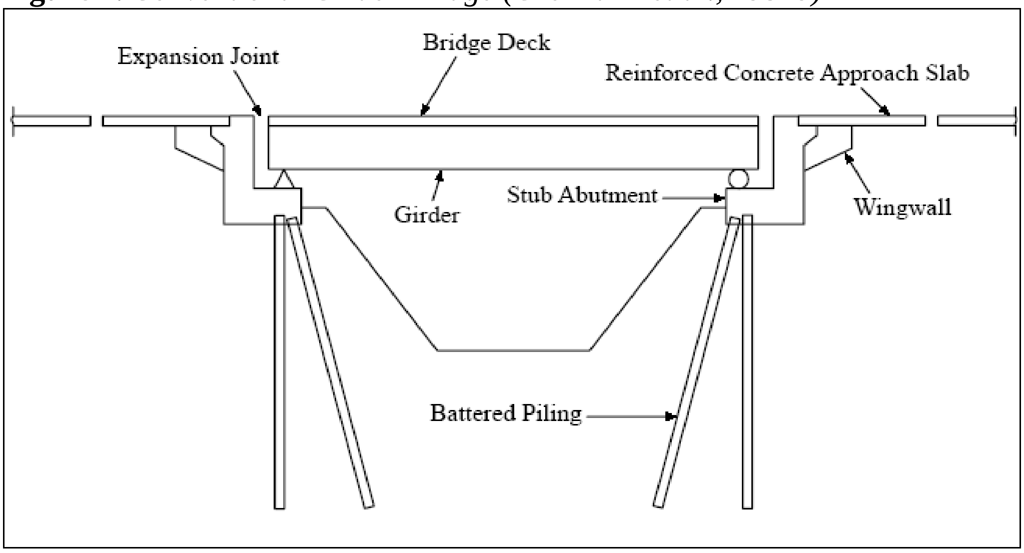
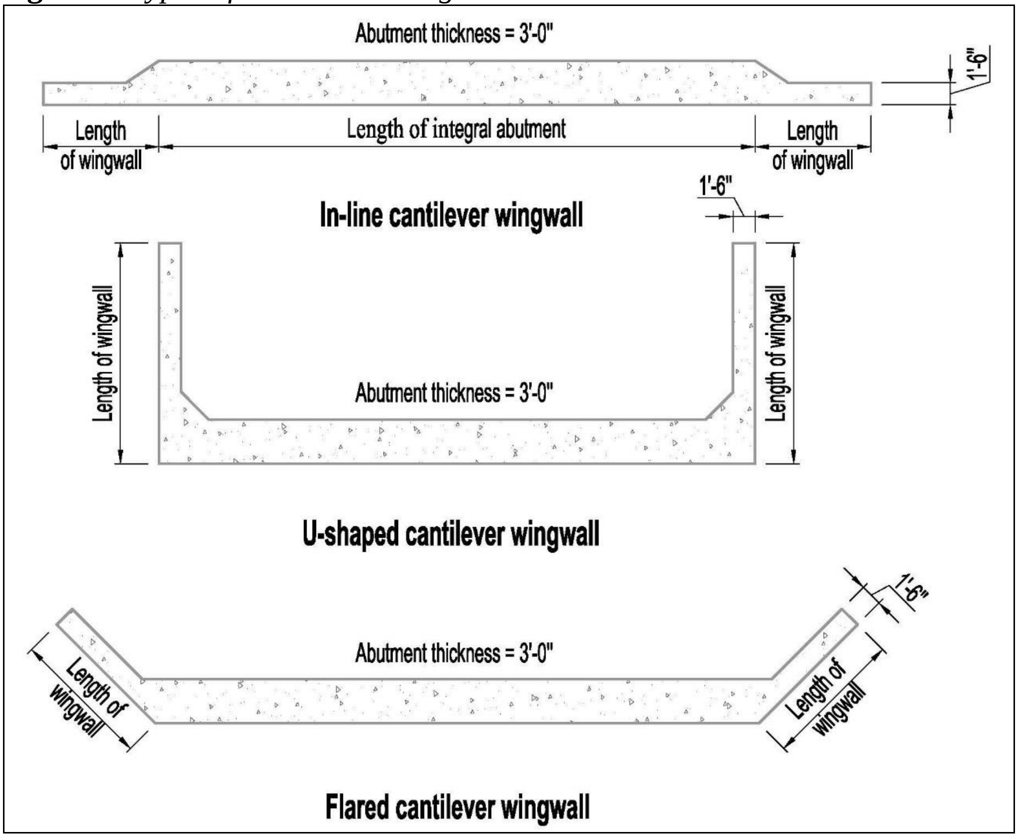


Figure 2. *Conventional Girder Bridge (Greimann et al., 1987b)*



Wing walls are located at the ends of a bridge and their function is to retain the approach roadway embankment. With regard to their connection to the abutment, wing walls are classified either as independent or cantilever wing walls. Independent wing walls are separated from the abutment with an expansion or construction joint. Cantilever wing walls are built integral with the abutment and are much more commonly used than independent wing walls in integral abutment bridge construction (Paraschos and Made, 2010). This is due to the fact that use of independent wing walls creates interaction issues with the integral abutments and complex joints are required. The problem is that current bridge design procedures used by bridge engineers to design integral abutment bridges built with cantilever wing walls do not necessarily account for the effects of wing wall forces on bridge elements already designed. This includes integral abutment piles. This paper investigates the effects of those wing wall forces on integral abutment piles for the case of inline cantilever wing walls (Figure 3).

Figure 3. *Types of Cantilever Wing Walls*



Overview of Integral Abutment Bridges

Integral abutments got their name because the abutment structure is made integral with the superstructure elements. Bridges with integral abutments are called integral abutment bridges; there are no bearings at the abutments and no expansion joints in the bridge deck. Integral abutment bridges accommodate superstructure movements by flexure of the piling and by provision of cycle-control (expansion) joints at the roadway end of the approach slabs. The integral abutment bridge concept is based on the assumption that due to the flexibility of piles thermal stresses are transferred to the substructure by way of a rigid connection between the superstructure and substructure meaning the temperature change causes the abutment to translate without rotation. The concrete abutment contains sufficient bulk to be considered rigid. A connection with the ends of the girders is provided by rigidly connecting the girders and by encasing them in reinforced concrete. This provides for full transfer of temperature variation and live load rotational displacements from the superstructure to the piles through the abutment. The abutment wall simply acts as a rigid link between the superstructure and the piles (Husain and Bagnariol, 1996).

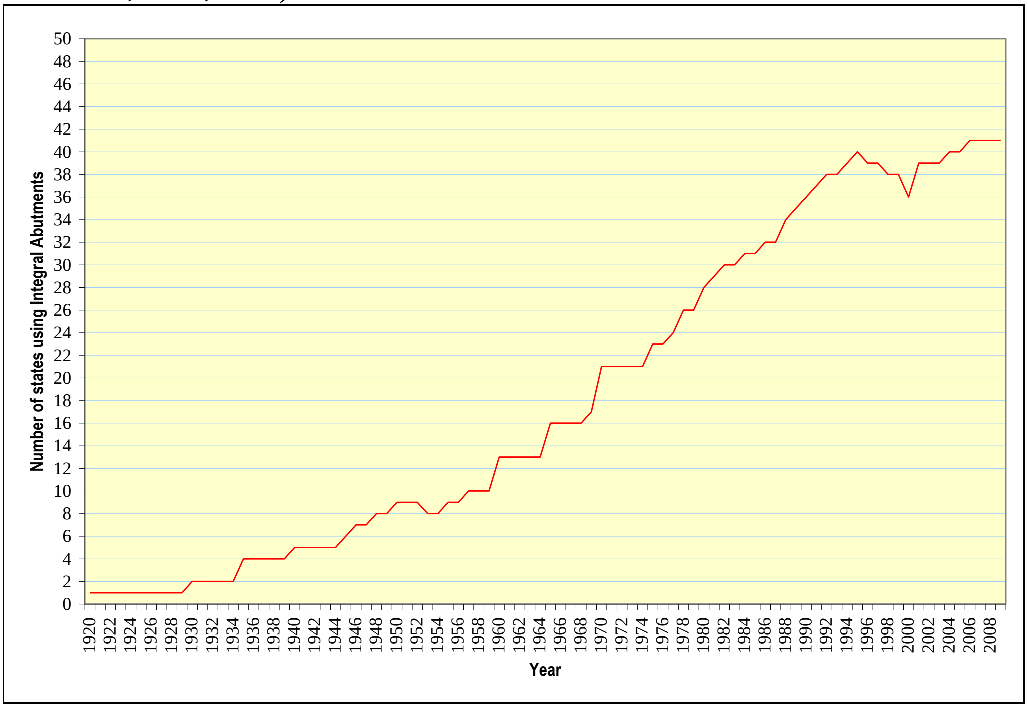
Evolution of Integral Abutment Bridges

Early bridge structures were designed as a series of simple spans. The introduction of the Moment Distribution Method developed by Professor Hardy Cross in 1932 allowed structural engineers to eliminate deck joints and one line of bearing devices at piers, and design bridges as continuous structures. As a result of the continuity and negative moments over the interior supports, midspan positive moments were reduced, which in turn led to the construction of longer bridges. Concrete bridge decks, however, experience expansion and contraction as a result of exposure to the environment and the imposition of loads. This led to the provision of deck joints to accommodate bridge deck expansion and contraction.

Unfortunately, the introduction of deck joints creates many problems to bridge owners. Joints are expensive to buy, install, maintain, and repair. Repair costs are high. Besides, joints leak over time, allowing the deicing chemicals used to lower the freezing point of water to attack the girders, bearings, and supporting reinforced concrete substructures. The result is corrosion and deterioration of girders and bearings as well as scaling and spalling of piers and pier caps along with corrosion of reinforcing steel in those members (Amde and Greimann, 1988). Bearings are generally much more durable than expansion joints. But, they are also expensive to buy and install and costly to replace. Over time steel bearings tip over and seize up due to loss of lubrication or buildup of corrosion. Elastomeric bearings can split and rupture due to unanticipated movements. Because of these problems, it is necessary to continuously inspect, maintain, and periodically replace the joints. In short, use of expansion joints and bearings to accommodate thermal movement requires maintenance work, even if they are correctly designed and detailed.

Integral abutment bridges eliminate the need to provide deck joints. In addition, they can save bridge owners a considerable amount of money, time, and inconvenience compared to conventional bridges. Because of these advantages, states began building integral abutments. Colorado was the first state to build integral abutments in the 1920s. Massachusetts, Kansas, Ohio, Oregon, Pennsylvania, and South Dakota followed in the 1930s and 1940s (Kunin and Alampalli 1999; Burke, 1990). California, New Mexico, and Wyoming built integral abutment bridges in the 1950s. With the National Interstate Highway System construction boom in the late 1950s and mid-'60s Minnesota, Tennessee, North Dakota, Iowa, Wisconsin, and Washington began moving toward continuous bridges with integral abutments, as standard construction practice (Figure 4).

Figure 4. *Evolution of Integral Abutment Bridges in the United States (Paraschos and Made, 2010, 2011)*



Advantages of Integral Abutment Bridges

Integral abutment bridges offer significant advantages over conventional bridges. The list includes:

- Lower construction costs compared to conventional bridge structures because of the elimination of deck expansion joints and bearings at the abutments. Additional cost savings come from the elimination of cofferdams and from using less concrete and reinforcing steel in the substructure and superstructure. Furthermore, integral abutments have a typical height that is less than that of conventional abutments, reducing the quantity of excavation and backfill materials.
- Expedite bridge construction compared to conventional bridge structures. Only one row of vertical piles is used meaning fewer piles need to be driven. Furthermore, expansion joints and bearings are eliminated. As a result, delays associated with the installation of bearings and expansion joints do not occur. Taking into consideration the fact that the construction of a conventional bridge substructure (abutments and piers) consumes 60 to 70 percent of the time required to construct a bridge (Sprinkel, 1978),

the advantage of building integral abutment bridges in reference to construction duration becomes obvious.

- Provide significant maintenance cost savings over the life of the structure because of reduced maintenance costs associated with deck expansion joints and bearings (Walker, 2013). This is due to minimization of inspection and maintenance operations required.
- Minimized traffic disturbances during the course of the life of the bridge due to reduced maintenance requirements.
- Show superior performance when compared to conventional bridges of similar age and exposure (Alampalli and Yannotti, 1999; Yannotti et al., 2005). In addition, they have longer service lives compared to conventional bridges (Burke, 1990; Xanthakos, 1996). This is due to the fact that they incur less damage during the course of their service life due to elimination of corrosion of girders and reinforcing steel caused by leaking joints loaded with deicing chemicals. According to Barbaccia (2014), 80 percent of state transportation departments cite corrosion, age, and traffic as the top three contributing factors causing the most damage onto the nation's bridges.
- Provide enhanced seismic performance compared to conventional bridges (Greimann et al., 1987; Hoppe and Gomez, 1996). Use of integral abutments eliminates the most common cause of damage to bridges in seismic events, loss of girder support.
- Allow a lower continuous-span ratio and therefore shorter end spans.

Limitations of Integral Abutment Bridges

- The use of integral abutment bridges has its limitations aiming to reduce the magnitude of stresses in the piles and passive earth pressures behind the integral abutments. The list of limitations includes:
- Limitations on bridge length; each state sets its own limit on bridge length.
- Limitations on skew.
- Limitations on horizontal alignment; only a limited number of states allow integral abutment bridges on horizontally-curved alignment.
- Limitations on the height of integral abutments (Kunin and Alampalli, 1999).
- Limitations on backfill material: compacted backfill behind integral abutments is the preferred option of the majority of states.
- Provisions for approach slabs (Burke, 1993) to prevent vehicular compaction of backfill adjacent to abutments, that is, to eliminate live load surcharging of backfill, and to minimize the adverse effect of consolidating backfill and approach embankments on movement of vehicular traffic.
- Provisions for cycle-control (expansion) joints at the roadway end of the approach slabs in order to accommodate the cyclic thermal movement of the bridge resulting from temperature variations (Burke, 1993).

- Limitations on both pile material and size of piles supporting the integral abutments (Burke, 1993).
- Limitations based on type of soil present at the bridge site; if the soil in the site is susceptible to liquefaction, integral abutment bridges are not suitable for the site.
- Use of minimum length of piling. This is due to the fact that the overall length of a pile is relevant to the pile's flexibility and its ability to accommodate abutment movement—the longer the pile, the more flexible is (Ganga Rao et al., 1996) and the higher is its lateral load carrying capacity (Begum and Muthukkumaran, 2008). Thus, piles should have sufficient flexibility to accommodate the horizontal displacements of the superstructure (Mistry, 2005) and that the depth of overburden provides fixed support conditions. This precludes the use of integral abutments where the depth to bedrock is considered shallow, less than 13 feet from the ground surface (Hartt et al., 2006) or where piles cannot be driven through at least 10 to 15 feet of overburden (Burke, 1993; Hoppe and Gomez, 1996).
- The anticipated scour at the abutments is within the limits of piles regardless of whether countermeasures have been installed (Virginia DOT, 2007).
- Span arrangement and interior bearing selection should be such that approximately equal movement will occur at each abutment (Amde and Greimann, 1988) to balance the passive pressures.
- Integral abutments are of equal height so lateral loads are balanced and to protect against sideway (Crovo, 1998; Husain and Bagnariol, 2000).
- The difference in elevation between the integral abutments does not exceed five percent of the bridge length (Amde and Greimann, 1988; Crovo, 1998).
- Construction of integral abutment bridges shall be performed with an appropriate construction sequence (Burke, 1999; Harvey and Kennedy, 2002; Wasserman, 2007).

Methodology

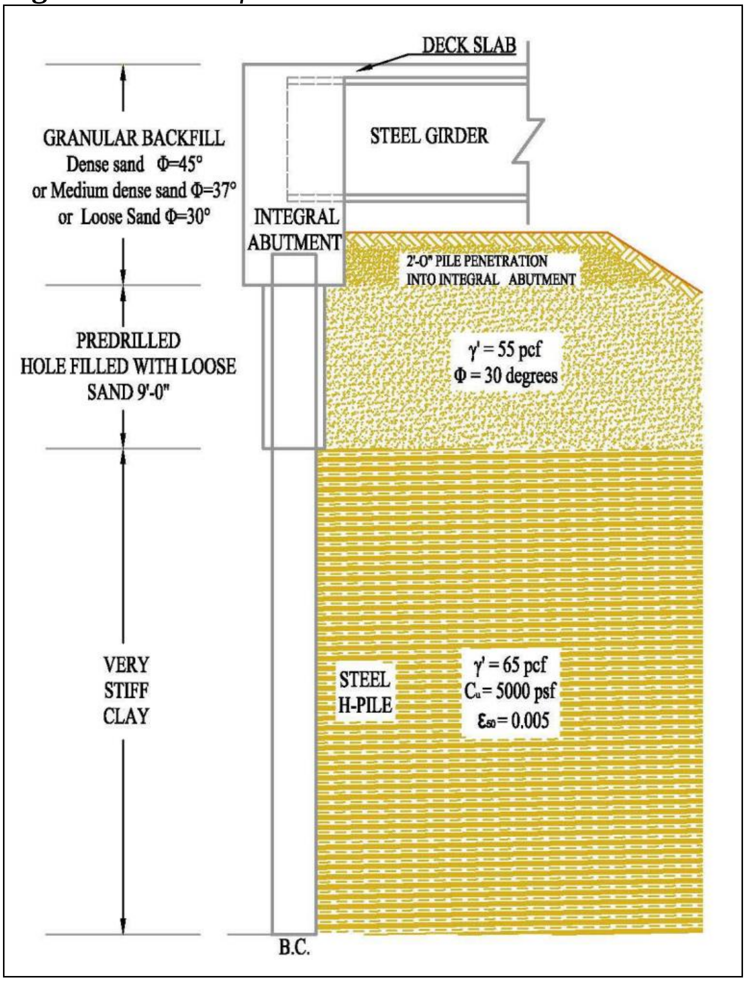
Bridge length for the parametric studies varies from 100 to 1200 feet. The shortest bridge is a single span 100-feet-long bridge and the longest is a 12-span 1200-feet-long bridge with 12 equal spans. The other bridge lengths used for the parametric studies are 200 feet, 300 feet, 600 feet, 900 feet, and 1200 feet. Table 1 presents the parameters used in the analysis.

Table 1. *Parameters used in the Analysis*

Parameter	Value or Range
Thickness of bridge deck	9.5"
Number of lanes	2 lanes
	4 lanes
Bridge width	40'-0" for 2-lane bridges
	64'-0" for 4-lane bridges
Overhang width	3'-0" for 2-lane bridges
	3'-6" for 4-lane bridges
Number of steel plate girders	5 girders for 2-lane bridges
	7 girders for 4-lane bridges
Steel plate girder spacing	8'-6" for 2-lane bridges
	9'-6" for 4-lane bridges
Steel plate girder size	Top flange 14"x1.5" Web 57"x 0.5" Bottom flange 14"x1.5"
Cross frame spacing	25'-0"
Cross frame size	W8X18
Integral abutment height	9'-0"
Integral abutment wall thickness	3'-0"
Integral abutment foundation type	Steel H piles
Integral abutment pile type	End bearing piles
Integral abutment pile size	HP10X57
Integral abutment pile spacing	6'-0"
Number of integral abutment piles	7 piles for 2-lane bridges
	11 piles for 4-lane bridges
Integral abutment pile orientation	Weak-axis bending
Integral abutment pile length	Total length 42'-0", which includes 2'-0" penetration into the integral abutment
Depth of predrilled holes around integral abutment piles	9'-0"
Inline cantilever wing wall length	8'-0"
	12'-0"
	15'-0"
	18'-0"
	21'-0"
	24'-0"
Inline cantilever wing wall height	9'-0"
Inline cantilever wing wall thickness	1'-6"
Inline cantilever wing wall foundation type	No special foundation
Loads and Load Combinations	Dead Load + Temperature Load

	Temperature variation is 100°F-(-30°F)=130°F thermal contraction 120°F -32°F = 88°F thermal expansion.

Figure 5. *Soil Profile*



Structural and Material Modeling

The structural elements of the bridge were modeled as linear elements while the soil adjacent to the piles and behind the abutments and wing walls was modeled as nonlinear springs. This is a condensed description of the three-dimensional model of a 2-lane bridge:

- The superstructure consists of a concrete slab in composite action with five steel girders spaced at 8'-6" and cross frames spaced at 25 feet.
- The deck slab was modeled using shell elements and the steel girders as beam elements. The intermediate piers were treated as roller supports.
- The integral abutments and cantilever wing walls were modeled using solid elements. The soil behind the abutments and wing walls as well as around the piles was modeled as nonlinear springs.

- Seven steel piles spaced at 6 feet with full fixity were connected to each integral abutment allowing full moment transfer. Piles were modeled using shell elements with common node for pile and the abutment wall.

For the case of 4-lane bridges, the bridge model includes seven steel girders spaced at 9'-6" and eleven steel piles spaced at 6 feet.

The analysis was performed using the ANSYS Release 13 Mechanical APDL to create input files. APDL stands for ANSYS Parametric Design Language, a scripting language that allows users to parameterize the model and automate tasks.

Table 2. *ANSYS Elements' Representation of Bridge Structural Elements*

Bridge Structural Elements and boundary conditions	ANSYS Element
Deck slab	SHELL181
Steel girders	BEAM188
Connection of deck slab to steel girder	MPC184
Abutment	SOLID45
Steel Piles	SHELL181
Wing wall	SOLID45
Soil-pile interaction	COMBIN39
Soil-structure (abutment/wing wall) interaction	COMBIN39

Figure 6. *Schematic of Integral Abutment Bridge Finite Element Model*

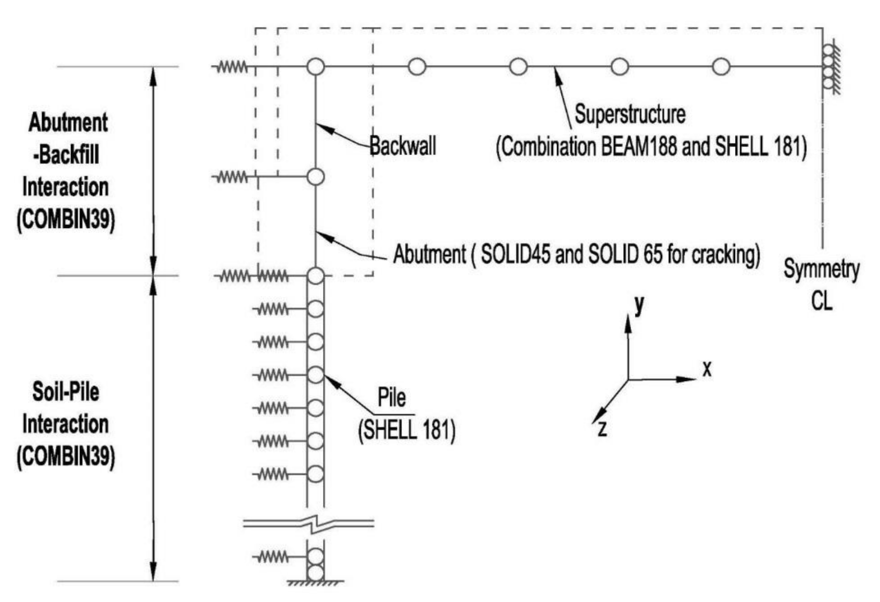
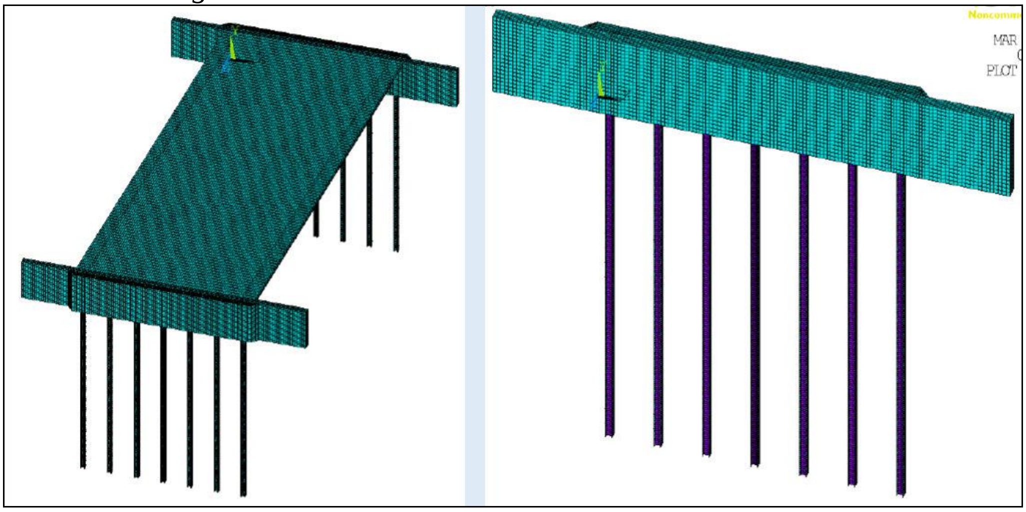


Figure 7. *Finite Element Model of an Integral Abutment Bridge with Inline Cantilever Wing walls*



Results

- Higher piles stresses are induced during thermal contraction rather than during thermal expansion. This is the result of wider temperature variation during temperature contraction compared to temperature variation during temperature expansion (temperature ranges are defined in Table 1). In addition, active soil pressures are aligned and in the same direction as the temperature-induced loading. Therefore, the resulting deformation in combination with the gravity forces acting on the piles (P-Δ effect) produces higher pile stresses during temperature fall. During temperature expansion, as the approach fill is pushed by the abutment, it tends to move the foundation soil in the same direction. This is beneficial as far as pile stresses are concerned because the foundation soil is moving in the same direction as the piles. The result is lower stresses in the piles during temperature expansion compared to those generated during temperature contraction.
- Use of inline cantilever wing walls instead of independent wing walls has an effect on pile stresses.
- Comparison of the effects of inline cantilever wing walls, predrilled holes, and backfill soil on pile stresses, leads to the conclusion that the most critical parameter among those three is by far the use of predrilled holes followed by the use of cantilever wing walls. The type of backfill soil is the least critical.
- The most critical combination of parameters on pile stresses occurs with piles oriented in weak-axis bending during temperature contraction (DL+TC), presence of stiff soil around piles with no predrilled holes at the top nine feet of piles, use of inline cantilever wing walls, and presence of dense sand as backfill soil behind the abutments and wing walls. This

critical combination of parameters generates pile plasticity at a bridge length of 77 feet (Table 3).

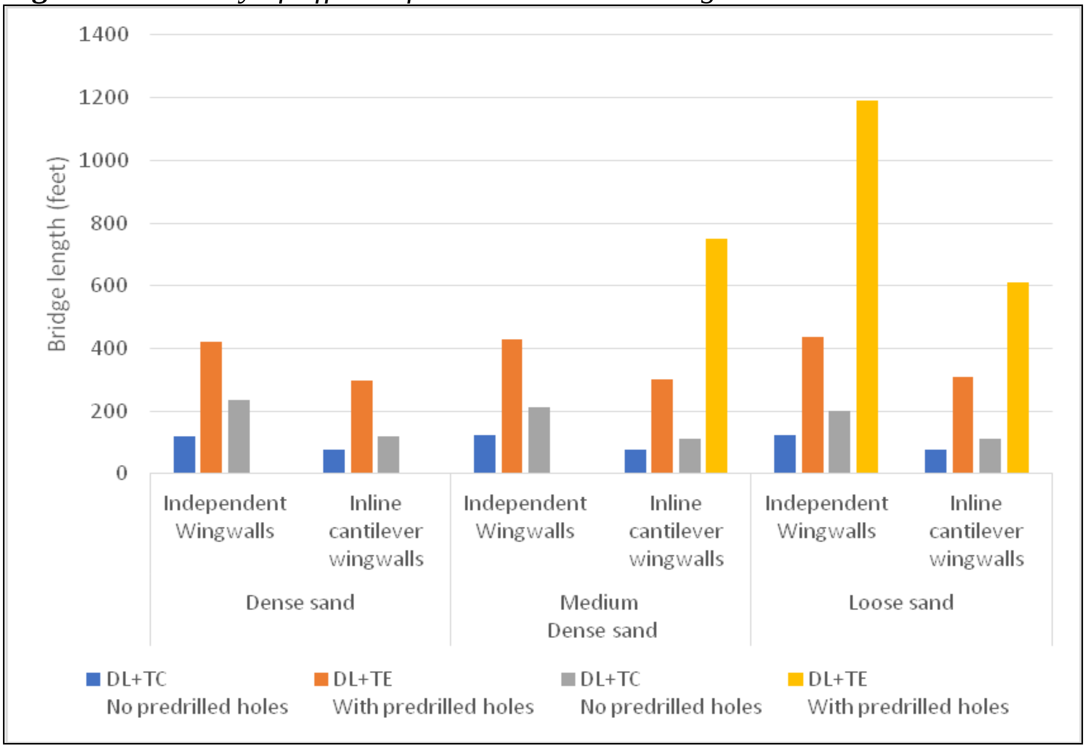
- During temperature contraction, plasticity in the piles of integral abutments with predrilled holes and independent wing walls is generated at bridge lengths between 422 and 438 feet depending on the type of backfill soil (Table 3). Use of inline cantilever wing walls induces plasticity in the piles at bridge lengths between 298 and 308 feet depending on the type of backfill soil (Table 3).
- Not using predrilled holes at the top nine feet of piles has a very serious effect on pile stresses. The results indicate that when no predrilled holes are used, plasticity in the piles of integral abutments with independent wing walls is generated at bridge lengths between 120 and 124 feet depending on the type of backfill soil (Table 3). However, when predrilled holes are used, pile plasticity is generated between 422 to 438 feet (Table 3). Use of inline cantilever wing walls with no predrilled holes results in generation of plasticity in the piles at bridge lengths ranging from 77 (Table 3). Using predrilled holes with inline cantilever wing walls results in generation of pile plasticity at bridge lengths between 298 and 308 feet as stated in the previous paragraph.
- During temperature expansion (DL+TE), pile plasticity is generated at bridge lengths substantially longer compared to those obtained during temperature contraction. This applies to all cases including use or not of predrilled holes or inline cantilever wing walls in combination with any type of backfill soil. This is due to the fact that higher piles stresses are induced during thermal contraction rather than during thermal expansion (Table 3).

Table 3. *Summary of Effects of Inline Wing Walls on Pile Stresses*

Bridge Length at Onset of Pile Plasticity (feet)					
Parameters		DL+TC No Predrilled Holes	DL+TC With Predrilled Holes	DL+TE No Predrilled Holes	DL+TE With Predrilled Holes
Dense Sand	Independent wing walls	120	422	236	-
	Inline cantilever Wing walls	77	298	119	-
Medium Dense Sand	Independent wing walls	122	430	213	-
	Inline cantilever wing walls	77	303	113	750
Loose Sand	Independent wing walls	124	438	200	1191
	Inline cantilever wing walls	77	308	110	612

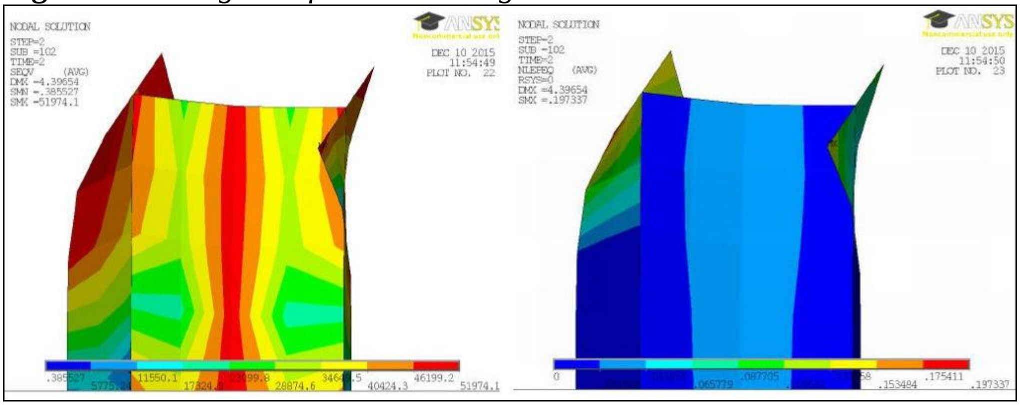
The results in Table 3 are shown graphically in Figure 8.

Figure 8. *Summary of Effects of Inline Cantilever Wing Walls on Pile Stresses*



- No plastic hinge is formed in the piles even under the most critical combination of parameters on pile stresses. This includes a bridge length of 1200 feet in combination with 24-feet-long inline cantilever wing walls, dense backfill soil, very stiff soil around the piles, and no predrilled holes at the top nine feet of piles during temperature contraction. This is shown in Figure 9.

Figure 9. *Investigation for Plastic Hinge Formation in the Piles*

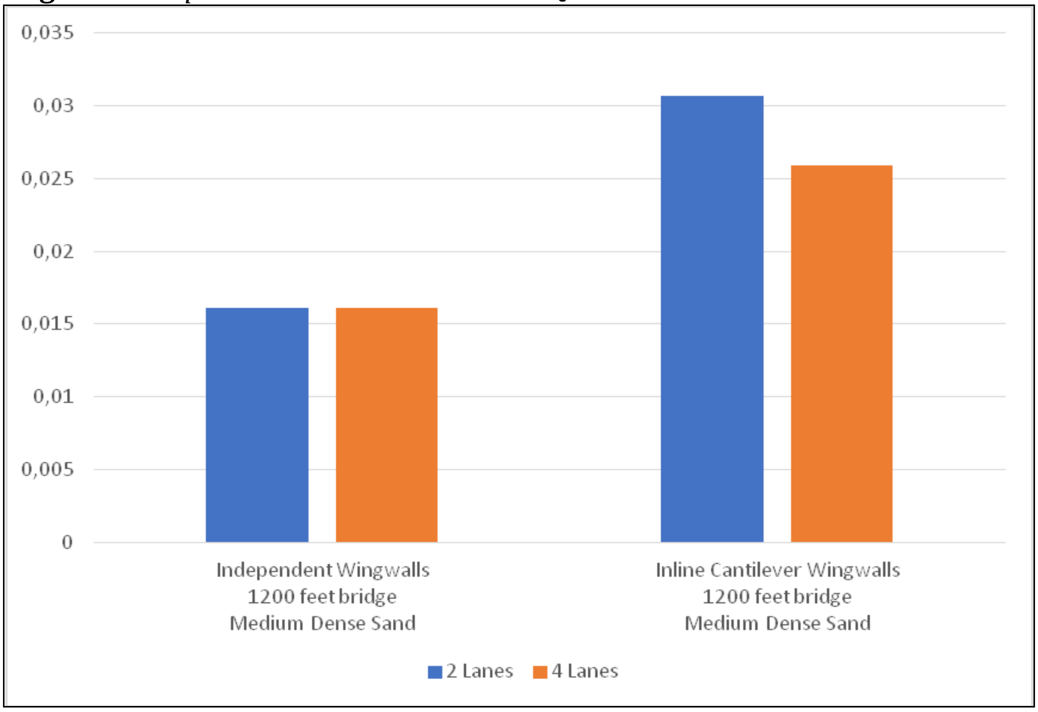


- Pile stresses in bridges with two lanes are slightly higher compared to bridges with four lanes. This is due to the fact that for two-lane bridges backfill soil pressures acting on the wing walls account for a larger portion of the total soil pressure acting on the combined abutment/wing wall length. The results are expressed in terms of the equivalent plastic strain for the case of a 1200-feet-long bridge with medium dense sand backfill (Table 4).

Table 4. *Equivalent Plastic Strain EPEQ in the Piles*

Equivalent Plastic Strain EPEQ in the Piles (in/in)		
Number of Lanes	Independent Wing walls 1200 feet bridge Medium Dense Sand	Inline Cantilever Wing walls 1200 feet bridge Medium Dense Sand
2 lanes	0.016152	0.030701
4 lanes	0.016091	0.025941

Figure 10. *Equivalent Plastic Strain EPEQ in the Piles*



Conclusions

Use of inline cantilever wing walls has a modest impact on integral abutment pile stresses. This includes generation of pile plasticity at shorter bridge lengths compared to bridges built with independent wing walls. In other words, for the same bridge length the stresses generated in the piles are higher when integral abutments are built with inline cantilever wing walls than when independent wing walls are built next to the integral abutments.

Parameters affecting the magnitude of integral abutment pile stresses include the bridge length, temperature variation, type of backfill soil behind the abutments and the wing walls, soil profile around piles, use of predrilled holes around the top nine feet of piles, pile orientation, span layout, abutment height, and use of cantilever wing walls. Comparison of the effects of four of those parameters (bridge length, use of predrilled holes, use of inline cantilever wing walls, and type of backfill soil) on the magnitude of stresses generated in the piles leads to the conclusion that the two most critical parameters are the use of predrilled holes and bridge length followed by the use of inline cantilever wing walls and type of backfill soil. Thus, considering only those four parameters, the most severe combination for overall integral abutment bridge behavior occurs with long bridges, no predrilled holes at the top nine feet of piles, use of inline cantilever wing walls, and presence of dense sand backfill soil behind the abutments and the wing walls.

It is worth mentioning that no plastic hinge is formed near the pile head even under the most critical combination of parameters. In addition, stresses in the piles of integral abutment bridges built with inline cantilever wing walls are higher when the bridge has fewer lanes.

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