Virginia Center *for* Transportation
INNOVATION
& RESEARCH

Thermal Response of Integral Abutment Bridges With Mechanically Stabilized Earth Walls

http://www.virginiadot.org/vtrc/main/online_reports/pdf/13-r7.pdf

ALFREDO E. ARENAS, Ph.D.
Graduate Research Assistant

GEORGE M. FILZ, Ph.D., P.E.
Professor

THOMAS E. COUSINS, Ph.D., P.E.
Professor

Department of Civil and Environmental Engineering
Virginia Tech

Final Report VCTIR 13-R7

VIRGINIA CENTER FOR TRANSPORTATION INNOVATION AND RESEARCH
530 Edgemont Road, Charlottesville, VA 22903-2454
www.VTRC.net

Standard Title Page—Report on State Project

Report No.: VCTIR 13-R7	Report Date: March 2013	No. Pages: 73	Type Report: Final Contract	Project No.: RC00010
			Period Covered: August 2007–September 2012	Contract No.:
Title: Thermal Response of Integral Abutment Bridges With Mechanically Stabilized Earth Walls				Key Words: Bridge, integral abutment, MSE walls
Author(s): Alfredo E. Arenas, Ph.D., George M. Filz, Ph.D., P.E., and Thomas E. Cousins, Ph.D., P.E.				
Performing Organization Name and Address: Virginia Polytechnic Institute & State University Via Department of Civil & Environmental Engineering, 200 Patton Hall Blacksburg, VA 24061				
Sponsoring Agencies' Name and Address: Virginia Department of Transportation 1401 E. Broad Street Richmond, VA 23219				
Supplementary Notes:				

Abstract:

The advantages of integral abutment bridges (IABs) include reduced maintenance costs and increased useful life spans. However, improved procedures are necessary to account for the impacts of cyclic thermal displacements on IAB components, including the foundation piling and the components of mechanically stabilized earth (MSE) walls that are often used around IABs.

As requested by the Virginia Center for Transportation Innovation and Research and the Virginia Department of Transportation (VDOT), this research focused on IABs with foundation piling in the backfill of MSE walls that have a "U-back" configuration, which indicates that the MSE wall has three faces, one parallel to the abutment and two parallel to the bridge alignment. During this research, more than 65 three-dimensional numerical analyses were performed to investigate and quantify how different structural and geotechnical bridge components behave during thermal expansion and contraction of the bridge. In addition, a separate series of three-dimensional numerical models were developed to evaluate the usefulness of corrugated steel pipes in-filled with loose sand around the abutment piles.

The results of this research quantify the influence of design parameter variations on the effects of thermal displacement on system components, and thus provide information necessary for IAB design. One of the findings is that corrugated steel pipes around abutment piles are not necessary. An estimate of the cost savings from eliminating these pipes is presented.

One of the most important outputs of this research is an easy-to-use Excel spreadsheet, named IAB v3, that quantifies the impact of thermal displacement in the longitudinal direction, but also in the transverse direction when the abutment wall is at a skew angle to the bridge alignment. The spreadsheet accommodates seven different pile sizes, which can be oriented for weak or strong axis bending, with variable offset of the abutment from the MSE wall and for variable skew angles. Both steel and concrete girders are considered. The spreadsheet calculates the increments of displacements, forces, moments, and pressures on systems components due to thermal displacement of IABs.

In addition, this report provides recommendations for implementing the research results in VDOT practice by proposing modifications to Chapter 17 of VDOT's *Manual of the Structure and Bridge Division, Volume V—Part 2, Design Aids and Particular Details,* and to Chapter 10 of *Volume V—Part 11, Geotechnical Manual for Structures.* The background for each recommended modification is discussed, and specific details for changes to wording and calculations in the manuals are presented.

FINAL REPORT

THERMAL RESPONSE OF INTEGRAL ABUTMENT BRIDGES WITH MECHANICALLY STABILIZED EARTH WALLS

Alfredo E. Arenas, Ph.D.
Graduate Research Assistant

George M. Filz, Ph.D., P.E.
Professor

Thomas E. Cousins, Ph.D., P.E.
Professor

Department of Civil and Environmental Engineering
Virginia Tech

VCTIR Project Managers
Edward J. Hoppe, Ph.D., P.E., and Michael C. Brown, Ph.D., P.E.
Virginia Center for Transportation Innovation and Research

Virginia Center for Transportation Innovation and Research
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

Charlottesville, Virginia

March 2013
VCTIR 13-R7

DISCLAIMER

The project that is the subject of this report was done under contract for the Virginia Department of Transportation, Virginia Center for Transportation Innovation and Research. The contents of this report reflect the views of the author(s), who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Virginia Department of Transportation, the Commonwealth Transportation Board, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation. Any inclusion of manufacturer names, trade names, or trademarks is for identification purposes only and is not to be considered an endorsement.

Each contract report is peer reviewed and accepted for publication by staff of Virginia Center for Transportation Innovation and Research with expertise in related technical areas. Final editing and proofreading of the report are performed by the contractor.

ABSTRACT

The advantages of integral abutment bridges (IABs) include reduced maintenance costs and increased useful life spans. However, improved procedures are necessary to account for the impacts of cyclic thermal displacements on IAB components, including the foundation piling and the components of mechanically stabilized earth (MSE) walls that are often used around IABs.

As requested by the Virginia Center for Transportation Innovation and Research and the Virginia Department of Transportation (VDOT), this research focused on IABs with foundation piling in the backfill of MSE walls that have a "U-back" configuration, which indicates that the MSE wall has three faces, one parallel to the abutment and two parallel to the bridge alignment. During this research, more than 65 three-dimensional numerical analyses were performed to investigate and quantify how different structural and geotechnical bridge components behave during thermal expansion and contraction of the bridge. In addition, a separate series of three-dimensional numerical models were developed to evaluate the usefulness of corrugated steel pipes in-filled with loose sand around the abutment piles.

The results of this research quantify the influence of design parameter variations on the effects of thermal displacement on system components, and thus provide information necessary for IAB design. One of the findings is that corrugated steel pipes around abutment piles are not necessary. An estimate of the cost savings from eliminating these pipes is presented.

One of the most important outputs of this research is an easy-to-use Excel spreadsheet, named IAB v3, that quantifies the impact of thermal displacement in the longitudinal direction, but also in the transverse direction when the abutment wall is at a skew angle to the bridge alignment. The spreadsheet accommodates seven different pile sizes, which can be oriented for weak or strong axis bending, with variable offset of the abutment from the MSE wall and for variable skew angles. Both steel and concrete girders are considered. The spreadsheet calculates the increments of displacements, forces, moments, and pressures on systems components due to thermal displacement of IABs.

In addition, this report provides recommendations for implementing the research results in VDOT practice by proposing modifications to Chapter 17 of VDOT's *Manual of the Structure and Bridge Division, Volume V—Part 2, Design Aids and Particular Details,* and to Chapter 10 of *Volume V—Part 11, Geotechnical Manual for Structures.* The background for each recommended modification is discussed, and specific details for changes to wording and calculations in the manuals are presented.

FINAL REPORT

THERMAL RESPONSE OF INTEGRAL ABUTMENT BRIDGES WITH MECHANICALLY STABILIZED EARTH WALLS

Alfredo E. Arenas, Ph.D.
Graduate Research Assistant

George M. Filz, Ph.D., P.E.
Professor

Thomas E. Cousins, Ph.D., P.E.
Professor

Department of Civil and Environmental Engineering
Virginia Tech

INTRODUCTION

Integral abutment bridges (IABs) are "jointless," and they offer several comparative advantages over bridges with expansion joints, including substantially reduced maintenance costs. Alampalli and Yannotti (1998) found that the predominant cause of bridge deterioration is the flow of deck drainage waters contaminated with deicing chemicals through expansion joints.

The most important advantages of IABs have been summarized by Arsoy et al. (1999):

- Lower construction costs due to joint elimination.
- Lower maintenance costs. Conventional bridges have higher maintenance costs due to deterioration of joints.
- Superior seismic performance.
- Fewer piles are needed per foundation, and no battered piles are needed.
- Simpler and faster construction.
- Improved riding quality because of the continuous bridge deck.

Figure 1 shows a typical cross section of an IAB. This figure shows how the bridge deck, girders, abutment, and abutment piles form an integral structure, and hence the name integral abutment bridge. This figure also shows a mechanically stabilized earth (MSE) wall located under the bridge deck and in front of the embankment. The MSE wall facing is held in place by the MSE wall reinforcing strips, which extend from the MSE wall facing into the backfill. Figure 1 also shows the approach slab, which is structurally connected to the abutment in Virginia Department of Transportation (VDOT) bridges, but the slab-abutment connection is not designed to transfer moment.

The full integral abutment design shown in Figure 1 incorporates a hinge between the pile cap and the upper portion of the abutment. The vertical steel bars extending through the hinge are called dowels. Figure 2 presents a detail of the hinge. The hinge is used by VDOT in most IAB designs, and the main purpose of this connection is to reduce shear loads and bending moments imposed on piles by thermal expansion and contraction of the bridge deck.

Figure 3 shows three abutment designs that have been used or considered for VDOT full IABs. From left to right, the abutment designs incorporate dowels, laminated pads, and solid abutments. Like dowels, laminated pads have the objective of reducing the transferred movements from the upper part of the abutment to the pile cap.

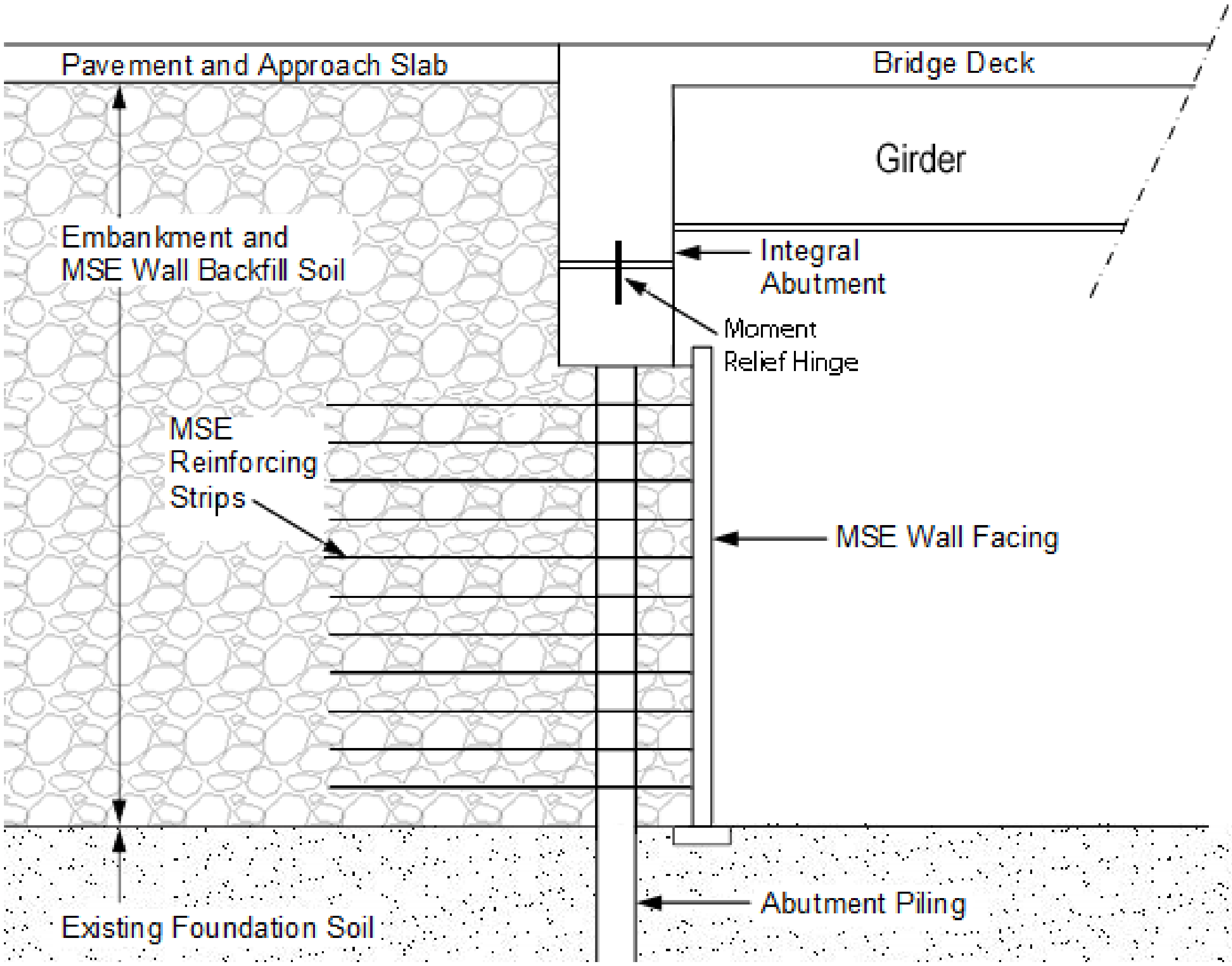


Figure 1 – Integral abutment bridge.

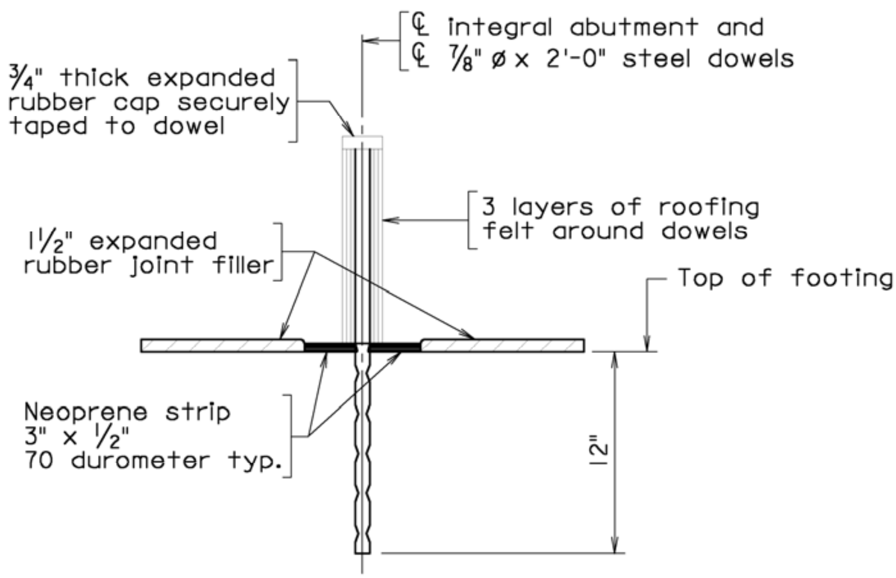


Figure 2 – Hinge detail (Chapter 17, Integral/Jointless Bridges, VDOT, 2011b).

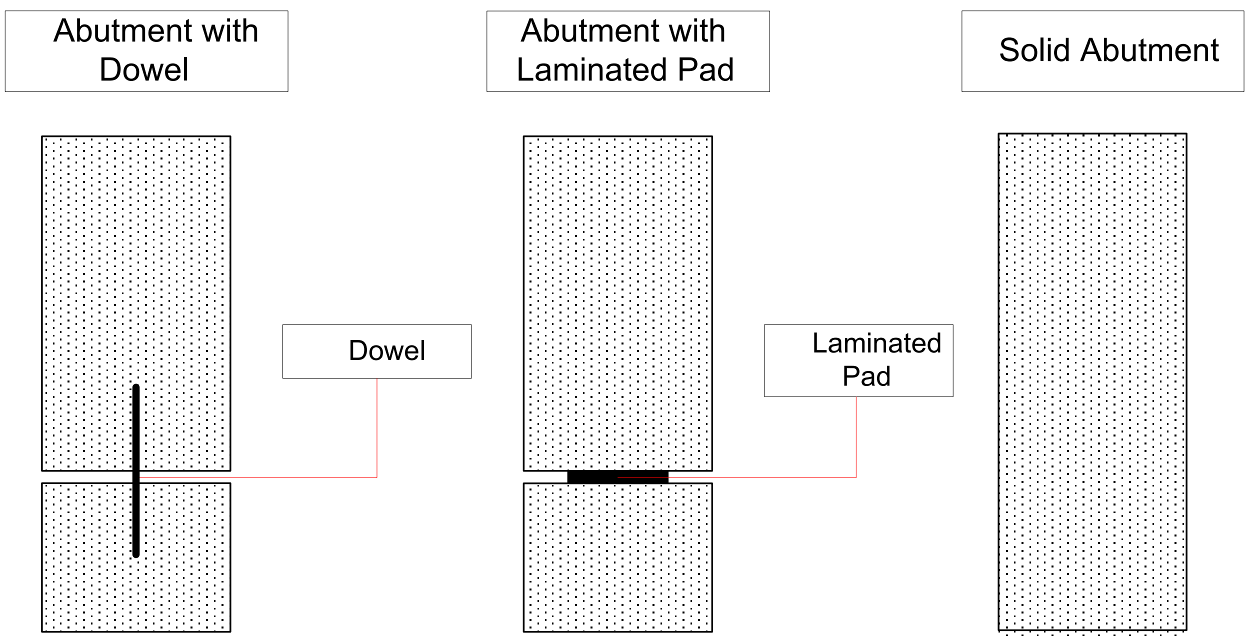


Figure 3 – Abutment design.

IABs are subject to thermal displacements, which are the product of daily and seasonal temperature variations. Since these bridges are designed without joints, the thermal displacements are directly transferred to the abutments and therefore to the embankments and the abutment foundation piles.

Currently, engineers face challenges when designing IABs because rational and validated procedures are not available to determine the magnitude and distribution of loads imposed due to thermal displacements. The nature of the problem is complex because of the vastly differing stiffnesses of the soil and structural components, the nonlinear response of the soil, and the complex three-dimensional geometries of IABs. Thus, the intent of this research is to quantify the magnitude and distribution of loads in IAB components due to thermal expansion of bridges under different conditions of interest to VDOT. As requested by the Virginia Center for Transportation Innovation and Research (VCTIR) and VDOT, the focus of this research is on IABs with foundation piling in the backfill of mechanically stabilized earth (MSE) walls that have a "U-back" configuration, which indicates that the MSE wall has three faces, one parallel to the abutment and two parallel to the bridge alignment.

This report describes the research and includes sections addressing the Purpose and Scope, Methods, Results, Discussion, Conclusions, Recommendations, Costs and Benefits Assessment, Acknowledgments, References, and two appendices. Appendix A identifies the monitoring locations for the numerical analyses. Appendix B provides detailed recommendations for implementing the findings of this research in Chapter 17 of VDOT's *Manual of the Structure and Bridge Division, Volume V—Part 2, Design Aids and Particular Details* (VDOT, 2011b). Additional information about the research is in the doctoral dissertation by Arenas (2010).

PURPOSE AND SCOPE

This research addresses several unknowns and points of controversy related to IABs. The following list includes several aspects of IABs for which no design guidelines exist or no consensus has been reached:

- Optimum distance between the back of MSE wall facing panels and abutment walls
- Orientation of piles with strong and weak axes, such as H-piles
- Pile loads and moments
- Influence of abutment design, i.e., dowel connections, laminated pads, or solid abutment
- Rotation and lateral displacement of skewed bridges
- Tensile forces in MSE wall reinforcing strips for both skewed and non–skewed bridges
- Lateral forces on piles in skewed bridges
- Quantitative impact of thermal displacement magnitude
- Distribution and magnitude of lateral earth pressures behind the abutment
- Influence of elasticized Expanded Polystyrene (EPS) foam behind the abutment and behind the MSE wall facing
- Impact of soil/rock foundation type
- Influence of reinforcing strips in the backfill behind the abutment (in the longitudinal direction of the bridge)
- Use of sand-filled steel pipes around abutment piles.

The purpose of this research is to address these issues through the use of numerical analyses and to develop easy-to-apply recommendations and analysis tools to help engineers with design of IABs.

Although there are many configurations of IABs, the scope of this research was limited to fully integral abutment bridges, with MSE walls retaining the embankments and with piling extending through the MSE backfill and into the foundation soil.

METHODS

The research was divided into the following six major tasks and several subtasks, which are listed below. The methods used to perform these tasks are described in the sections of the report that follow the list of tasks.

1. Numerical model of an IAB in New Jersey
   - Thermal variation
   - Model development
   - Validation

2. Survey of DOTs regarding IAB practices

3. Analysis of corrugated steel pipes around piles
   - Model development
   - Analysis cases

4. Numerical model based on a Virginia IAB
   - Model development
   - Parametric study

5. IAB v3 spreadsheet

6. Recommendations for implementing the research results in VDOT manuals.

Numerical Model of an IAB in New Jersey

An IAB in New Jersey was instrumented, monitored, and analyzed by Hassiotis et al. (2006). This case history provided a data source that was used to validate the numerical analysis methods employed in this research. The method for applying displacements induced by thermal variations, the numerical model development, and validation of the numerical model are described below.

Thermal Variation

The following formula was used to compute the total thermal displacement:

$$d = \alpha * \Delta T * L \qquad \text{(Eq. 1)}$$

where

d = the total displacement experienced by the bridge. The total displacement experienced by each abutment is one-half of d.

α = the coefficient of linear thermal expansion of the bridge. For steel, α is approximately 6.5×10^{-6} per ºF, and for concrete, α is approximately 5.5×10^{-6} per ºF.

ΔT = the difference between the maximum and minimum temperatures that the bridge will experience.

L = the length of the bridge.

Eq. 1 is used to calculate the total thermal displacement that a bridge will experience throughout a year. When determining ΔT for calculating the maximum yearly displacement, extreme values of bridge temperature are considered. Arsoy et al. (2005) developed a double sine displacement function to represent both daily and seasonal thermal displacement as a function of time, as shown in Eq. 2. The displacements computed using this equation can be applied to the mid-point of the bridge deck in the numerical model to represent thermal expansion and contraction of the bridge. The maximum displacements imposed at the mid-point of the bridge will be half of those computed with Eq. 1. Because the bridge girders are very stiff axially, the displacement imposed in the numerical model at the mid-point of the bridge is essentially equal to the displacement that results at the abutment.

$$\text{Displacement } d(t) = A \sin(2\pi t) + B \sin(2\pi t / 365) \qquad \text{(Eq. 2)}$$

where

A = half of daily thermal displacement.

B = complement of half of the total displacement, so that the following is true: $d = 4(A + B)$, with d from Eq. 1.

t = time measured in days.

Eq. 2, which provides the displacement function for the girders, has two parts: the first controls the daily displacement and the second controls the seasonal displacement. Eq. 2 has a cyclic period of one year. A graphical representation of Eq. 2 is shown in Figure 4.

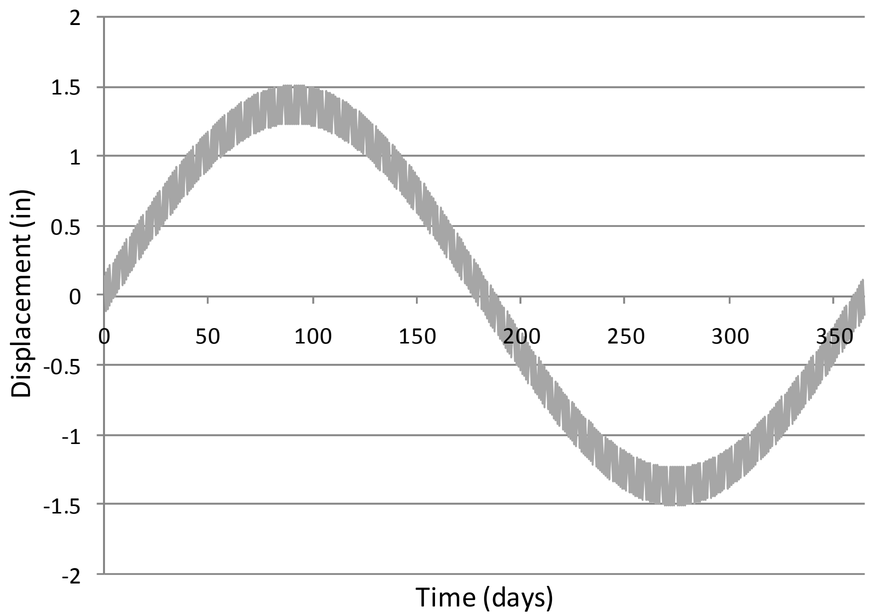


Figure 4 – Total thermal displacement of 3 inches with a daily fluctuation of 0.27 inches. Displacement experienced by one abutment.

Model Development

Hassiotis et al. (2006) studied and performed numerical analyses of an IAB bridge located over Interstate 95 in the vicinity of Trenton, NJ. Using the program ABAQUS, Hassiotis et al. (2006) developed a finite element model of the bridge. This model included shell elements representing the bridge deck, solid elements representing the abutment, beam elements representing the piles, and spring elements representing the interaction between the structural components and the adjacent soils. The soil materials were not separately represented in the analyses. A temperature gradient was imposed at the bridge deck to represent a temperature change of 27˚ C.

For the research described in this report, the computer program FLAC3D was selected to perform all the numerical analysis because it is one of the few 3D geotechnical programs available that provide the user with a high degree of flexibility. In addition, FLAC3D has been widely used by practitioners and the research community, becoming a relatively standard program for geotechnical numerical analysis. Finally, FLAC3D is based on a finite difference analysis method that has some advantages over finite element codes, including ability to analyze large displacements and unstable systems, including yield/failure of soil over large areas.

Figure 5 shows the New Jersey IAB elevation and plan view. The main characteristics of the bridge are as follows:

- The bridge has six lanes, with an overall width of 104.3 ft.
- The bridge consists of two continuous spans.
- The deck is supported by eleven HPS70W steel girders with a total length of 298 ft each, and a center-to-center spacing of 9.5 ft.

- The bridge has a skew angle of 15°.
- The abutments are 11 ft high with a thickness of 3 ft. The abutments are solid, i.e., each abutment is continuous between the upper portion holding the girders and the lower portion into which the piles are embedded.
- Each abutment is supported on a single row of nineteen HP360x152 (HP14x102) piles at a center-to-center spacing of 5.5 ft.
- Piles are oriented for weak axis bending.
- The piles are approximately 38.5 ft long, with 26.2 ft of the piles extending through the MSE wall backfill.
- Each pile is surrounded by a steel corrugated sleeve backfilled with loose sand.

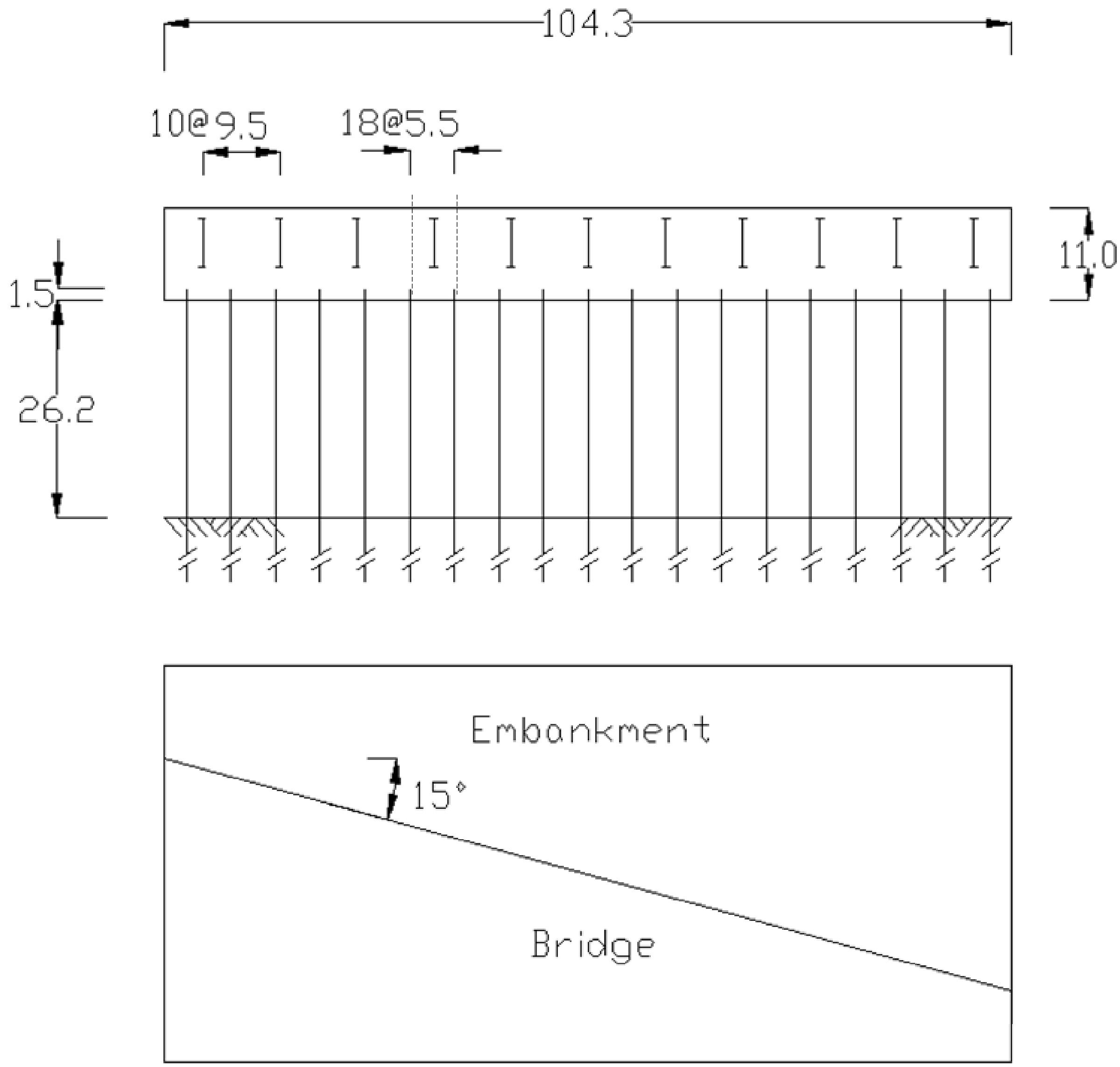


Figure 5 – New Jersey IAB elevation and plan view (after Hassiotis et al., 2006),

The FLAC3D model of the New Jersey IAB developed for this research included solid elements to represent the soil and abutment, structural elements to represent the piles and girders, and sequential placement and loading of system components to represent the real construction sequence. After self-weight (i.e., gravity) forces were applied to the foundation soil, the MSE wall and backfill was built in a series of steps. Then piles, abutment, and girders were placed in the model, and the backfill material was placed behind the abutment. The thermal simulation was imposed at the girder center line.

Table 1 shows a list of material property values along with the constitutive models used in FLAC3D. These property values were obtained using boring log information and correlations. Steel and concrete were represented as linear elastic materials, and soils were represented as linear-elastic, perfectly plastic materials with a Mohr-Coulomb failure criterion. Although FLAC3D requires the shear modulus and bulk modulus as inputs, values of Young's modulus and Poisson's ratio are listed in Table 1 because those parameters allow most engineers to have a better understanding of the physical characteristics of the materials.

Table 1 – Material Properties

Material	Elastic Modulus E, psf	γ, pcf	ϕ, deg	Cohesion, psf	Constitutive Model	Poisson Ratio ν
Concrete	597,000,000	145	-	-	Elastic	0.14
Steel	4,177,000,000	485	-	-	Elastic	0.3
Loose Sand	280,000	115	30	-	Elastic-plastic, Mohr-Coulomb	0.3
Medium Sand	540,000	123	34	-	Elastic-plastic, Mohr-Coulomb	0.3
Dense Sand	800,000	130	38	-	Elastic-plastic, Mohr-Coulomb	0.3
Backfill	800,000 to1,300,000	120	38	-	Elastic-plastic, Mohr-Coulomb	0.2
Silt	350,000	120	33	0 - 150	Elastic-plastic, Mohr-Coulomb	0.3
Elasticized EPS	5,500	0.87	-	-	Elastic	0.1

Validation

Hassiotis et al. (2006) made field measurements of the New Jersey bridge response for over three years. A wide range of field measurements are described in their report, but the most important for model validation of this research are:

- Pile bending moments at different elevations
- Abutment earth pressures at two elevations
- Girder horizontal displacements.

Initially, material and soil-structure interaction property values were obtained from standard geotechnical references, such as *Soil Mechanics in Engineering Practice* (Terzaghi et al., 1996), as well as recommendations in the FLAC3D manual. The initial property values were modified within a realistic range to achieve reasonable agreement between FLAC3D response and field measurements.

Survey of DOTs Regarding IAB Practices

A nation-wide survey was conducted with the purpose of collecting information about integral bridge abutments that have foundation piling for the abutments extending through the backfill of MSE walls.

The survey was distributed to Departments of Transportation (DOTs) and companies working in this area of practice. The survey included questions ranging from general aspects of IABs to specific design details.

One of the goals of this survey was to determine current design practices in different agencies, to obtain information about the principal challenges that engineers face when designing IABs, and to identify concerns about current design procedures.

Analysis of Corrugated Steel Pipes around Piles

Designers of IABs have used corrugated steel pipes in-filled with loose sand placed around abutment piles in an attempt to provide a medium within which the abutment piles have an increased ability to move laterally. VDOT/VCTIR asked us to analyze the effectiveness of this approach, which we did using a FLAC3D model.

Model Development

The 3D numerical model consists of a horizontal slice through the MSE wall backfill, the corrugated steel pipe, the loose sand infill, and an IAB foundation pile. Figure 6 shows the numerical model mesh that was developed for these analyses.

The model consists of 2160 mesh zones representing the pile, the in-filled sand inside the steel pipes, and the backfill soil. In addition, 240 shell elements were used to represent the steel pipe (Figure 6) as a cylinder in the numerical model. This was done in accordance with mesh generation requirements in FLAC3D.

Even though the steel pipes are in-filled with loose sand, three sand densities were used during the numerical simulations: loose, medium, and dense. This was done to investigate the influence of density, and because initially loose sand might be densified by cyclic pile movements.

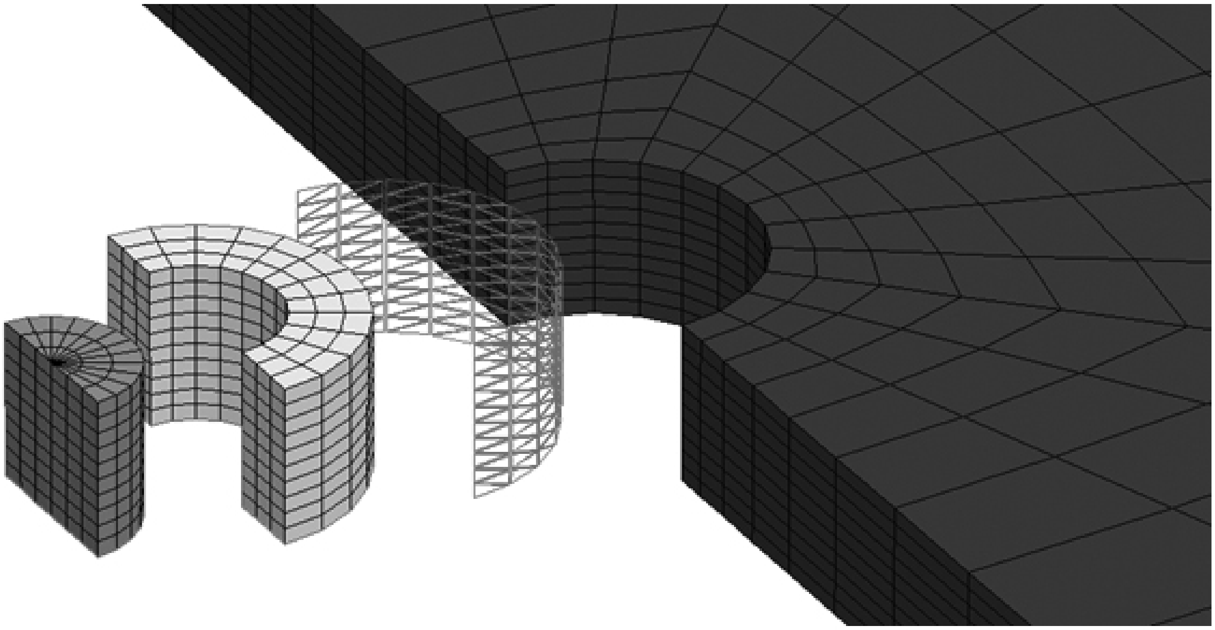


Figure 6 – Zoomed-in and exploded view of pile-sand-pipe-backfill system, from left to right: pile, sand, steel pipe and backfill.

Analysis Cases

Two cases were analyzed, each case with two lateral loading sequences.

First Case

In the first case, the model was initially subjected to self-weight forces, and then a vertical pressure of 1,300 psf was applied to the mesh surface, with no lateral displacement allowed at the mesh boundaries. Once the model was in equilibrium, one of the lateral loading sequences was applied.

Second Case

The second case is almost identical to the first case, but it differs in the boundary condition imposed at the mesh surface. In this case, after the model reached equilibrium with the 1,300 psf vertical pressure, the mesh boundary condition at the surface was changed to rollers, before one of the lateral loading sequences was applied. Thus, no displacements are allowed in the direction normal to the model surface in this case.

The above cases represent two extreme boundary conditions, and the actual boundary condition for a segment of laterally loaded pile is between these two cases.

Lateral Loading Sequences

Two lateral load sequences were applied for each of two boundary-condition cases described above.

- Loading Sequence 1: Pile is displaced monotonically to a large displacement.

- Loading Sequence 2: Pile is subjected to one year of cyclic displacement, and then it is displaced monotonically to a large displacement. The cyclic displacements correspond to one year of thermal fluctuations, with a maximum thermal displacement of 1 in., which represents a jointless bridge that is about 320 ft long and subject to a temperature variation of 80 ºF.

Numerical Model Based on a Virginia IAB

Model Development

The base case for this research study was taken from a fully integral bridge located at the intersection of Interstate I-95 and Telegraph Road in Alexandria, Virginia.

This bridge was selected because it represents the current state of practice of VDOT's designs of IABs. In addition, the west abutment (B672 – A) of this bridge was instrumented, so it is logical to model this bridge for later comparison between numerical data and field measurements.

The bridge has a 166 ft long span, and it is supported by seven HP 12x53 piles oriented for weak bending moment at each abutment. Five girders support the bridge deck. The girders are 5.9 ft tall and their flanges vary from 16 to 18 inches wide. The design incorporates a U-back MSE wall, which means that the MSE wall wraps back around the approach embankment such that the MSE side walls are parallel to the road centerline.

The abutment is 10.25 ft high and 3 ft thick. The abutment incorporates a joint between the upper portion, which holds the girders, and the pile cap. The joint is created by 32 steel dowels located along at the pile cap centerline. The dowels are 2 ft long steel rods that are embedded 1 ft in the pile cap and 1 ft in the abutment above the pile cap. Although not used at the Telegraph Road Bridge, VDOT sometimes uses laminated pads instead of dowels at the joints above the pile caps. Figure 7 shows the Telegraph Road IAB elevation and plan view.

At the direction of VDOT engineers, three modifications were made to the base case to produce a model that represents conditions of interest for VDOT bridges. First, the HP 12x53 piles in the bridge were replaced by HP 10x42 piles in the model. Second, reinforcing strips that were present behind the abutment of the Telegraph Road bridge were removed from the base case model. Third, the total thermal displacement magnitude was increased from 0.75 inches to 3 inches to investigate the effects of longer bridges on integral abutment performance. The remaining characteristics of the design of the Telegraph Road Bridge are unchanged in the model.

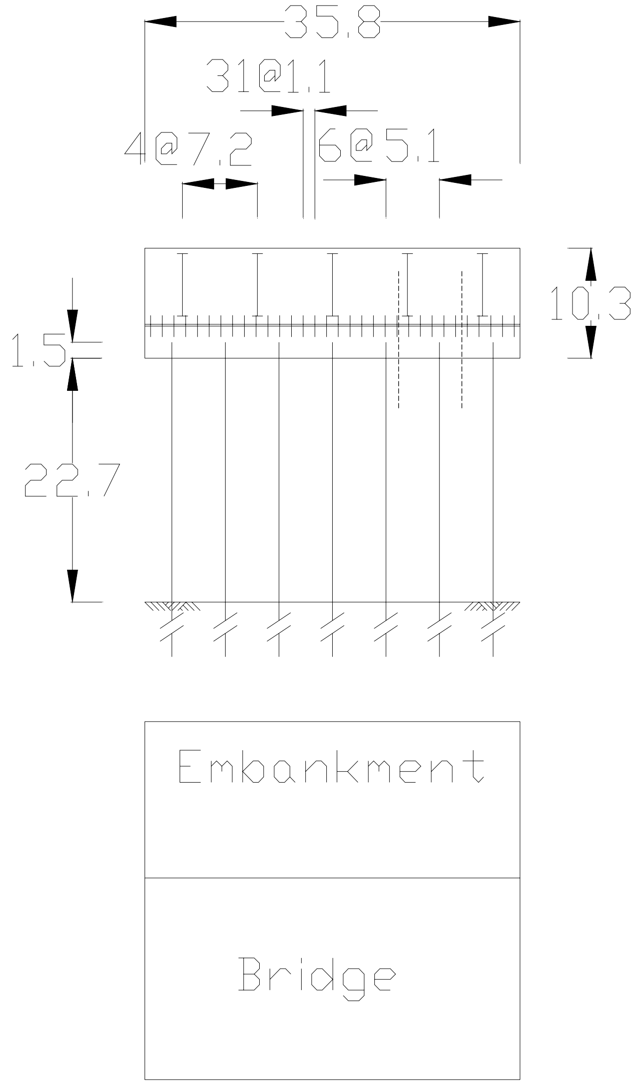


Figure 7 – Telegraph Road IAB elevation and plan view (adapted from project construction plans).

Figure 8 shows an image of the numerical model. Table 2 provides the bridge dimensions, and Figure 9 shows a sketch of the bridge with letters designating the principal dimensions.

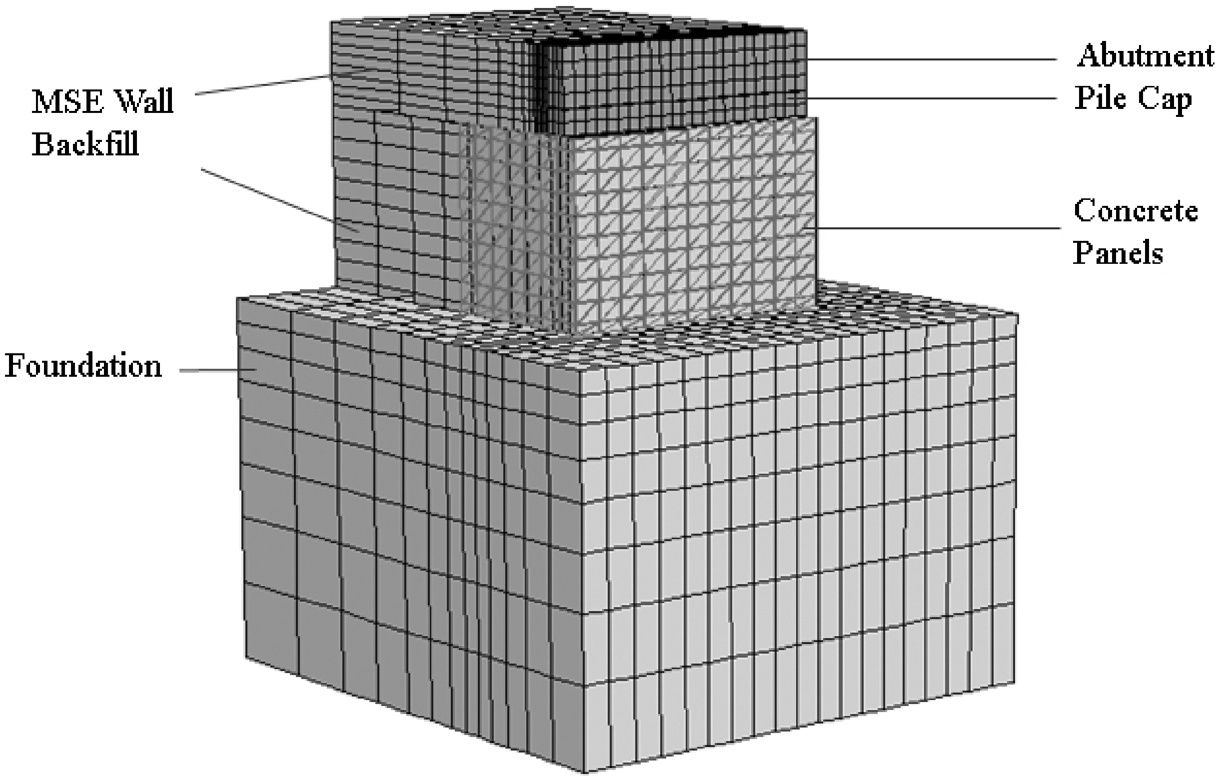


Figure 8 – Numerical model of the mesh representing the Telegraph Road bridge abutment. The figure displays the concrete abutment, elasticized EPS, abutment and foundation soil, and the MSE wall elements. The rest of the elements have been omitted for clarity.

Table 2 – Base Case Geometry

Item Description	Letter in Figure 9	Number of elements Across the Bridge	Dimension
Embankment height	A	-	30.00 ft
Abutment height (above dowel)	B	-	7.25 ft
Abutment height (below dowel)	C	-	3.00 ft
Strip vertical spacing	D	10	2.50 ft
Elasticized EPS thickness	E	-	2.67 ft
Abutment thickness	F	-	3.00 ft
Dowel	G	32	2.00 ft
Distance between abutment backwall and MSE wall	H	-	2.00 ft
Girder height	I	5	5.90 ft
MSE wall height	J	-	23.70 ft
Pile embedment (in foundation)	K	-	45.00 ft
Piles	L	7	70.00 ft
Strip length	M	10	23.00 ft
Abutment width		-	35.80 ft

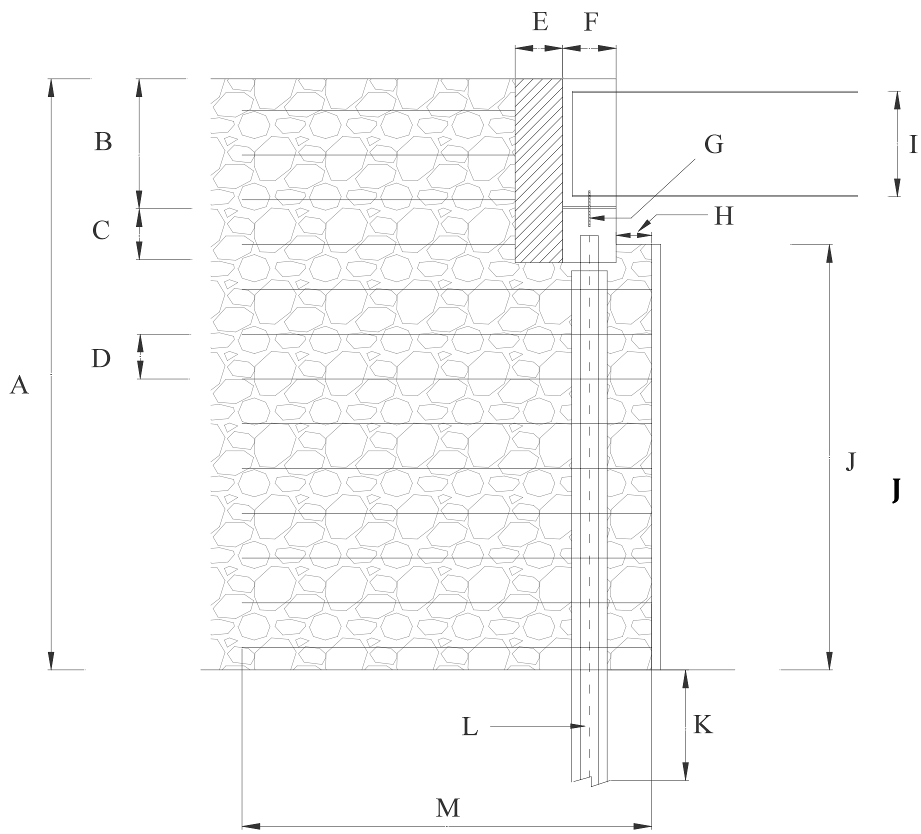


Figure 9 – Integral Bridge Abutment cross section. Abutment B672 – A.

The numerical model was constructed and analyzed using FLAC3D software. The model was developed using the following components: grid points representing soil mesh nodes, spring elements that link structural elements and soil, beam elements to represent dowels and girders, pile elements, shell elements to represent MSE concrete panels, cable elements to represent MSE wall strips, and interface elements to allow sliding and opening between dissimilar materials. Altogether, more than 15,000 numerical entities were used in the model.

The foundation mesh dimensions are large enough that the boundaries do not affect the output related to the abutment, foundation piles, or MSE wall components. The mesh size was optimized such that a larger foundation size will not affect the results, and a smaller foundation will begin to affect the results due to the boundary proximity. The mesh nodes at the bottom of the foundation were fixed against movement in all three directions, and the mesh nodes on the sides of the foundation were restrained against movement normal to each side.

The construction and loading sequence was imposed as follows:

- Self-weight forces were applied to the foundation soil.
- The foundation piles were installed.
- The embankment fill was placed in lifts, and the MSE wall components were installed.
- The bridge girders were installed.

- The thermal displacements described by Eq. 2 were applied at the girder centerline.

Parametric Study

The parametric study consists of creating a numerical base case model and then changing parameter values to disclose the impact of parameter variations on the bridge response.

Monitoring Output

A series of monitoring output points were defined to capture the bridge response to thermal displacements over a range of model geometries and property values. Each monitoring point tracks displacement or force changes at a specific position or element on the bridge. For example, shear forces were tracked during one year of thermal displacement simulation at the top of selected piles.

Table 3 summarizes the individual monitoring output points used in this study. Appendix A provides the exact locations of the individual monitoring output points.

In addition to the individual monitoring output points described in Table 3, the global monitoring points listed in Table 4 were also established. The difference between the single monitoring points in Table 3 and the global monitoring points in Table 4 is that the single monitoring points track changes in one element, whereas global monitoring points are the sum or average of a related group of individual monitoring points. For example, one of the global monitoring points is the total pile shear force in the longitudinal direction, which is the sum of the longitudinal shear forces in all the abutment piles. Global monitoring points are useful to understand what forces are acting on the entire abutment and pile cap.

Table 3 – Summary of Individual Monitoring Output Points

Measured Parameter	**Direction[1]**	**Where Measured**	**Number of Monitored Points**
Displacement	Longitudinal and Transverse	Abutment	18
Shear Force	Longitudinal and Transverse	Dowels and Piles	20
Moment	Longitudinal and Transverse	Piles	24
Earth Pressure	Longitudinal	Behind EPS	10
Lateral Pressure	Longitudinal	Behind Abutment	10
Strip Tensile Force at Connection	Along Strip	Strips	21
Strip Max Tensile Force	Along Strip	Strips	21
Strip Max Tensile Force Position	Along Strip	Strips	21
Earth Pressure	Longitudinal and Transverse	MSE Wall	21
Axial Force	Axial Direction	Piles	9
Total			**175**

[1]Two directions were defined in this study for global orientation: “Longitudinal” direction is parallel to the bridge centerline and “Transverse” direction is perpendicular to the bridge centerline. These definitions of “longitudinal” and “transverse” apply to the results presented in this report regardless of abutment skew angle.

Table 4 – Global Monitoring Output

Monitored Parameter	Direction	Where Monitored	Number of Monitored Points
Total Shear Force	Longitudinal and Transverse	Dowels and Piles	6
Total Moment	Longitudinal and Transverse	Dowels and Piles	6
Total Lateral Force	Longitudinal	Interface between EPS and Abutment	2
Total Shear Force	Vertical	Interface between EPS and Abutment	2
Total Axial Force	Axial Direction	Dowels and Piles	2
Total			18

Individual Parameter Variations

Each analysis case listed in Table 5 represents a change of only one parameter from the base case model. Table 5 provides the case number, the value of the parameter in the base case model, the value of the parameter in the numbered case, and a brief description of what was changed. Table 6 shows the geometries of Cases 12, 13, 14 and 15.

Multiple Parameter Variations

Initially, the plan for this research only included varying one parameter at a time, but as the research progressed, it became apparent that varying multiple parameters simultaneously was necessary to fully investigate and quantify thermal effects on the bridge abutment. In particular, combining parameter variations helped determine whether the influence of two parameters is multiplicative, additive, or should be combined in some other fashion. Table 7 shows a list of the cases of combined parameter variations analyzed during this research.

Although Cases C3 and C4 are combination cases (pile webs aligned with the pile cap and variation in skew angle), they are special cases because the effects of pile orientation and skew angle are not combined quantitatively. Instead, these combinations address a specific question from VDOT engineers about whether the forces acting on piles in skewed bridges could be reduced by orienting the pile webs in alignment with the pile cap, regardless of skew angle.

Table 5 – Single Parameter Variations From Base Case

Case	Base Case Parameter Value	Changed Parameter Value	Description
1	Dowels	Laminated Pad	Instead of using dowels, a laminated pad was used to connect the pile cap with the abutment.
2	Dowels	Solid	There is no joint between the abutment and the pile cap. The abutment is one solid structure.
3	Distance 2 ft	Distance 0.5 ft	The distance between the abutment backwall and the back of the MSE wall was changed to 0.5 ft.
4	Distance 2 ft	Distance 1 ft	The distance between the abutment backwall and the back of the MSE wall was changed to 1 ft.
5	Distance 2 ft	Distance 4 ft	The distance between the abutment backwall and the back of the MSE wall was changed to 4 ft.
6	Distance 2 ft	Distance 6 ft	The distance between the abutment backwall and the back of the MSE wall was changed to 6 ft.
7	Displacement 3 in	Displacement 0.75 in	The total thermal displacement was decreased to 0.75 in.
8	Displacement 3 in	Displacement 1.5 in	The total thermal displacement was decreased to 1.5 in.
9	Displacement 3 in	Displacement 4.5 in	The total thermal displacement was increased to 4.5 in.
10	No elasticized EPS on the MSE wall	Elasticized EPS on MSE wall	A 3 in layer of elasticized EPS material was layered behind the MSE wall face.
11	Silty Sand	Shale Rock	The foundation geomaterial was changed from silty sand to shale rock.
12	Geometry – Base Case	Geometry 1	Girder and abutment dimensions were reduced. See Table 6.
13	Geometry – Base Case	Geometry 2	Girder and abutment dimensions were increased. See Table 6.
14	Geometry – Base Case	Geometry 3	MSE wall height reduced to 17 ft. See Table 6.
15	Geometry – Base Case	Geometry 4	MSE wall height increased to 30 ft. See Table 6.
16	Elasticized EPS on Abutment	No elasticized EPS abutment	The layer of elasticized EPS material behind the abutment was removed.
17	Pile orientation – Weak	Pile orientation – Strong	The orientation of the piles was changed from weak to strong bending axis.
18	Pile size – 10x42	Pile size – 12x53	The size of the piles was increased from the base case.
19	Pile size – 10x42	Pile size – 14x73	The size of the piles was increased from the base case.
20	No Skew angle	Skew angle 10	Skew angle of 10 degrees was included in the numerical model
21	No Skew angle	Skew angle 20	Skew angle of 20 degrees was included in the numerical model
22	No Skew angle	Skew angle 35	Skew angle of 35 degrees was included in the numerical model
23	No Skew angle	Skew angle 40	Skew angle of 40 degrees was included in the numerical model
24	No Skew angle	Skew angle 45	Skew angle of 45 degrees was included in the numerical model
25	No Skew angle	Skew angle 50	Skew angle of 50 degrees was included in the numerical model
26	No strips on Abutment	Strips on Abutment	Strips behind the abutment were included.

Table 6 – Dimensions of Cases 12, 13, 14 and 15

Description	Dimensions				
	Base Case	**Case 12**	**Case 13**	**Case 14**	**Case 15**
Abutment thickness	3 ft	3 ft	3 ft	3 ft	3 ft
Total abutment height	10.25 ft	9.5 ft	11 ft	10.25 ft	10.25 ft
Girder flange width	16 in	16 in	16 in	16 in	16 in
Girder flange thickness	0.75 in	0.75 in	0.75 in	0.75 in	0.75 in
Girder web height[1]	69 in	60 in	78 in	69 in	69 in
MSE wall height	23.7 ft	23.7 ft	23.7 ft	17 ft	30 ft

[1]Does not includes flanges.

Table 7 – Multiple Parameter Variations From Base Case

Case		Parameter 1 Value	Parameter 2 Value	Parameter 3 Value	Parameter 4 Value	Parameter 5 Value
C1	29	4.5 in. Displ.	Skew 20º			
C2	30	4.5 in. Displ.	Skew 45º			
C3	31	Skewed Pile Axis	Skew 20º			
C4	32	Skewed Pile Axis	Skew 45º			
C5	33	4.5 in. Displ.	Big MSE			
C6	34	Laminated Pad	Skew 20º			
C7	35	Laminated Pad	Skew 45º			
C8	36	Laminated Pad	1.5 in. Displ.			
C9	37	Laminated Pad	4.5 in. Displ.			
C10	38	Pile 14x73	4.5 in. Displ.			
C11	39	Pile 14 x 73	4.5 in. Displ.	Skew 20º		
C12	40	Pile 14 x 73	4.5 in. Displ.	Skew 45º		
C13	41	Pile 12 x 53	Strong orientation			
C14	42	Pile 14 x 73	Strong orientation			
C15	43	Pile 14 x 73	4.5 in. Displ.	Skew 20º	Strong orientation	
C16	44	Pile 14 x 73	4.5 in. Displ.	Skew 45º	Strong orientation	
C17	45	Laminated Pad	Skew 10º			
C18	46	Laminated Pad	Skew 35º			
C19	47	Laminated Pad	Skew 50º			
C20	48	Laminated Pad	Pile 10 x 42	Strong orientation		
C21	49	Laminated Pad	Pile 12 x 53			
C22	50	Laminated Pad	Pile 12 x 53	Strong orientation		
C23	51	Laminated Pad	Pile 14 x 73			
C24	52	Laminated Pad	Pile 14 x 73	Strong orientation		
C25	53	Laminated Pad	Pile 14 x 73	Skew 20º		
C26	54	Laminated Pad	Pile 14 x 73	Skew 45º		
C27	55	Laminated Pad	Pile 14 x 73	Skew 20º	Strong orientation	
C28	56	Laminated Pad	Pile 14 x 73	Skew 45º	Strong orientation	
C29	57	Laminated Pad	Pile 14 x 73	Skew 20º	4.5 in. Displ.	
C30	58	Laminated Pad	Pile 14 x 73	Skew 45º	4.5 in. Displ.	
C31	59	Laminated Pad	Pile 14 x 73	Skew 20º	4.5 in. Displ.	Strong orientation
C32	60	Laminated Pad	Pile 14 x 73	Skew 45º	4.5 in. Displ.	Strong orientation
C33	61	Laminated Pad	0.75 in. Displ.			
C34	62	Laminated Pad	0.5 ft Dist. to MSE			
C35	63	Laminated Pad	1 ft Dist. to MSE			
C36	64	Laminated Pad	3 ft Dist. to MSE			
C37	65	Laminated Pad	5 ft Dist. to MSE			

IAB v3 Spreadsheet

One of the principal goals of this research is to develop an easy-to-use method for VDOT engineers to apply the findings, without needing to use an advanced computer program like FLAC3D.

After evaluating different formats for presenting the results, such as tables, graphs, closed-form equations, or a combination of these, a conclusion was reached that a spreadsheet with a simple user interface would be the most appropriate solution for handling multiple complex equations to represent the results of the numerical analyses. In the input page of the spreadsheet, the user is required to enter just a few values. For the output page, the key results from this research, as selected by VDOT engineers who design IABs, are presented.

Implementing Research Results

After the research was essentially complete, VCTIR asked that we assist in implementing the research results in VDOT practice by developing specific recommendations for changes to Chapter 17 of VDOT's *Manual of the Structure and Bridge Division, Volume V—Part 2, Design Aids and Particular Details,* and to Chapter 10 of *Volume V—Part 11, Geotechnical Manual for Structures.* This was accomplished by reviewing the relevant portions of Chapter 17 and Chapter 10, identifying the locations where the research results could benefit VDOT practice, developing a format for presenting the recommendations, and reviewing the format and content of the recommendations with VDOT and VCTIR engineers.

RESULTS

Numerical Model Based on the New Jersey IAB

Validation

Figures 10 and 11 shows the earth pressure measured behind the abutment of the New Jersey IAB (Hassiotis 2006), right where pile number 9 is located, near the centerline of the bridge. The earth pressure was measured at elevation 56.5 m (Figure 10) and 58 m (Figure 11), which correspond to 1/3 and 2/3 of the abutment height, respectively. The data show erratic fluctuations, but systematic yearly patterns of pressure fluctuation can be seen, as well as erratic daily fluctuations.

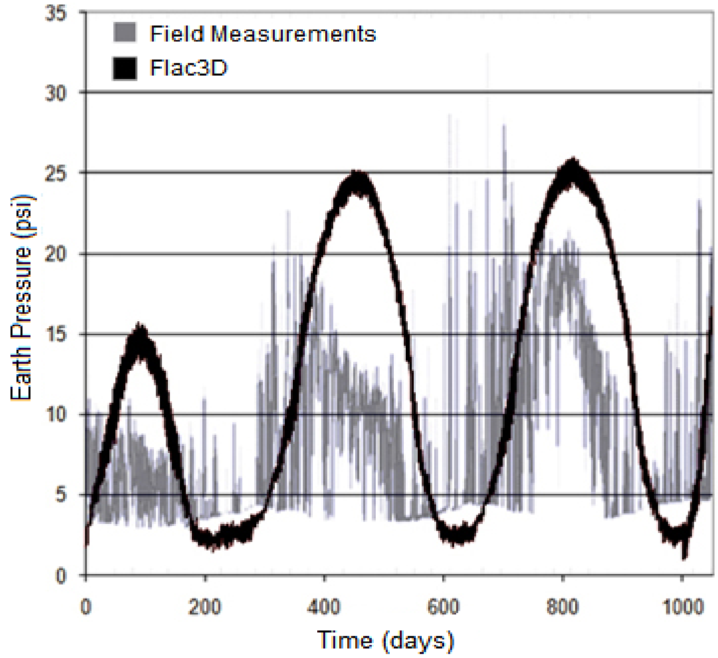


Figure 10 – Field and FLAC3D data comparison. Soil pressure at 1/3 of the abutment height.

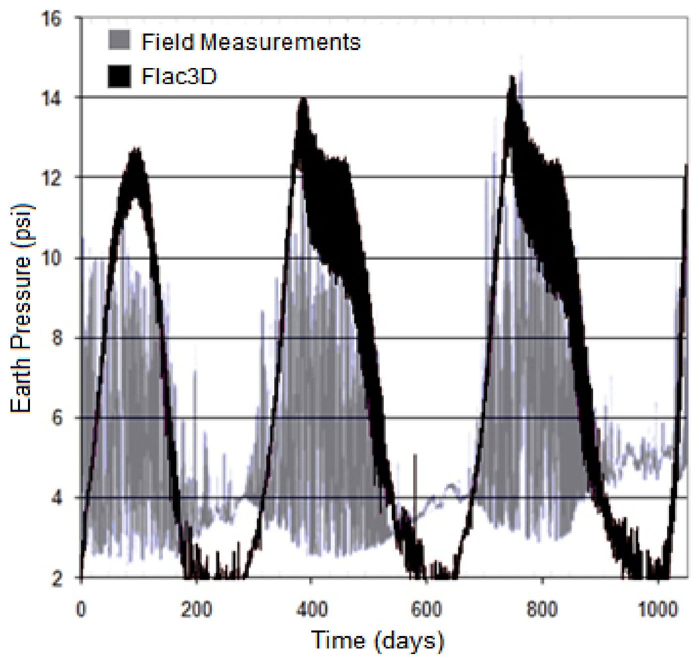


Figure 11 – Field and FLAC3D data comparison. Soil pressure at 2/3 of the abutment height.

Specific values of strength and deformability parameters for the backfill material were selected to obtain a reasonable agreement between field measurements and numerical model outputs, with primarily focus on the systematic yearly fluctuations of peak pressure and not the erratic daily variations. Figure 10 shows the superposition of the numerical model outputs (black) over the field measurements (dark gray).

The results shown in Figure 10 validate that the numerical model is capable of representing important features of the soil-structure interaction, such as earth pressure build-up and response to cyclic thermal displacements.

Survey

Response Rate

A total of 45 surveys were distributed, and 27 responses were received. Of the 27 responses, 21 agencies answered questions in the survey. The agencies that answered survey questions are Alberta Transportation, Iowa DOT, VDOT, Oklahoma DOT, Missouri DOT, Kansas DOT, Nebraska Department of Roads, Utah DOT, South Dakota DOT, West Virginia DOT, New Hampshire DOT, Caltrans, Pennsylvania DOT, New Jersey Turnpike Authority, Maryland State Highway, Tennessee DOT, Illinois DOT, Wyoming DOT, Oregon DOT, Canada Ministry of Transportation, and South Carolina DOT.

The main reason that the following six agencies did not complete the survey was that they do not use IABs or do not combine IABs with MSE walls in their designs:

- Arkansas DOT has not used a fully integral bridge abutment in an MSE embankment.

- Texas DOT does not use fully integral abutments bridges. They indicated that they do not have the soil conditions necessary for integral bridge abutments.

- New York DOT explained that they try to avoid the use of MSE walls when the abutments behind them require piles because of the difficulty of placing the MSE fill and strips around the piles. NYSDOT does not feel comfortable combining an integral abutment with an MSE wall when the abutment is expected to experience a lot of movement. They have concerns about cyclic movements and the response of the MSE wall face panels.

- The Arizona State Highway and Transportation Department does not use IABs with MSE walls in front of the abutments because they have had limited experience with IABs and tend to use them only for straight, short W-beam span bridges. They have not had a project where both methods (IABs and MSE walls) were considered appropriate for the same bridge.

- IABs are not used in Washington DOT bridges because WSDOT does not have any criteria for this type of bridge. WSDOT has concerns about the performance of integral abutments bridges in high seismic zones.

Overall Bridge Issues

The first question on the survey asked about the maximum span length and the maximum overall length of IAB bridges. Only a few agencies responded to the part of the question about the maximum span length, but for those that did, the typical maximum span length was 150 ft. The longest reported span was 590 ft by Pennsylvania DOT. There was substantial variation in maximum overall bridge length, ranging from 300 ft in Alberta up to the longest bridge of 1175 ft in Tennessee. Common values of the maximum IAB length used by several agencies range from 500 ft to 600 ft.

Almost all agencies use a skew angle limit of 30°. The biggest skew angle limit is 60° by Pennsylvania DOT.

None of the agencies indicated that they have a limit for IAB bridge curvature.

Only 2 out of 21 of the responding agencies reported having problems due to effects of skew angle in IABs. VDOT has experienced lateral movements towards the acute corner in bridges with skew angles as small as 5°.

Piles

Twenty-one agencies responded to the question about use of different pile types in IABs: 12 agencies use steel H-piles only; 5 agencies use steel H-piles and pipe piles; and 4 agencies use H-piles, pipe piles, and concrete piles.

It is important to highlight that all of the agencies use steel H-piles in their IAB designs. Although the agencies that use more than one type of pile did not specify how often they use each type of pile, the survey data indicate that steel H-piles are the most common pile type for IABs.

Twenty-one agencies responded to the question about orientation of steel H-piles: 15 agencies orient steel H-piles with their weak axes perpendicular to the bridge centerline direction; 3 agencies orient steel H-piles with their strong axes perpendicular to the bridge centerline direction; and 3agencies orient steel H-piles in either direction.

The survey asked for descriptions of the IAB pile design methodology, and 17 agencies responded: 9 agencies use axial load as the only consideration for pile design; 4 agencies consider both axial load and bending moment in design; and 4 responded by checking the “other” alternative, but none of the agencies selecting “other” provided any clarifying information in the comment area of the survey provided for this question.

None of the agencies provided a design methodology that supports the use of a particular pile orientation.

Some of the agencies provided maximum lateral deflection for piles. The values range from 0.5 to 2.25 in., with the average being 1.5 in.

The survey also asked whether IAB designs include consideration of bending moment produced by skew angle and/or curvature. Five of 18 agencies responding to this question indicated that they do consider moments produced by the skew angle when larger than 20°. None of the surveyed agencies consider moments produced by curvature of the bridge alignment.

Corrugated steel sleeves filled with loose sand surrounding piles are used by 11 of the 20 agencies responding to this question. This topic is an investigation subject of the current research project because it was of concern to VDOT and because data in support of the practice is lacking.

MSE Wall

The offset between the MSE wall and the abutment piles used by the surveyed agencies ranges from 3 to 5 feet for those agencies using corrugated steel sleeves filled with sand and from 3 to 5.6 feet for those that do not use the corrugated steel sleeves. The average distance used is 4.5 feet for both. This suggests that the corrugated steel sleeves do not influence the offset distance applied in practice.

None of the agencies indicated that they account for higher tensile stresses on the MSE strips due to thermal contraction of the bridge. Only Caltrans designs for higher stresses on the MSE strips than result from standard MSE wall design for static conditions. For Caltrans, the higher MSE strip loads are defined by the seismic load, which governs the design. Because Caltrans uses IABs with a maximum length of 400 ft, loads imposed by thermal contraction probably do not exceed those imposed by seismic loads.

Fourteen agencies responded to a question about backfill type for MSE wall fill: 9 agencies use a well graded, free draining granular material; one agency indicated that they compact the natural site soil as MSE wall fill; and 3 agencies use other types of fill material consisting of a select engineering fill with special requirements. For example, Caltrans specifies a select backfill with low corrosion potential and high “compaction grading.” These results reflect that good quality material is generally used among the surveyed agencies.

Fourteen agencies also responded to a question about backfill compaction: 12 agencies require 95% of the standard Proctor maximum density; one agency requires 100% of the standard Proctor maximum density; and one agency requires at least 4 passes with a heavy vibratory roller.

Abutment

Regarding the question about abutment backfill type, 21 agencies answered: 15 agencies use a well-graded, free-draining granular material; 3 agencies compact the natural site soil as abutment backfill; and 3 agencies use other types of backfill material consisting of granular material with special requirements that they did not specify in their survey responses.

Eighteen agencies provided information about abutment backfill compaction: 11 agencies require 95% of the standard Proctor maximum density; and the other 7 agencies employ a wide variety of compaction specifications. Missouri DOT requires a density equal to the adjacent road fill, Nebraska Department of Roads has no density requirements, Idaho DOT requires an un-compacted material, and Wyoming DOT requires compacting the material as much as possible without damaging reinforcement under or in the abutment backfill.

Twenty agencies responded to a question about the earth pressure used for design behind the abutment: 4 agencies use an active earth pressure distribution; 6 agencies use a passive earth pressure distribution; 1 agency uses an at-rest earth pressure distribution; and 9 agencies use a combination of earth pressure distributions. An example in the latter category is Utah DOT, which uses an active pressure distribution for wing-walls and a passive pressure distribution for the abutment.

After the survey was complete, some agencies were asked to specify the background supporting the use of an active earth pressure distribution behind the abutment. New Jersey Turnpike Authority indicated that abutment design is based upon AASHTO LRFD Bridge Design Specifications, which generally stipulate that all "retaining structure" designs are to consider active earth pressure. Iowa DOT requires the MSE wall supplier to design a soil reinforcement anchorage system connected to the rear of the abutment to resist an active earth pressure of 40 pcf equivalent fluid pressure with a triangular distribution. Maryland State Highway uses a triangular active earth pressure distribution, based on AASHTO Standard Specifications and the assumption that the integral abutment deflects enough to produce active stress conditions.

Twenty agencies responded to a question about use of expanded polystyrene (EPS) or other method to reduce lateral earth pressures behind the abutment: 18 agencies do not do this; and 2 agencies do. VDOT encourages use of elasticized EPS, but it is not mandatory. Pennsylvania DOT specifies a 1 inch thick sheet of Styrofoam (which is a trade name of Dow Chemical Company for non-elasticized EPS) to be placed against the entire area of the back face of the abutment below the bottom of the approach slab. Although the technical literature (Hoppe 2005) shows that the use of elasticized EPS reduces the lateral earth pressure behind the abutment, its use does not yet appear to be widespread.

Approach Slab

All the 21 agencies that answered the survey questions indicated that they require an approach slab in their designs. Regarding approach slab details: 8 agencies provide some type of special treatment to reduce friction beneath the slab; 2 agencies bury the approach slab; and 5 agencies extend the approach slab beyond the sides of the road onto the areas supported by wing walls. Most of the agencies use one of the three following types of connections between the approach slab and the bridge: a pinned connection with the abutment, a corbel with reinforcement, or a reinforced connection with the backwall. At the free end, away from the bridge, most of the agencies rest the approach slab on a sleeper slab, and some of them rest the approach slab directly on the underlying soil.

Miscellaneous

The surveyed agencies were asked to provide the most important concerns that need to be addressed for IABs with MSE walls. The answers to this question were widespread, but it is possible to classify them into the categories shown in Table 8.

Table 8 – Principal Concerns Related to IABs

Most Important Concern	Number of Agencies
Joint details at end of approach slab for various bridge lengths.	1
Pile sleeve details and interaction	1
Moment produced by skew angles	1
EPS on backfills	1
Thermal movement interactions and design requirements	8
Seismic movement interactions and design requirements	2
Minimum distance between wall and abutment piles (including front and sides)	3
Distribution and magnitude of earth pressure	3
Creep behavior of geogrid and corrosion reducing life of IABs	1
Compaction of materials adjacent to structures such as piles, panels	1
Settlement when approach slab is not present	1
Piles stresses	2
Arrangement of piles and strips	2

These results indicate that many agencies are concerned about the effects of thermal movements on bridge structures. However, when agencies mention that thermal movement interactions and design guidelines to accommodate them are the most important issues, they also typically include several other topics, such as: minimum distance between the MSE wall and abutment piles, forces on the strips/anchors/panels, moments and axial loads on piles, stresses on the abutment, embankment settlement, earth pressure magnitude and distribution, etc.

Seismic concerns are important for Caltrans and Washington DOT.

An interesting result is that only one agency emphasized the importance of pile sleeve details and interactions, although approximately half, 11 of the 20 agencies responding to this question, are using it.

General comments from the survey respondents about IABs are that they exhibit very good performance, and they are preferred due to elimination of expansion joints. Many agencies state that they will continue to use them and push their limits until problems arise. In addition, many agencies also recognize the need for guidelines for this type of bridge when designed with MSE walls.

Information regarding possible instrumentation of bridges was provided by Utah DOT, West Virginia DOT, New Jersey Turnpike Authority, and Canada Ministry of Transportation. Iowa DOT planned to instrument and monitor a bridge in Des Moines with MSE walls during 2011 and 2012.

Key Findings

The following list provides key findings from the survey of DOTs regarding IABs:

- Twenty-seven responses were collected. Of these, 21 answered the survey, and the other 6 explained why they do not use IABs.
- The longest IAB is located in Tennessee, with an overall length of 1175 ft. Typical maximum IAB lengths ranged from 500 to 600 ft for most agencies.
- Most of the agencies use a skew limit of 30º, and only 2 agencies reported problems with skewed bridges.
- A slight majority of the agencies use exclusively H piles for the abutment support, and the rest use pipe piles and/or concrete piles in addition to H piles.
- Most of the responding agencies orient the abutment piles for weak moment resistance (flanges parallel to bridge alignment).
- About half of the agencies that responded to the question about pile design criteria only use axial load criteria when designing piles, and the rest of the responding agencies use a combination of axial and bending moment criteria.
- Five of 18 agencies responding to question about bridge skew indicated that they employ special design considerations for abutment piles when the skew angle is larger than 20º.
- Eleven of 20 agencies responding to a question about sand-filled, corrugated steel pipes around piles indicated that they use them, but none of the agencies provided instrumentation data, visual observations, analyses, or other justification for using them.
- An average clearance of 4.5 ft is used between the MSE wall facing panels and piles.
- None of the agencies apply special considerations for thermal displacements when designing MSE walls for IABs.
- The survey shows that no consensus has been reached regarding whether to use active, at-rest, or passive lateral earth pressure behind the abutment.
- Only 2 of 20 agencies responding to a question about use of compressible inclusions behind abutments indicated that they use them, and both use some type of EPS.
- All the agencies require approach slabs in their designs, but the design of approach slabs varies greatly among agencies.
- The most important concerns when designing IABs are: thermal displacement effects in bridge components, distance between MSE wall facing panels and piles, and lateral earth pressures behind abutments.

Corrugated Steel Pipes Around Piles

Figures 12 through 15 show the results of the numerical analyses of corrugated steel pipes around abutment piles. Figures 12 and 13 show the results of the first-case analysis, which incorporates a constant pressure boundary condition on the top and bottom surfaces of the horizontal slice. Figure 12 is for a single cycle of increasing load, which is referred to here as "monotonic loading," and Figure 13 is for 365 daily thermal cycles of displacement superimposed on one annual thermal cycle of displacement followed by monotonic loading, which is referred to here as "cyclic followed by monotonic loading." Figures 14 and 15 show the results of the second-case analysis, which incorporates a no-displacement boundary condition on the top and bottom surfaces. Figure 14 is for monotonic loading, and Figure 15 is for cyclic followed by monotonic loading.

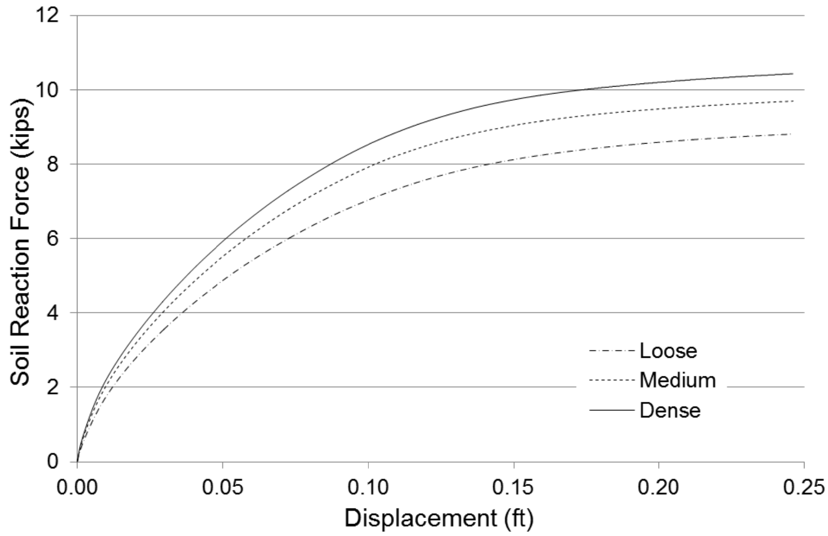


Figure 12 – Corrugated steel pipes, first case (constant pressure). Monotonic loading.

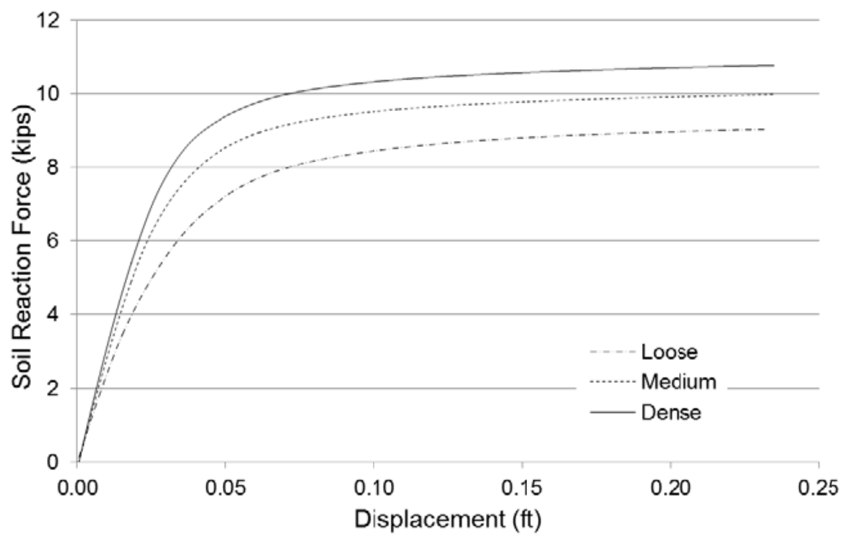


Figure 13 – Corrugated steel pipes, first case (constant pressure). Cyclic and then monotonic loading.

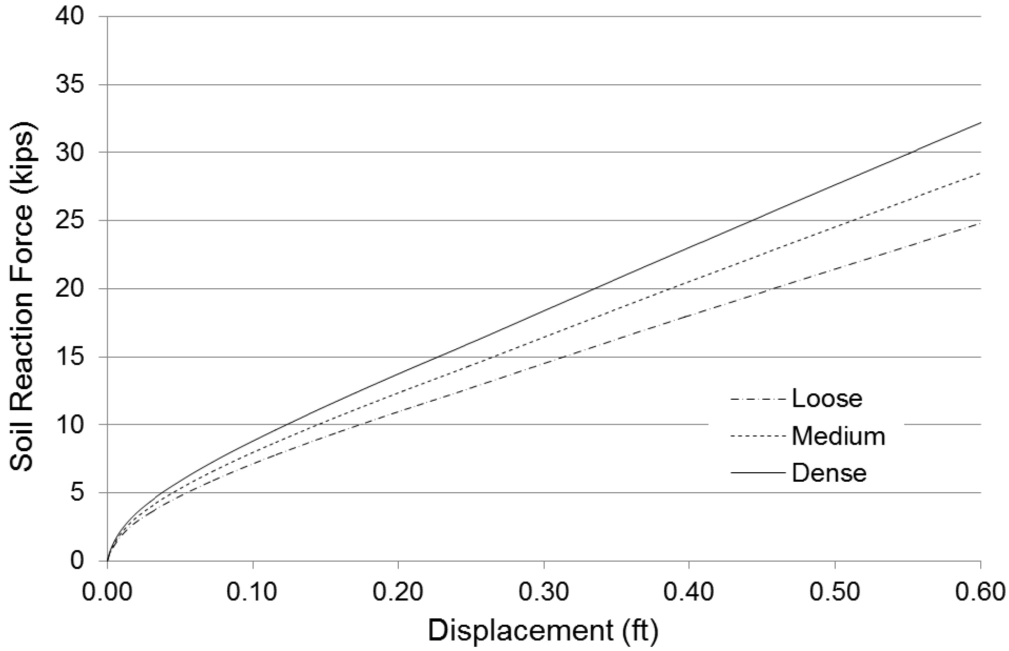


Figure 14 – Corrugated steel pipes, second case (no-displacement boundary). Monotonic loading.

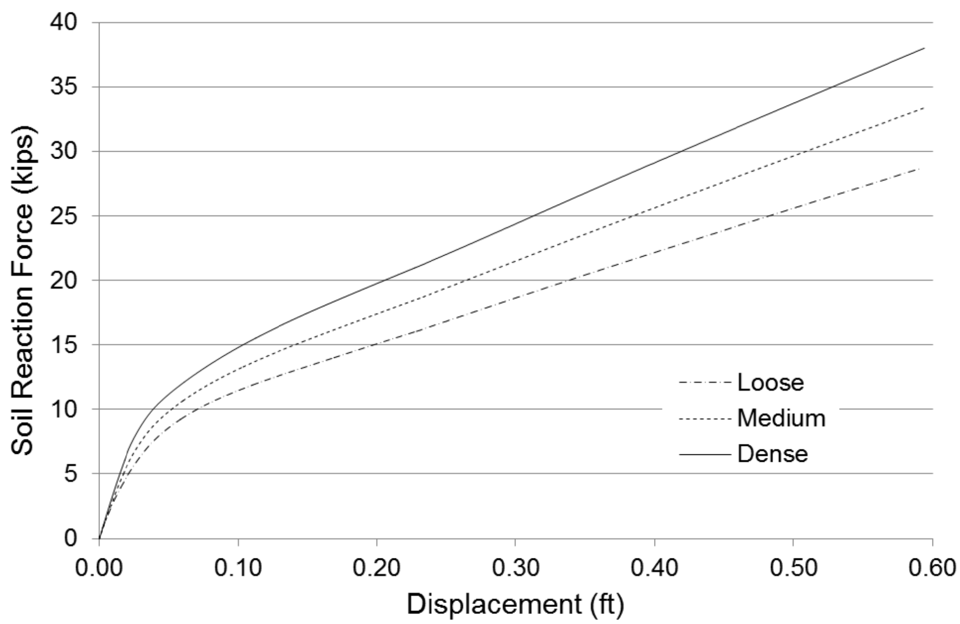


Figure 15 – Corrugated steel pipes, second case (no-displacement boundary). Cyclic and then monotonic loading.

For both boundary conditions, the soil has stiffened after one year of cyclic thermal displacement simulation. This can be seen by observing that the initially loose, medium, and dense curves in Figure 13 and 15 represent stiffer response than the corresponding curves in Figures 12 and 14, respectively. In fact, for the initial portion of the load-displacement curves, the initially loose curve in Figures 13 and 15 exhibit stiffer response than the initially dense curves in Figures 12 and 14, respectively. Thus, these analyses indicate that infilling steel pipes with loose sand will not reduce loads on the pile because of the stiffening that occurs due to the cyclic displacements.

Numerical Model Based on Virginia IAB

Base Case

Since the same input displacements are imposed at the bridge centerline for all girders and because the girders are very stiff, the displacements are expected to produce similar responses for most of the monitoring points at the same elevation and distance from the girders. Also, thermal displacements produce bigger responses on those bridge components near the abutment, and the thermal response decreases for bridge components located farther from the abutment.

The following describe the most important aspects of the bridge response for the base case conditions.

Displacements

The cyclic character (Figure 4) of the imposed displacement at the girder centerline is reflected in the bridge response.

The displacements at the top of the pile cap are about half of those at the top of the abutment, and displacements at the bottom of the pile cap are about one third those at the top of the abutment.

Shear Force and Moments

Shear forces and moments also present a very well defined cyclic response. Shear forces and moments were tracked for piles and dowels. Figures 16 and 7 show that, for elevations near the abutment pile cap, the maximum shears and moments imposed by thermal displacements are about 10 to 20 times larger than those imposed by self-weight forces. For example, the shear in the center dowel due to self-weight forces at day zero is about 300 lbs, and the maximum value imposed during the simulation year is about 3800 lbs, which is a ratio of about 13.

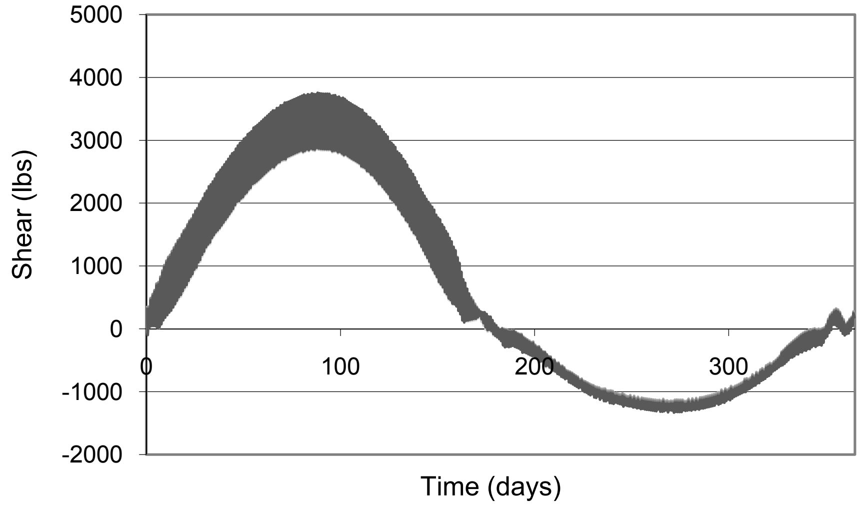


Figure 16 - Shear in center dowel in the longitudinal direction.

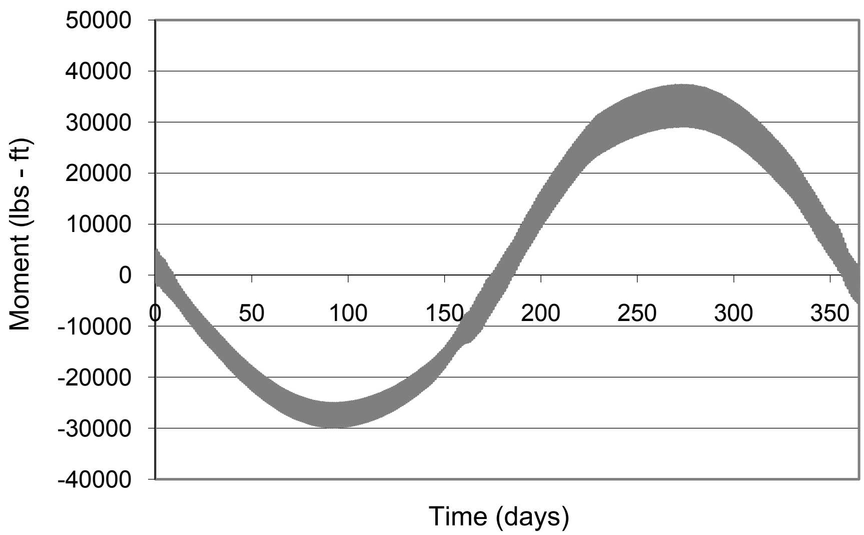


Figure 17 – Moment in center pile in the longitudinal direction.

Earth Pressure behind Abutment

Figure 18 shows that, during expansion, the earth pressure behind the abutment builds up and reaches a local maximum value when the bridge is fully expanded (point A). When the bridge has returned to the initial position, the earth pressure decreases and finally it reaches a residual value that is similar to its initial value (point B). After that, the bridge moves to its fully contracted position. During bridge contraction, the soil behind the abutment experiences settlement and particle rearrangement. From the moment the bridge starts to expand from its fully contracted position, the earth pressure builds up. Once the bridge has reached the initial position (end of the first year), the earth pressure has built up to an earth pressure value (point C) that is 3 to 5 times larger than the initial value. The earth pressure distribution behind the abutment with elasticized EPS is approximately the same at all locations along the length of the abutment.

The earth pressure peak value for the second year is 60% larger than the first year peak value, i.e., peak at D compared to peak at A. The third year peak value is only 6% larger than the second year peak value (peak at E compared to peak at D). This suggests that the soil behind the abutment settles significantly during the first year, and it will experience much smaller increments of additional settlement during subsequent years. The calculated backfill settlement magnitude is 1.2 inches for a total thermal displacement of 3 inches, which corresponds to 1.5 inches of lateral displacement at the abutment.

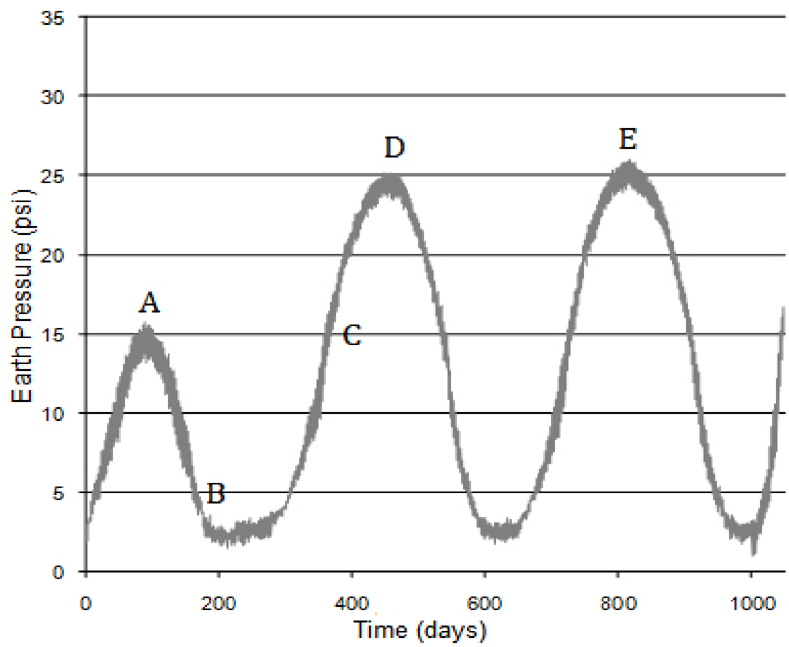


Figure 18– Earth pressure behind the abutment.

Strip Tensile Force

Strip tensile forces were tracked for the front MSE wall and for the side MSE walls. For every monitored strip, three values were recorded: the tensile force at the MSE wall connection, the peak value of tensile force along the strip and, the distance from the strip connection to the location where the peak value occurred.

Only the strips in the upper quarter of the MSE wall experience significant incremental tensile force due to thermal displacements. The largest increment occurs in the strips directly under the abutment, and an example is shown in Figure 19.

A build up in the strip tensile force is observed at the end of the first year in the strips connected to the upper quarter of the front MSE wall. This effect is similar to the one produced by earth pressure behind the abutment, although an additional increment in subsequent years is very small or non-existent.

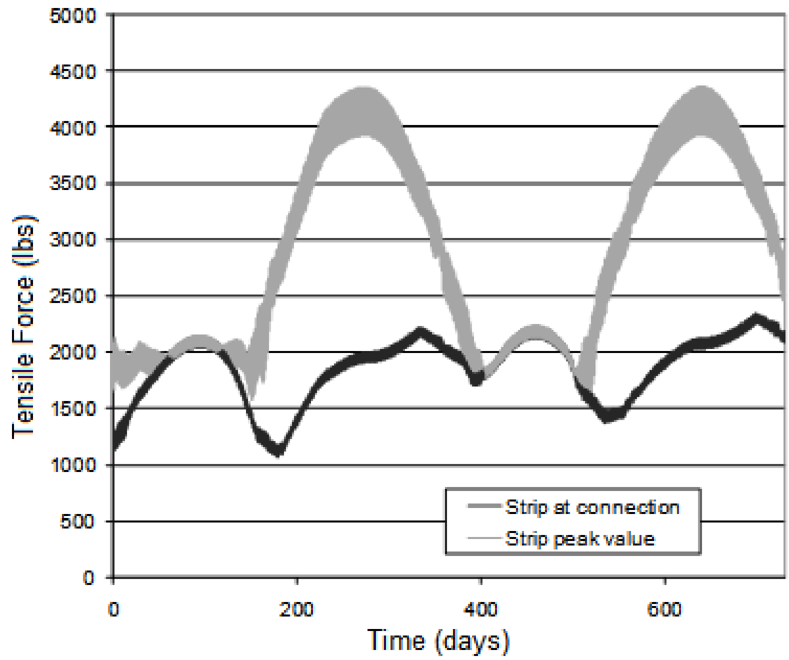


Figure 19 – Strip tensile forces for a selected strip located directly under the abutment and connected to the front MSE wall.

During the bridge expansion stage, the location of the peak value oscillates for the strips connected to the front MSE wall, from a location behind the abutment to a location in front of it. During the contraction stage, the location of the peak value is stationary at about 8 ft from the front MSE wall face.

Since the base case has a skew angle of zero, the tensile force variation on the lateral walls due to thermal displacements is small. The monitored strips near the abutment present a variation of 10% or less with respect to the self-weight value. The peak tensile force occurred at the connection to the MSE walls for all strips monitored in both side walls.

MSE Wall Earth Pressure

MSE wall earth pressures were tracked at approximately the same positions as for the strip tensile forces at the MSE wall connections.

The MSE earth pressure presents a behavior similar to that behind the abutment, but the response is much smaller. Also, the response is only significant for those MSE wall panels in the upper portion of the wall, near the abutment.

Axial Force

The axial loads in the dowels remain approximately constant during thermal displacements. They only change about ±5% with respect to the self-weight values.

Pile axial loads are the only bridge response that decreases due to thermal displacements. Right under the abutment, the axial loads decrease about 25% from their self-weight values, and this effect diminishes with depth. The pile axial load reduction is an indirect response to thermal displacements. The axial load reduction is a consequence of an increment in shear forces acting on the back side of the pile cap. Since the pile cap rotates when the bridge is under expansion, the shear forces increase in the pile cap, producing a lifting effect on the abutment. The opposite is not true when the bridge is under contraction because of the separation tendency between the elasticized EPS and the abutment backwall.

Parametric Study with Individual Parameter Variations

The following quantify the impacts of changing the design from the base case conditions, one parameter at a time. The changes to the base case are described in the methodology section and are listed in Table 5.

Displacements

Bridges with a zero skew angle do not display transverse displacement. In skewed bridges, the magnitude of the transverse displacement increases with the skew angle, as shown in Figure 20.

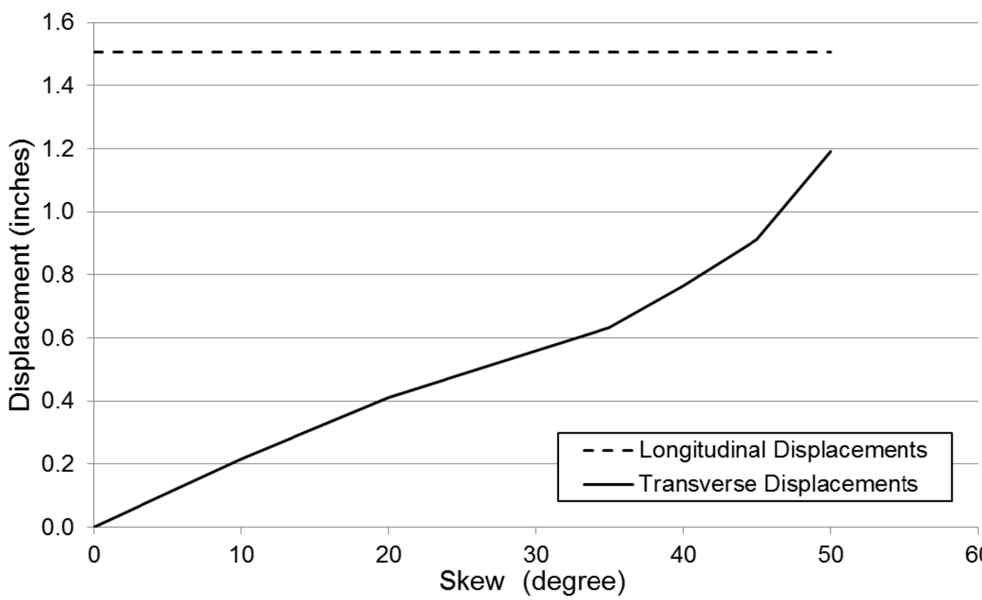


Figure 20 – Bridge abutment longitudinal and transverse displacements vs. skew angle.

Shear Forces

Changing the abutment design from dowels to a laminated pad or a solid abutment increases the shear forces in the piles

Increasing thermal displacements proportionally increase shear forces for both dowels and piles.

Using elasticized EPS material behind the front MSE wall reduces the initial, i.e., due to self-weight, shear forces exerted on dowels and piles, but using elasticized EPS this way does not affect the shear force variations induced by thermal displacements. No reduction in shear forces on dowels and piles is obtained by placing elasticized EPS material behind the front MSE wall.

Shear forces in dowels and piles increase in both directions, longitudinal and transverse, for skewed bridges. Transverse shear forces on piles reach values comparable to longitudinal shear forces for higher skew angles, as shown in Figure 21.

As the pile size increases, shear forces also increase in dowels and piles. Strong pile orientation (web parallel to bridge alignment) considerably increases shear forces in both dowels and piles.

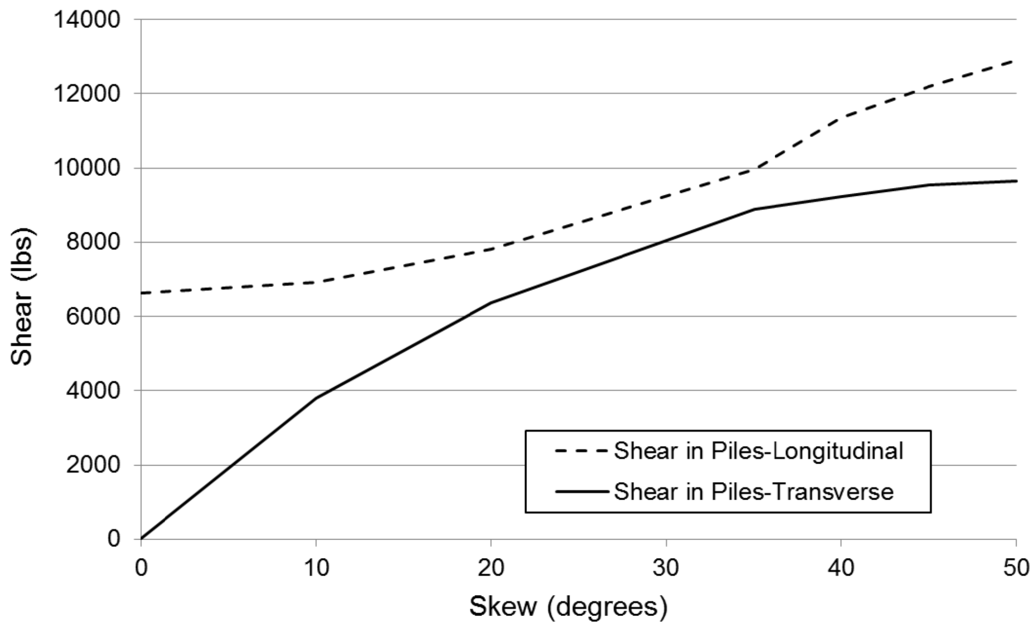


Figure 21 – Pile shear Forces, Longitudinal and Transverse magnitude vs. skew angle.

Moments

The laminated pad abutment design reduces moments in piles, while the solid abutment design increases moments in piles. Laminated pads do not transfer moments as efficiently as dowels, but a solid abutment design increases the amount of moment transferred to the pile cap.

Increasing thermal displacements increase moments for both dowels and piles.

Elasticized EPS material behind the front MSE wall does not affect moment variations induced by thermal displacements.

Moments in dowels increase in both directions, longitudinal and transverse, as the skew angle increases. For the piles, the peak longitudinal moments experience a reversal in the direction of the moment as the skew angle increases, as shown in Figure 22. This occurs because the pile cap becomes more restricted against rotation, and therefore, the pile fixity condition imposed by the pile cap changes as the skew angle increases. The transverse pile moment increases as the skew angle increases.

As the pile size increases, moments also increase in dowels and piles. Strong pile orientation (web parallel to the bridge alignment) considerably increases moments in both dowels and piles.

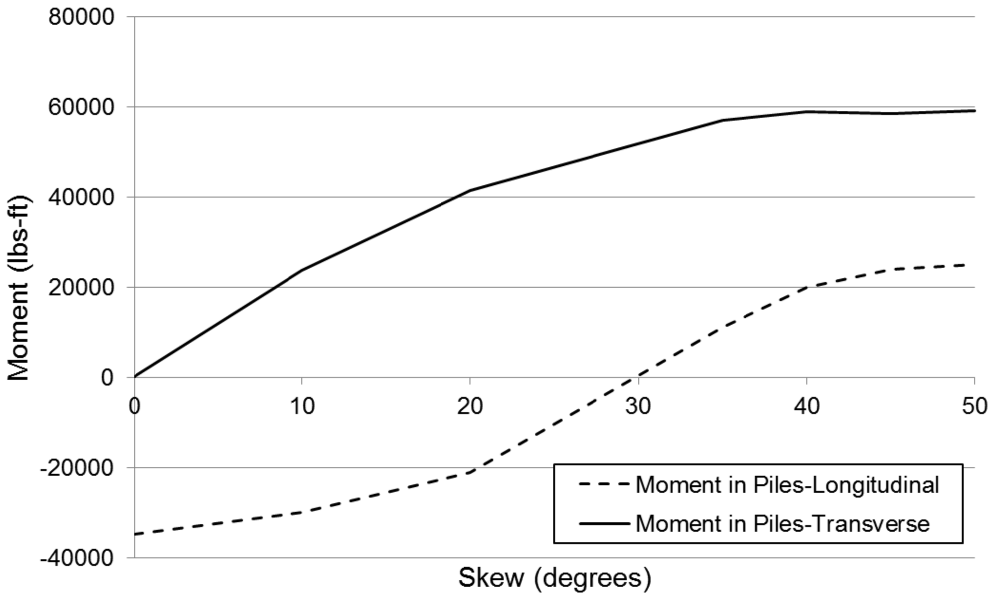


Figure 22 – Moments, Longitudinal and Transverse magnitude vs. skew angle.

Earth Pressure Behind Abutment

Increasing thermal displacement produces increasing earth pressure behind the abutment, as shown in Figure 23. The lower and higher monitoring points exhibit very similar responses. Following VDOT design guidelines, the thickness of the elasticized EPS material behind the abutment in the numerical models are greater for larger magnitudes of imposed thermal displacement. For this reason, the earth pressure response to increased thermal displacement is muted, with an increase of 50% in the magnitude of thermal displacement producing an earth pressure increase of about only 15%. This is another indication that use of elasticized EPS is beneficial for reducing lateral earth pressures.

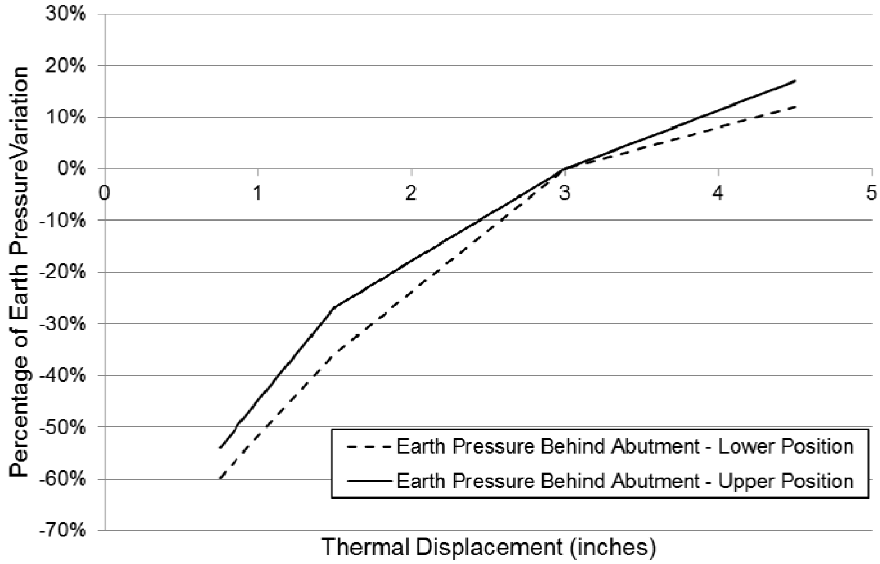


Figure 23 – Earth pressure behind the abutment, percentage change from base case at 3 inches of thermal displacement.

An IAB issue of special interest to VDOT is the effect of elasticized EPS material at the back of the abutment. This was investigated by analyzing a case without elasticized EPS, for which the horizontal earth pressure on the abutment is about 9 times larger at the upper monitoring level and about 20 times larger for the lower monitoring level. Figure 24 shows that the elasticized EPS greatly reduces the lateral pressure on the abutment.

Skewed models produce a complex variation of the earth pressure behind the abutment. These changes are in response to the different movement that occurs in the abutment when skew is present, i.e., transverse displacement and reduction of pile cap rotation. On skewed bridges the earth pressure behind the abutment is higher at the obtuse corner than at the acute corner of the bridge.

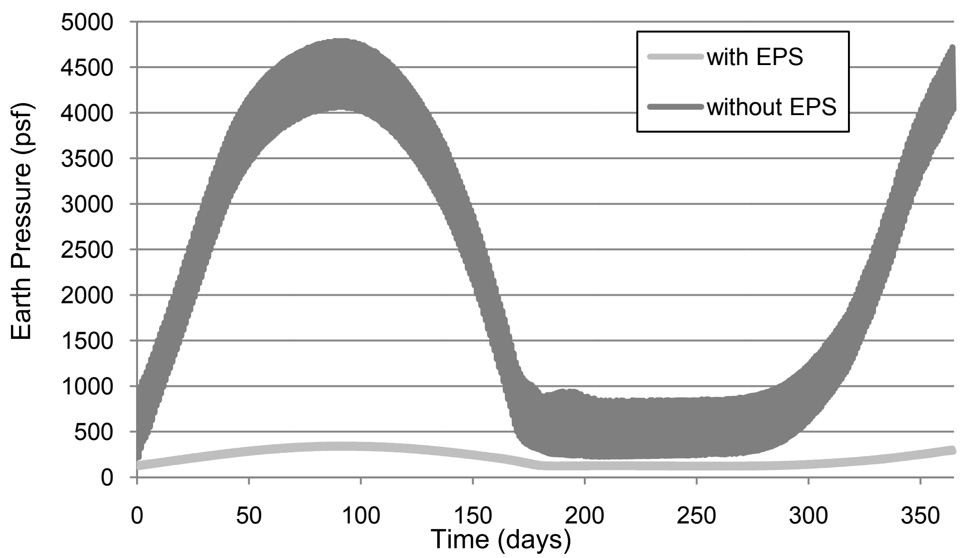


Figure 24 – Earth pressure behind abutment vs. time. Lower monitored level. Comparison between cases with and without elasticized EPS behind the abutment.

Tensile Forces in Strips and Earth Pressure Behind MSE Wall

Solid abutment designs impose larger displacements in the pile cap, and therefore higher values of tensile forces are observed in the MSE wall reinforcing strips due to thermal displacements. The same finding applies to MSE wall earth pressures.

When the distance between the abutment and the MSE wall is reduced, the tensions in the strips increase, and the earth pressure on the MSE wall increases. When the MSE wall – abutment distance is reduced from 2 ft to 0.5 ft, the tensile force in the strips at the connection with the MSE wall can increase by 88%, while the peak value of the tensile force only increases by 10%. Under the same scenario, the earth pressure acting on the MSE wall increases by 67%.

The strip tensile force increases as the thermal displacement increases. Similar response is observed for the earth pressure behind the MSE wall.

Elasticized EPS on the back side of the MSE wall only shifts the response of the strip and the earth pressure on the MSE wall, i.e., it only affects the self-weight component of the response, not the increment due to thermal displacements.

The pile size and orientation affect the response of strip tensile forces and the earth pressure on the MSE wall. For larger pile sizes, larger responses are observed from both outputs. Strong pile orientation also increases the observed responses.

During the developmental phase of this research, the pile design was changed from a combination of friction and end bearing to primarily end bearing, i.e., the initial analyses were performed with the pile embedded 30 ft in the foundation soil, and subsequent analyses were performed with the pile extending through 45 ft of foundation soil and the pile tip pinned to simulate contact with rock. This change did not affect the thermal response, but it did significantly reduce the tensile forces induced in the strips near the bottom of the MSE wall due to self-weight (gravity) loads.

Axial Force

Throughout the different parameter variations, the axial loads changed with respect to their self-weight values in response to thermal displacements. Dowels increase their axial load by an average of 5%, and piles reduce their axial load by an average of 25% at the elevation immediately beneath the pile cap. The reduction in pile axial load diminishes with depth below the pile cap.

Multiple Parameter Variations

Many cases of multiple parameter variations were also analyzed, as indicated in Table 7. Most of these cases were used to develop the regression equations incorporated in the IAB v3 spreadsheet described in the next section. The cases incorporating multiple parameter variations permitted identifying and quantifying interactions between design inputs for IABs.

An issue of special interest to VDOT was pile orientation for skewed bridges. In Cases C3 and C4 (Table 7), the pile webs are parallel to the skewed abutment alignment, and in Cases 21 and 24 (Table 5), the pile webs are perpendicular to the bridge alignment. Otherwise Cases C3 and C4 are the same as Cases 21 and 24, respectively.

Orienting the pile webs parallel to the skewed abutment alignment reduces the moments and shear forces in the dowels by about 7% in the longitudinal direction, but this orientation increases the same outputs by about 13% in the transverse direction.

Orienting the pile webs parallel to the skewed abutment alignment increases moments in the piles in the longitudinal direction by about 52% and reduces shear in the piles in the longitudinal direction by about 32%. In the transverse direction, moments are reduced by 38% and shear force are increased by 23% as a result of orienting the pile webs parallel to the skewed abutment alignment.

IAB v3 Spreadsheet

After analyzing 65 numerical models, an immense amount of information was available for use in creating an easy-to-use spreadsheet for IAB designers.

Combining different parameter variations was not as simple as multiplying or adding effects. Instead, combined effects are represented by multi-parameter polynomial equations of second and third order that were fitted to the results of the numerical analyses. A total of 62 equations were calibrated against the data, and then implemented in the Excel spreadsheet “IAB v3.” The details of the equation fitting are presented by Arenas (2010).

Of the 65 models, 53 correspond to piles oriented for weak moment and the rest correspond to piles oriented for strong moment. Therefore, the use of higher order equations with a good fit to the data was possible for piles in the weak orientation. Given the limited data for piles in the strong orientation, only linear equations could be fit to the data, and the accuracy in predicting system response is lower for this orientation. VDOT typically uses piles oriented for weak axis bending, i.e., the H-pile web is oriented perpendicular to the bridge alignment.

It is important to recognize that the spreadsheet only computes the incremental forces, moments, pressures, and displacements due to imposed thermal displacements. Therefore, to establish complete design forces, moments, pressures, and displacements, IAB designers must add the effects of self-weight loads, live loads, and other loads to the increments produced by thermal displacements that are computed by IAB v3. The effects of these self-weight loads, live loads, and other loads besides those produced by thermal displacements should be calculated using VDOTs standard analysis and design procedures. We are not recommending changes to VDOTs practices for loads other than those imposed by thermal displacements.

The IAB v3 spreadsheet was developed based on numerical models of bridges with steel girders and with concrete girders, so bridges employing either type of girder can be analyzed.

Figure 25 shows the input data for the IAB v3 software, and Figure 26 provides the definition sketch for bridge skew angle, which is also provided on the spreadsheet input page. Table 9 provides descriptions of inputs, and Table 10 provides AASHTO temperature ranges

Geometry			
Bridge Length	1	L (ft)	150
Skew Angle	2	α (°)	25
Is skew defined as Figure A or B	3	(•) Fig. A	( ) Fig. B
Bridge Width	4	W (ft)	40

MSE wall			
Distance between MSE wall and Abutment	5	D (ft)	2

Thermal Displacement			
Annual Temperature Variation	6	ΔT (°F)	120

Piles		
Type	7	HP 10 x 42
Number of Piles	8	5
Orientation	9	(•) Weak ( ) Strong

Girders		
Material	10	Steel

Abutment			
Abutment height?	11	H (ft)	9.33
Abutment design	12	(•) Dowels ( ) Laminated Pad	
Number of Dowels	13	62	

Figure 25 – IAB v3 spreadsheet input page. See Table 9 for input descriptions.

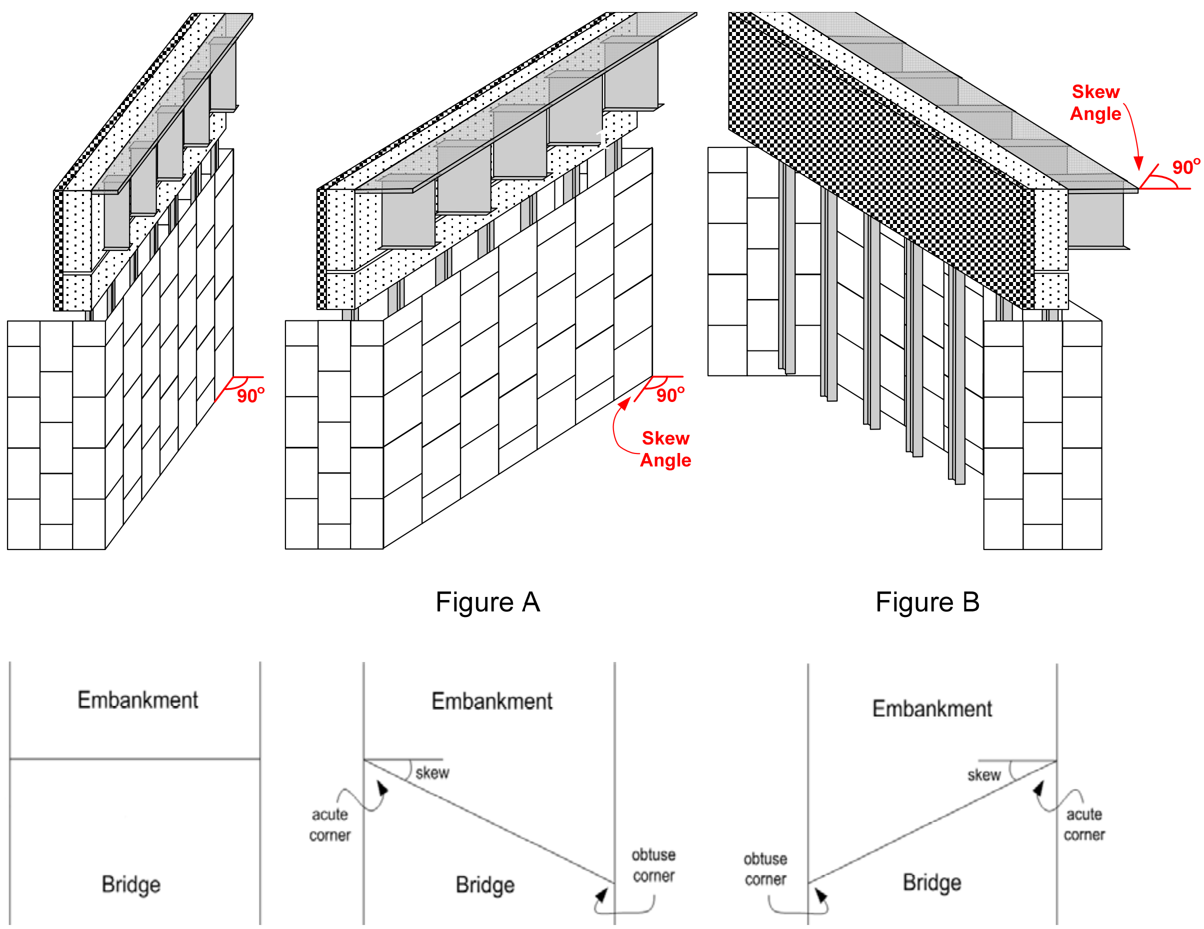


Figure 26 – Skew angle definition.

Table 9 – Description of Inputs for IAB v3

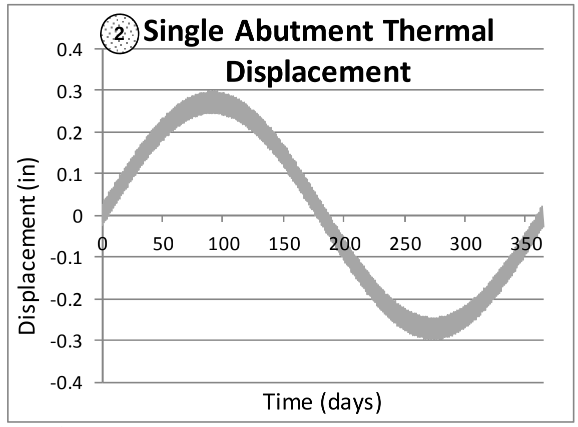
Item	Description
1	Total bridge length, from one abutment to the other.
2	Skew angle. Use only positive values ranging from 0 to 50 degrees
3	Defines the orientation of the skew angle, as shown in Figure 26.
4	Total bridge width.
5	Distance between the back face of the front MSE wall and the front face of the abutment front wall (the face towards the bridge, closest to the MSE wall panels). This dimension, which is designated as H in Figure 9 but is changed to D in the IAB v3 input because D is a more natural symbol for this dimension, is used to compute the distance between the pile centerline and the back face of the front MSE wall. A standard abutment thickness of 3 ft is used in this computation. Thus, the distance between the pile centerline and the back face of the front MSE wall equals 1.5 + D, and D is limited to $0.5 \leq D \leq 5$ ft.
6	Annual temperature variation. AASHTO defines the temperature ranges shown in Table 10. The spreadsheet allows using AASHTO recommended values, or entry of other values that may be more appropriate for a specific location. For example, if the lowest bridge temperature in winter is 20 °F and highest bridge temperature in summer is 100 °F, then a value of 80 °F can be used for input #6. The resulting abutment displacement, which depends on the bridge length and the bridge girder material type, is listed on the output page shown in Figure 27 and described in the list of output items in Table 11. If a designer would rather control the abutment displacement, this can be done using by selecting ΔT to produce the desired abutment displacement. Also, the designer should read the paragraph in the Discussion section that addresses construction of IABs during different seasons of the year.
7	Pile drop down menu (7 pile types are listed).
8	Number of piles embedded in the pile cap across the bridge width.
9	Pile orientation with respect to the bridge alignment. Select between weak or strong. Weak axis means that the web of the H pile is perpendicular to the bridge longitudinal direction. Note that the spreadsheet only accommodates these two pile orientations, not with the pile axes oriented parallel or perpendicular to skewed abutment alignments.
10	Select the girder material type, steel or concrete, from the pull-down menu.
11	Height of the abutment, measured from the bottom of the pile cap to the top of the abutment. This is designated H in the IAB v3 input shown on Figure 25, and it is the sum of B and C shown on Figure 9.
12	Abutment design. Select between doweled or laminated pad.
13	If dowels are selected for the abutment design, the number of dowels must be input in this cell.

Table 10 – AASHTO Temperature Ranges

	AASHTO Temperatures Range			
	Metal Structures		Concrete Structures	
Climate	From	To	From	To
Moderate	0˚F	120˚F	10˚F	80˚F
Cold	-30˚F	120˚F	0˚F	80˚F

Figure 27 shows the output page for the IAB v3 software, and Table 11 provides descriptions of the outputs. Figure 28 provides the sign convention for the shear loads and bending moments in the piles.

Thermal Displacement 1		
Total Annual Thermal Disp.	1.19	in
Total Daily Thermal Disp.	0.10	in
Annual Disp. at one Abutment	0.59	in
Daily Disp. at one Abutment	0.05	in
Parameter A in eq. 2	0.03	in
Parameter B in eq. 2	0.27	in



EPS 3		
Recommended EPS thickness	15	in

Note: Results below apply only for IABs with the recommended EPS thickness

MOMENTS 4		Global		Per element	
Moment in Dowels - Longitudinal		1.4	kips-ft	0.02	kips-ft
Moment in Dowels - Transverse		-0.3	kips-ft	-0.01	kips-ft
Moment in Piles - Longitudinal	2 ft under Abutment	30.6	kips-ft	6.1	kips-ft
Moment in Piles - Transverse	Under Abutment	103.1	kips-ft	20.6	kips-ft

SHEAR FORCES 5		Global		Per element	
Shear force in Dowels - Longitudinal		28.7	kips	0.5	kips
Shear force in Dowels - Transverse		6.9	kips	0.1	kips
Shear in Piles - Longitudinal	Under Abutment	-11.9	kips	-2.4	kips
Shear in Piles - Transverse	Under Abutment	-19.6	kips	-3.9	kips

AXIAL FORCES 6	Global		Per element	
Axial force in Dowels	4.8	kips	0.1	kips
Axial force in Piles	-11.4	kips	-2.3	kips

EARTH PRESSURE BEHIND ABUTMENT 7			
Acute Corner	Elev. 2/3 H	46	psf
	Elev. 1/3 H	135	psf
Obtuse Corner	Elev. 2/3 H	45	psf
	Elev. 1/3 H	124	psf

MSE WALL EARTH PRESSURE 8		
MSE wall earth pressure	20	psf

STRIP TENSILE FORCE 9		
At connection with MSE Wall	16	psf
Maximum Value	23	psf

TRANSVERSE DISPLACEMENT 10		
Transverse Displacement	0.09	inch

Figure 27 – IAB v3 spreadsheet output page. See Table 11 for output descriptions.

Table 11 – Description of Outputs for IAB v3

Item	Description
1	Thermal Displacement: This section presents six results: a) Total annual thermal displacement experienced by the bridge. b) Total daily thermal displacement experienced by the bridge. c) Annual thermal displacement experienced by one abutment. Half of result (a). d) Daily thermal displacement experienced by one abutment. Half of result (b). e) The next two results are parameters A and B, defined in Eq. 2 in this report.
2	Graphical representation of Eq. 2, using parameters A and B from output 1.
3	Recommended elasticized EPS thickness. Chapter 17 (Integral/Jointless Bridges) of VDOT's *Manual of the Structure and Bridge Division, Volume V—Part 2, Design Aids and Particular Details* (VDOT, 2011b) , provides the following equation for the elasticized EPS thickness, EPS_t, in inches: $EPS_t = 10\ [0.01\ h + 0.67\ \Delta L]$ where h is the height of integral backwall in inches, and ΔL is the total thermal displacement in inches. Not including the recommended elasticized EPS thickness would dramatically increase the earth pressure behind the abutment and will change its distribution.
4	Moments: This section includes 4 sets of results, each one with a "global" and "per element" result. The "global" result is the overall bridge response, and the "per element" result is simply the global result divided by the number of elements across the bridge. The first two sets of results correspond to dowel moments, one in the longitudinal direction and one in the transverse direction. The next two sets of results are analogous results for piles. Moments in piles have one extra cell of information. Right next to the cell describing the direction, there is another cell indicating whether the maximum moment occurs right under the abutment or 2 ft below the abutment. The location for the maximum moment depends on the pile cap fixity condition, which is influenced by abutment type and skew angle.
5	Shear Forces: The same comments that apply to output Item 4, moments, also apply to shear forces.
6	Axial forces: This section consists of two sets of results. The first is the increase in axial load experienced by dowels due to thermal displacements of the bridge deck, and the second is the reduction of axial force experienced by piles. For design purposes, it is conservative to ignore the reduction in axial forces in the piles.
7	Earth Pressure behind Abutment: This section includes two sets of results, each set providing results for two elevations. One elevation is at 1/3 of the abutment height, and the other is at 2/3 of the abutment height. The results are provided at the acute and obtuse corners, which are defined as shown in Figure 26.
8	MSE Wall Earth Pressures: This section provides the increment in earth pressure behind the upper quarter of the front wall due to thermal displacements. This value can also be applied to the upper quarter of both side walls for the MSE facing panels closest to the abutment (within one abutment height) when the skew angle is 10 degrees or larger. At other locations and for smaller skew angles, the FLAC3D results indicate that it is not necessary to apply an increment of pressure to the MSE side walls due to thermal displacements.
9	Strip Tensile Force: Two results are provided in this section: first, the strip tensile force at the MSE connection, and second, the maximum tensile force along the strip. These values apply to the upper quarter of the front MSE wall face. When the skew angle is 10 degrees or larger, these values can also be applied to the upper quarter of both side walls for a distance of one abutment height back from the front MSE wall. The results for the strip tensile force have units of pressure, which was obtained by dividing the increment of strip tensile force by the strip tributary area (horizontal spacing times vertical spacing). The reverse procedure should be used to obtain the increment of strip tensile force to be used for design.
10	Transverse Displacement: This result provides the maximum displacement in the transverse bridge direction, when skew angle is non-zero.

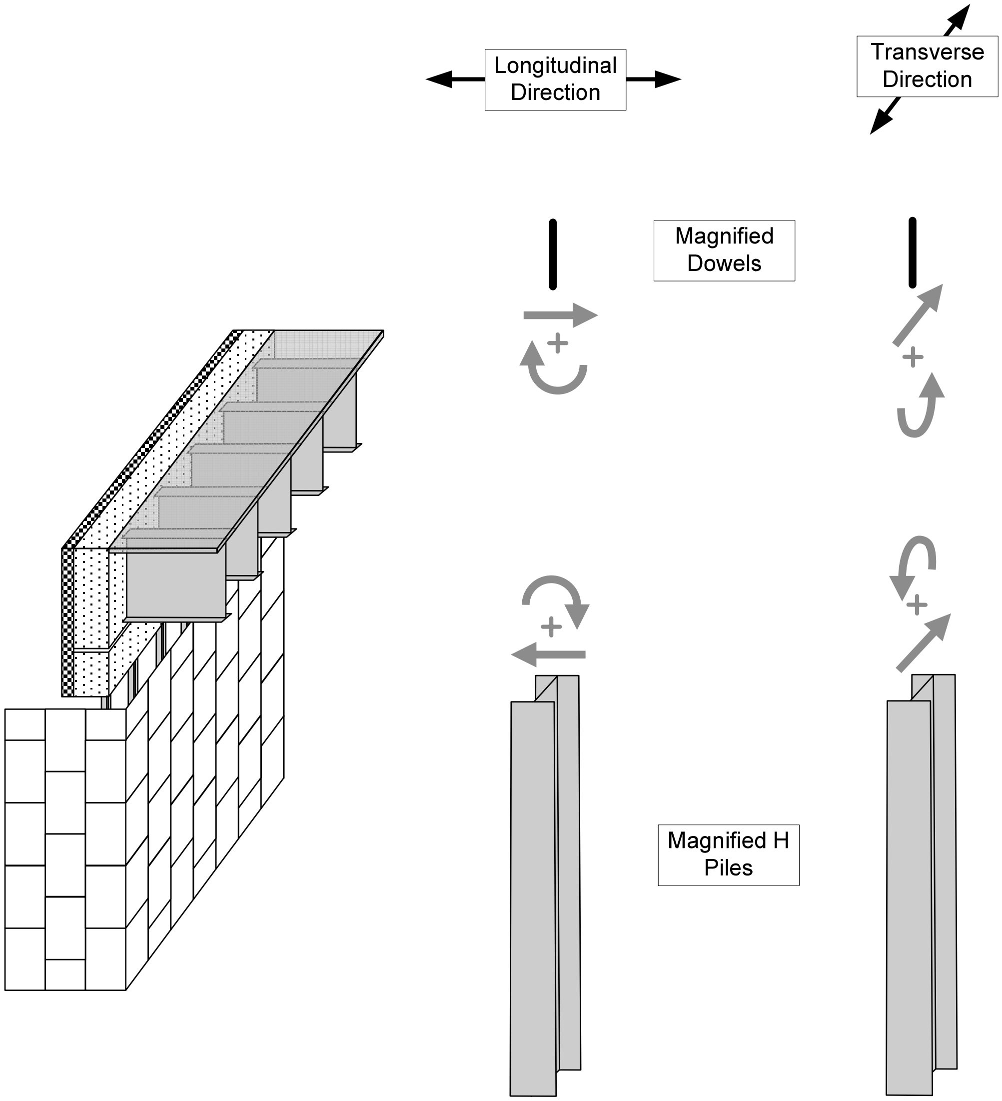


Figure 28 – Sign convention. Arrows denote positive shear force and moment directions.

DISCUSSION

The multi-parameter polynomial equations developed for this research were fit to the results from numerical models that incorporate the essential features of IABs with foundation piling in MSE wall backfill. The numerical models were validated by comparison with field measurements at the New Jersey IAB. The equations used in the spreadsheet IAB v3 are the best fit equations to the numerical results, and they do not incorporate factors of safety. Bridge designers should apply appropriate load factors to the loads and moments obtained from IAV v3.

The work described here only considers IABs with abutment piling in MSE wall backfill, with U-back designs for the MSE walls, i.e., the MSE wall wraps the abutment with MSE side walls parallel to the bridge alignment. Other MSE wall arrangements may respond differently.

One limitation is that the imposed thermal displacements are neutral position centered, as shown in Figure 4. This models a bridge that is completed during spring, around April to May, producing close to symmetrical expansion and contraction displacements. If a bridge is set during summer, most of its thermal displacement will be of contraction character, therefore the assumption of symmetrical expansion and contraction will no longer apply. A conservative way to address this situation is by doubling the annual temperature range. Although the resulting doubled displacements are not an accurate representation of the actual thermal displacements, this approach will provide safe output for loads, moments, and pressures, since either the response is symmetrical around the self-weight values (Figure 17b) or the maximum values occur during the contraction phase.

Reducing the distance between the back of the MSE wall and the front of the abutment wall to less than 2 ft can significantly increase the tensile forces in the strips at the connection with the MSE wall, as well as the earth pressures acting on the front MSE wall. If the distance is less than 2 ft, MSE wall designers should take these load increments into account. The IAB v3 spreadsheet can be used to compute the magnitude of these load increments.

VDOT uses a hinged pile cap to reduce shear forces and moments on piles. The numerical results support the effectiveness of the hinge. When comparing a solid abutment with a doweled abutment, the solid abutment increases the pile shear forces up to 500% and moments up to 200%, with respect to the doweled case.

Since VDOT mainly designs IABs with weak pile axis orientation, only a few analyses were run with strong pile axis orientation. Given the small number of strong pile axis orientation models, linear equations were used to fit the data, and relatively low reliability is associated with predicting forces and moments when the strong orientation is selected for piles.

CONCLUSIONS

- *The survey of state DOT practice indicates that there is not a clearly defined standard of practice to account for the effects of thermal displacement of IABs on MSE wall components or abutment piling.*

- *The analyses described in this report indicate that steel pipe sleeves in-filled with loose sand do not reduce forces and moment in the piles because the loose sand inside the sleeve becomes densified after cyclic loading by thermal displacements.*

- *The distance between the pile centerline and the back of the MSE wall does not affect moments and shear forces of dowels and piles, but it does affect the strip tensile forces and MSE wall earth pressures.*

- *The earth pressure behind the abutment builds up during a one-year cycle of thermal displacements. The peak earth pressure can increase up to 60% after the first year but increases by less than 6 additional percentage points during the following year. The earth* *pressure buildup is due mainly to soil settlement and rearrangement behind the abutment. The soil rearrangement produces a calculated settlement of about 1.2 inches for a total thermal displacement of 3 inches, which corresponds to 1.5 inches of displacement at each abutment.*

- *End bearing piles significantly reduce the tension in the reinforcing strips at the bottom of the MSE wall. When the pile tip is supported by a deformable media and the superstructure is positioned, load transfer from the pile to the adjacent ground produces higher tensile loads in the strips. The numerical analyses indicate that strips near the bottom of the MSE wall are more affected by this load transfer than the strips near the top of the MSE wall.*

- *Shear forces and moments in the dowels and piles due to 3 inches of total thermal displacement are, on average, 10 to 20 times larger than those imposed by self-weight.*

- *Peak tensile forces in the reinforcing strips near the abutment can increase substantially due to thermal displacements. Depending on the reinforcement details, designs may need to take this into account.*

- *The use of 3 inches of elasticized EPS behind the MSE wall has marginal benefits on the effects of thermal displacements in the MSE wall, but it can reduce the strip tensile force and pressure on the MSE wall due to self-weight.*

- *Thermal displacements only affect the pressures and strip tensions in the upper quarter of the MSE wall. The maximum MSE wall panel pressures and maximum MSE reinforcing strip tensions occur during the bridge contraction cycle.*

- *Pile axial load is the only output parameter that is reduced in magnitude by the thermal displacements.*

- *Elasticized EPS behind the abutment reduces the lateral earth pressures induced by 3 inches of total thermal displacement by a factor of 9 for the upper portion of the abutment (i.e., at an elevation of 2/3 of the abutment height including the pile cap) and by a factor of 20 for the lower portion of the abutment (i.e., at an elevation of 1/3 of the abutment height including the pile cap), according to the numerical analyses.*

- *For skewed bridges, displacements in the transverse direction can reach magnitudes similar to the longitudinal displacements. This is also true for the transverse and longitudinal shear forces in piles.*

- *Skew angle progressively increases pile cap fixity, producing a reversal in the sign of the maximum pile moments in the longitudinal direction.*

- *Orienting piles with their webs parallel to the abutment alignment for skewed bridges produces a decrease in the bending moment in the longitudinal direction and an increase in the transverse direction. More research is warranted to develop a complete understanding of the net effects of this pile orientation.*

RECOMMENDATIONS

Recommendations for IAB Design

1. *VDOT's Structure & Bridge Division should discontinue the use of steel pipe sleeves around abutment piles in MSE wall backfill.* The steel sleeves do not accomplish their intended purpose of reducing pile shear forces and moments. Furthermore, this is a somewhat difficult construction procedure that unnecessarily increases costs.

2. *VDOT's Structure & Bridge Division should incorporate elasticized EPS into abutment backwall designs*. Using elasticized EPS at this location is highly recommended because it significantly reduces the earth pressure behind the abutment. However, the use of elasticized EPS behind the MSE wall is not recommended, because it has only marginal beneficial effects, and it is expected to significantly complicate construction procedures.

3. *VDOT's Structure & Bridge Division should orient abutment H-piles for weak axis bending, with H pile webs perpendicular to the bridge alignment, for bridges with less than 20° skew angle*. For larger skew angles, pile orientation should be analyzed on a case-by-case basis because transverse bending moments may reach considerable values due to bridge transverse movements. For large skew angles, the optimal pile orientation is a function of the abutment type, skew angle, and pile type.

4. *VDOT's Structure & Bridge Division should use the spreadsheet named IAB v3 for computing the response of different bridge components to thermal displacements*. The designer should apply appropriate load factors to the loads and moments calculated by IAB v3 when using the results from the spreadsheet for bridge design.

5. *VDOT's Structure & Bridge Division should incorporate the modifications provided in Appendix B of this report into Chapter 17 of VDOT's Manual of the Structure and Bridge Division, Volume V—Part 2, Design Aids and Particular Details* (VDOT, 2011b), and into Chapter 10 of *Volume V—Part 11, Geotechnical Manual for Structures* (VDOT, 2011a).

Recommendations for Further Research

6. *VCTIR should conduct or sponsor additional research to address bridge construction during different seasons.* The analyses in this research represent bridges completed during the spring, for which expansion and contraction cycles are neutral centered. Additional analyses should be performed to investigate the influence of bridge completion during other times of the year. A conservative approach is provided in the "Discussion" section for addressing completion during the summer, but more accurate results could be obtained by performing detailed analyses.

7. *VCTIR should conduct or sponsor additional research based on instrumentation data from the Telegraph Road Bridge in Alexandria, Virginia.* These data should be reduced and assessed, and the results compared with IAB v3. If the instrumentation data were consistent

with IAB v3, then this would support the research results, and no further investigation would be needed. If the data were not consistent with IAB v3, then it may be necessary to numerically analyze the Telegraph Road Bridge to recalibrate the numerical modeling procedures to the new data, repeat the analyses of the parameter variations with the revised modeling procedures, and revise the IAB v3 spreadsheet.

8. *VCTIR should conduct or sponsor additional research to instrument other VDOT IABs when such opportunities arise.* The most important data to collect include the abutment displacement, the tension in the MSE reinforcing strips, the pressures on the MSE wall panels, the strains in the piles to permit determination of the bending moments in the piles, and the pressures on the abutment wall.

COSTS AND BENEFITS ASSESSMENT

The primary benefit of this research is increased reliability for designing IABs with abutment piling in MSE wall backfill with the MSE wall in a U-back configuration. This is an important bridge technology for VDOT, and prior to this research, there was no reliable method to design these systems for thermal displacements. As a result, designs were based on assumptions that may have been too conservative in some cases and unconservative in others. Now, a rational methodology exists for this aspect of IAB design, so that these bridges can be designed more safely and economically.

An additional benefit of this research is that corrugated steel sleeves in-filled with loose sand can be eliminated from IAB designs. According to Barry Bryant of Bryant Contracting, the following costs are associated with installation of corrugated steel pipes:

- Corrugated steel pipe: a 24-in-diameter, 16 gauge corrugated steel pipe is about US$ 16.50 per linear foot.
- Sand infilling the steel pipe is about US$ 1.5 per linear foot.
- Labor, overhead and equipment is about US$ 4.50 per linear foot.
- Total US$ 22.50 per linear foot. More generally, the cost is between US$ 20 and US$ 30 per linear foot.

The analyzed base case needs 23 ft of corrugated steel pipe per pile. Therefore the cost per pile is between US$ 460 and US$ 690, and using 7 piles per abutment, the total cost of installing corrugated steel pipes in the base case bridge is US$ 6,440 to US$ 9,660. This cost can be saved as a result of this research. For wider bridges with more abutment piles the savings of not using corrugated steel piles filled with sand increase.

ACKNOWLEDGMENTS

The authors appreciate VDOT and VCTIR support of this research. The contributions of Keith Weakley, Bruce Shepard, Ashton Lawler, Kevin Lee, and J. Michael Hall (VDOT), and Edward Hoppe and Jose Gomez (VCTIR) were especially valuable.

REFERENCES

American Association of State Highway Transportation Officials. *LRFD Bridge Design Specifications, SI Units,* Fourth Edition. Washington, 2007.

Alampalli, S., and Yannotti, A.P. In-Service Performance of Integral Bridges and Jointless Decks. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1624. Transportation Research Board of the National Academies, Washington, DC, September 1998, pp. 1-7.

Arenas, A.E. *Thermal Response of Integral Abutment Bridges With MSE Walls: Numerical Analyses and a Practical Analysis Tool.* Doctoral Dissertation, Virginia Tech, Blacksburg, 2010.

Arsoy, S., Barker, R.M., and Duncan, J.M. *The Behavior of Integral Abutment Bridges.* VTRC 00-CR3. Virginia Transportation Research Council, Charlottesville, 1999.

Arsoy, S., Duncan, J.M., and Barker, R.M. Approach to Evaluating Damage From Thermal Bridge Displacements. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1936. Transportation Research Board of the National Academies, Washington, DC, pp. 124-129.

Hassiotis, S., Khodair, Y., Roman, E., and Dehne, Y. Evaluation of Integral Abutments. FHWA-NJ-2005-025. Stevens Institute of Technology, Hoboken. NJ, 2006.

Hoppe, E. Field Study of Integral Backwall With Elastic Inclusion. In *Proceedings of the Integral Abutment and Jointless Bridges Conference*. Federal Highway Administration, Washington, DC, 2005, pp. 257-269.

Hoppe, E. *Field Study of Integral Backwall with Elastic Inclusion.* VTRC 05-R28. Virginia Transportation Research Council, Charlottesville, 2005.

Itasca Consulting Group. FLAC3D, Fast Lagrangian Analysis of Continua in 3 Dimensions, Version 3.1. Minneapolis, MN, 2006.

Terzaghi, K., Peck, R., and Mesri, G. *Soil Mechanics in Engineering Practice*, Third Edition. John Wiley and Sons, 1996.

Virginia Department of Transportation. Chapter 10: Earth Retaining Structures. In *Manual of the Structure and Bridge Division, Volume V—Part 11, Geotechnical Manual for Structures.* Richmond, 2011a.

Virginia Department of Transportation. Chapter 17: Integral/Jointless Bridges. In *Manual of the Structure and Bridge Division, Volume V—Part 2, Design Aids and Particular Details.* Richmond, 2011b.

APPENDIX A

SINGLE MONITORING OUTPUT POINT LOCATIONS

Displacement

Displacements were recorded in longitudinal and transverse directions (x and y directions in Figure A1), at three elevations and at three positions along the bridge.

The selected elevations for measuring displacements were Top, Cap, and Bottom, as shown in Figure A1. Thus, rotation of the cap and upper section of the abutment were captured. Along the abutment direction, displacements were recorded at left, middle, and right positions. Thus, horizontal rotation of the bridge abutment and cap were captured.

Altogether, 18 displacement values were recorded at 9 positions in the bridge for each time at which results were monitored.

Shear Forces in Piles and Dowels

Shear forces were recorded in the longitudinal and transverse directions, i.e., x direction and y direction, respectively (Figure A2).

Shear forces were obtained from piles 1, 2, 4, 6, and 7, right under the abutment, and they were recorded in both directions. In addition, shear forces in both directions were obtained from dowels that best aligned with those piles, as shown in Figure A2.

Therefore, shear forces were recorded in longitudinal and transverse directions at 10 positions (5 dowels and 5 piles).

Moments in Piles

Moments in piles were recorded in the longitudinal and transverse directions, as shown in Figure A3.

Moments were monitored in piles 1, 4, and 7 at four elevations: right under the abutment, next downward element, middle pile elevation (above ground level), and ground level.

Therefore, moments in piles were recorded in the longitudinal and transverse directions at 12 positions.

Lateral Pressure at Abutment

Lateral earth pressures were recorded at 20 different positions, as shown in Figure A4. Ten of them are between the elasticized EPS and the upper part of the abutment, and the rest of them are between the backfill and the elasticized EPS. Five of the lateral pressures between the abutment and the elasticized EPS are at the upper elevation of 2/3 of the abutment height, and the other five are at the lower elevation of 1/3 of the abutment height. The same elevations were selected for the monitoring points between the backfill and the elasticized EPS.

Therefore, there are four groups of five measurement positions, for a total of 20 monitoring points.

Strap Tensile Forces

Sixty-three parameter histories were obtained from the MSE wall straps. Figure A5 shows 21 selected positions for extracting strap information, 9 at the front wall, 6 at the left wall, and 6 at the right wall. At each one of these positions, 3 parameters histories were extracted: strap tensile force at the connection with the MSE wall panel, strap peak tensile force, and distance from the wall where the peak occurs.

Earth Pressure at MSE Wall

Earth pressure was recorded at 21 positions on the back of the MSE wall. The positions are the same as those shown in Figure A5.

Pile Axial Forces

Axial forces were recorded at piles 1, 4, and 7 at the following elevations: under the abutment, pile middle height, and ground level, as shown in Figure A3.

Therefore, axial forces in piles were recorded at 9 positions.

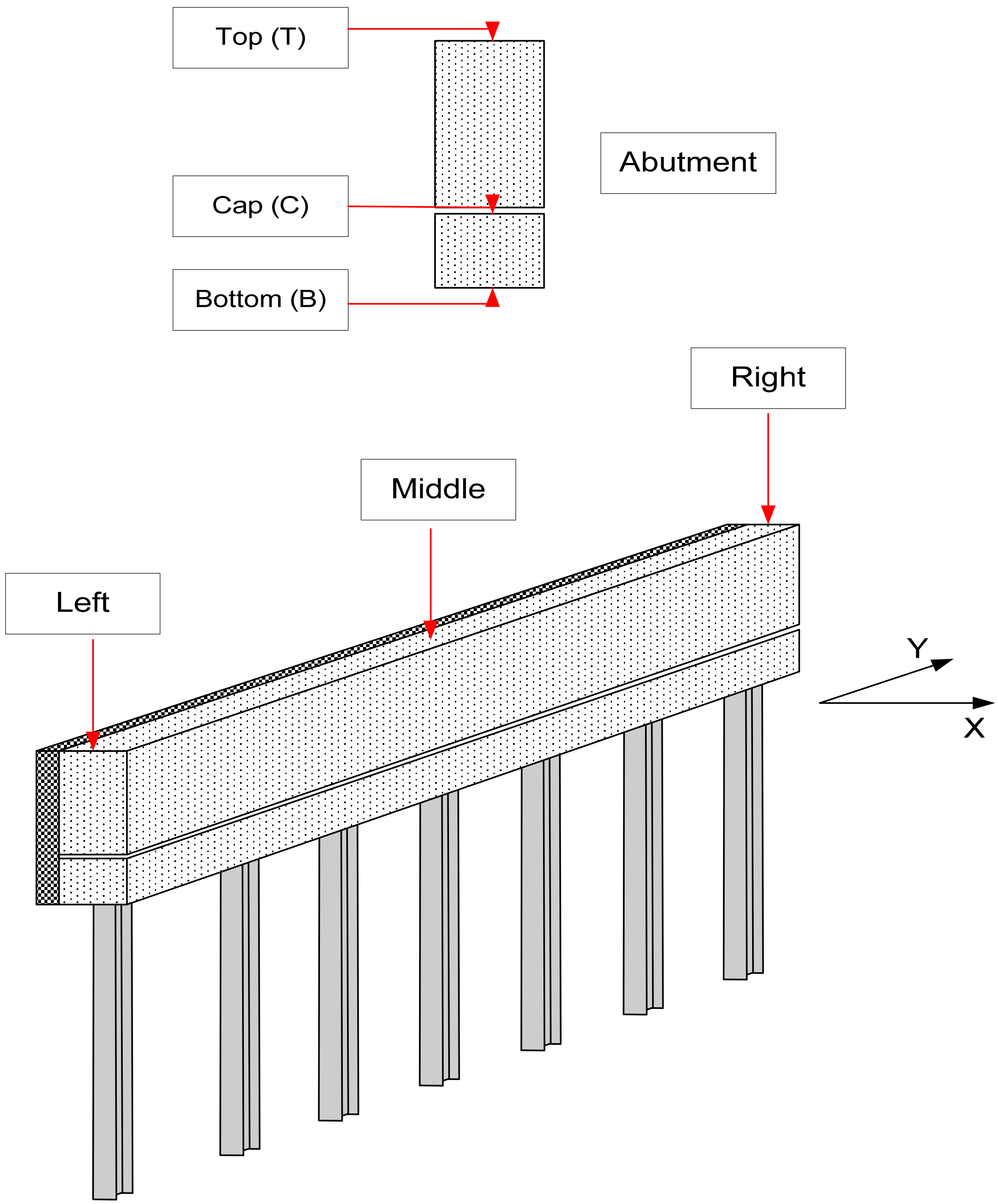


Figure A1 – Displacement monitoring positions.

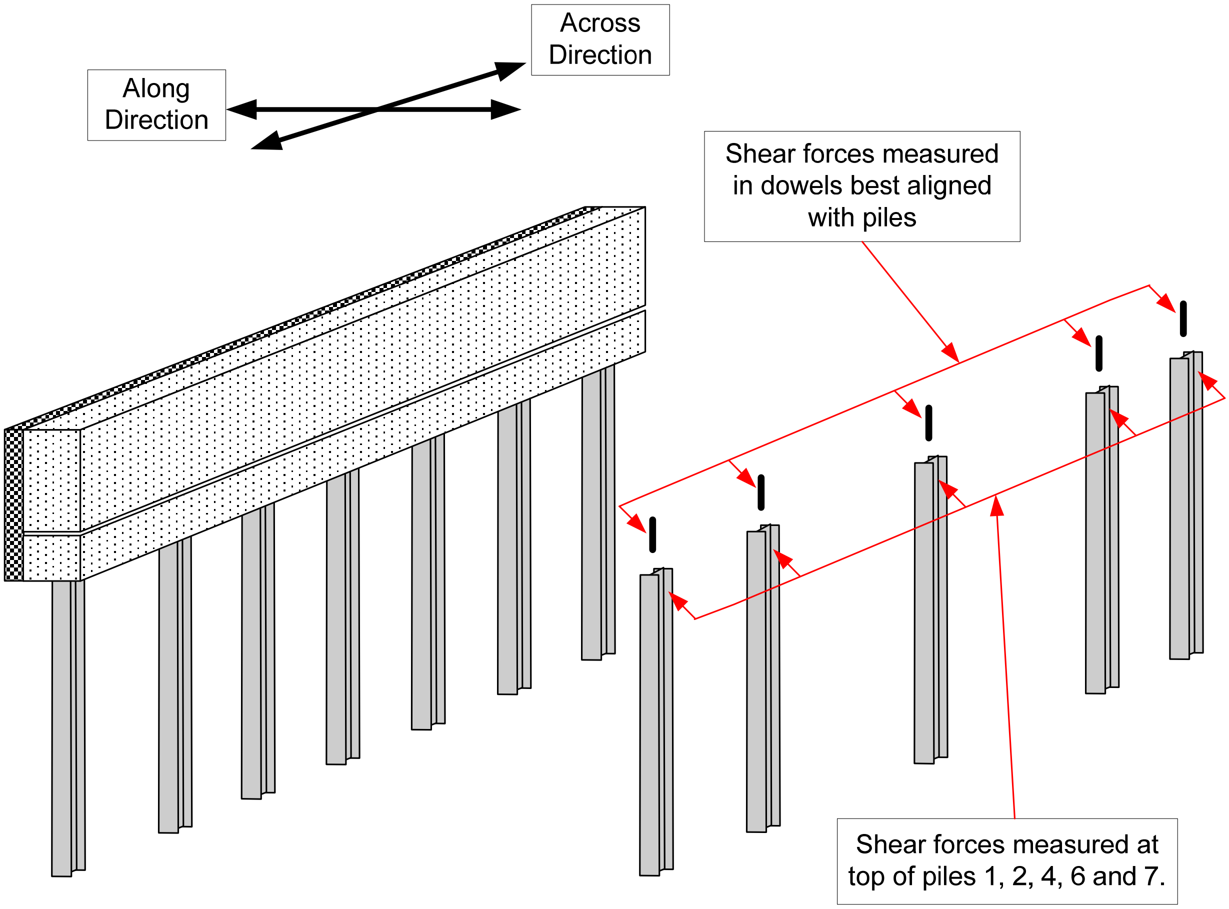


Figure A2 – Shear force monitoring positions.

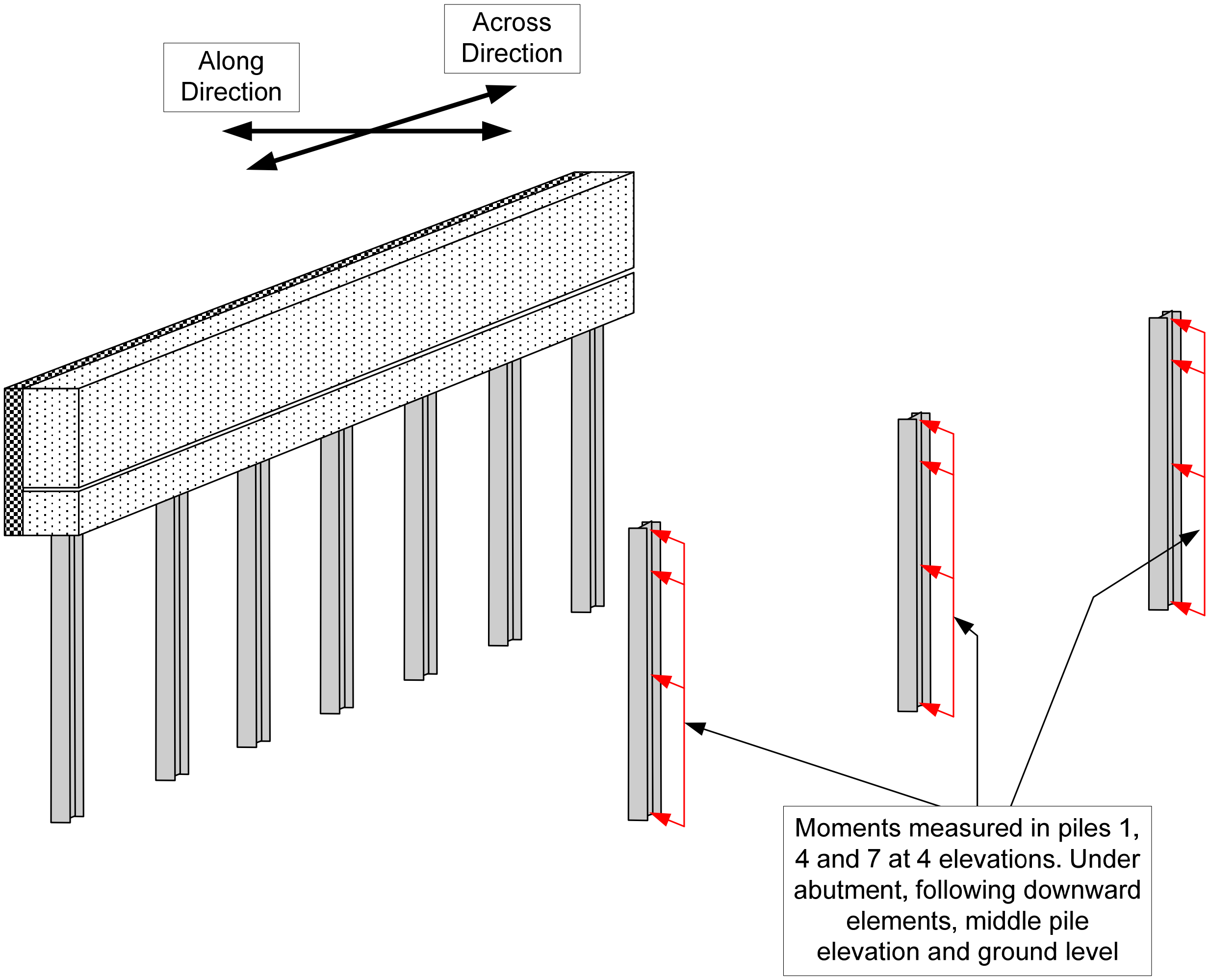


Figure A3 – Moment monitoring positions.

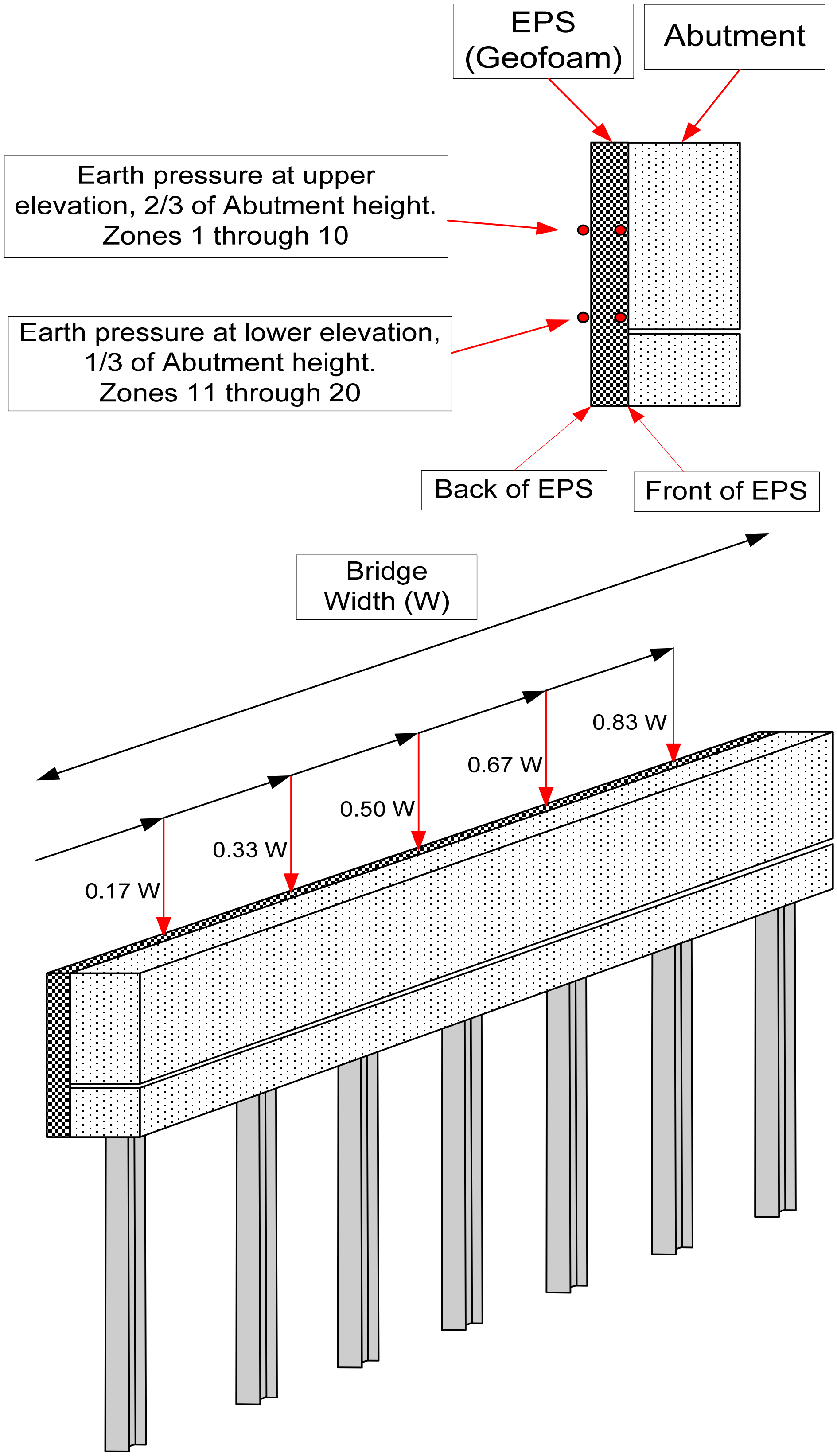


Figure A4 – Lateral pressure monitoring positions.

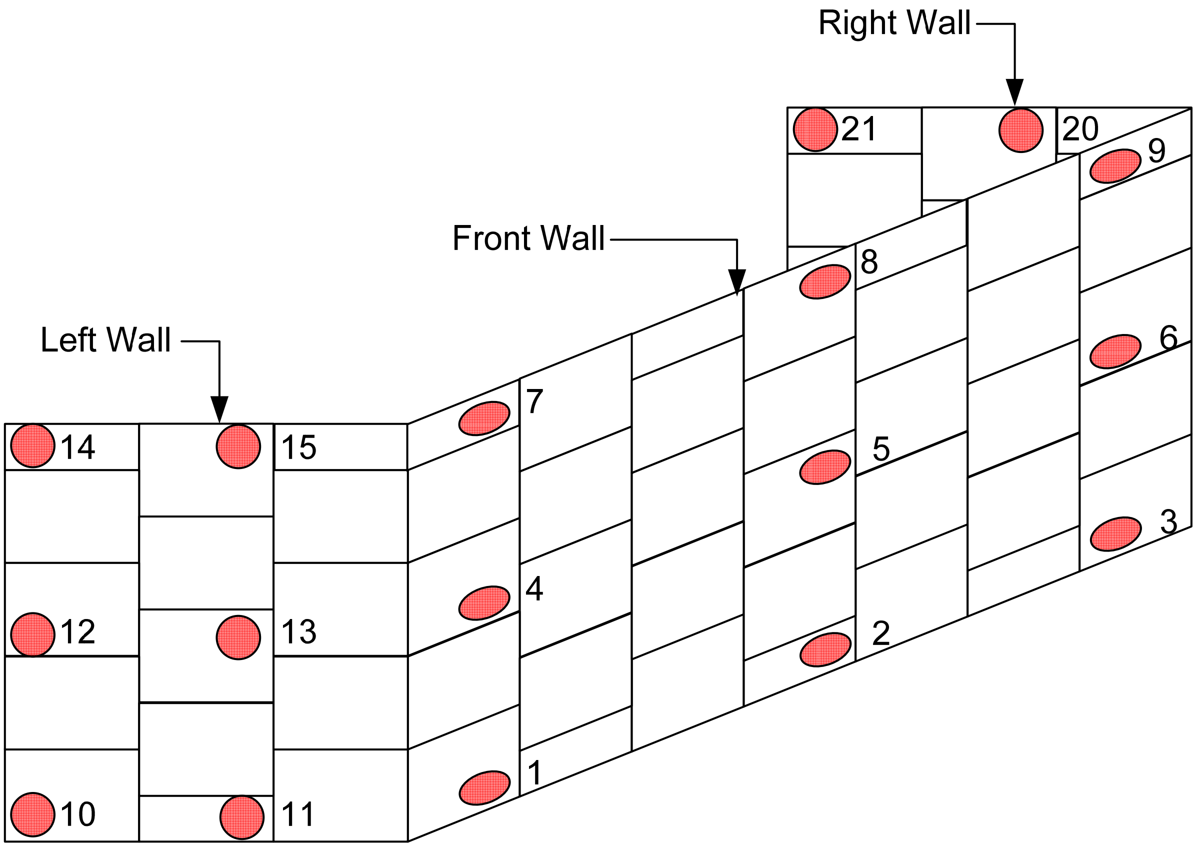


Figure A5 – Strip tensile force and MSE wall earth pressure monitoring positions.

APPENDIX B

IMPLEMENTATION: RECOMMENDED MODIFICATIONS TO VDOT MANUALS

This appendix describes recommended modifications to Chapter 17 of VDOT's *Manual of the Structure and Bridge Division, Volume V—Part 2, Design Aids and Particular Details* (VDOT, 2011b) and to Chapter 10 of *Volume V—Part 11, Geotechnical Manual for Structures* (VDOT, 2011a). These recommendations are based on the research results described in the main body of the report. The authors understand that in order to achieve various goals such as simplicity and conservatism in design, VDOT may choose not to adopt and/or to change some or all of these recommendations.

Modification No. 1

Topic: Maximum Bridge Length

Location: Chapter 17, File No. 17.01-1, Item 3

Application: Full integral abutment bridges with steel or concrete girders and with foundation piling in MSE walls that have a "U-back" configuration. The "U-back" designation indicates that the MSE wall has three faces, one parallel to the abutment and two parallel to the bridge alignment.

Current Status: Full integral abutment bridges with steel girders are limited to 300 ft and 150 ft when the skew angles are 0 and 30 degrees, respectively. Full integral abutment bridges with concrete girders are limited to 500 ft and 250 ft when the skew angles are 0 and 30 degrees, respectively.

Discussion: This research indicates that integral bridge abutments can be longer than the current limits. Integral abutment bridges with the characteristics that were considered in this research can be designed using results from the IAB v3 spreadsheet, and the bridge length should be limited to produce thermal movements that are not any larger than the maximum values applied in this research.

Recommendation: Add the following paragraph to Item 3.

> For full integral abutment bridges with steel or concrete girders and with foundation piling in MSE walls that have a "U-back" configuration, the bridge length is not subject to the length limitations listed above. Instead, longer bridges are allowed, provided that the total thermal movement at each abutment does not exceed 4.5 inches (total thermal movement of 9 inches for the bridge) and all other design criteria are satisfied based on analysis using the spreadsheet IAB v3 (Arenas and Filz 2013) and the procedures and criteria described in this chapter.

Modification No. 2

Topic: Use of elasticized EPS at Bridge Abutments

Location: Chapter 17, File No. 17.01-3, Item 5

Application: Single span, full integral bridges (steel or concrete beams, with or without MSE walls, and with any wing wall configuration).

Current Status: For single span bridges, elasticized EPS is only placed at one abutment, for both full integral and semi-integral bridges.

Discussion: For single span, full integral bridges, elasticized EPS should be used behind both abutments to distribute thermal movements to both abutments and thereby reduce maximum pressures, forces, and moments. For single span, semi-integral abutments, the current practice of placing elasticized EPS behind only one abutment should be maintained to provide some restraint against progressive and excessive displacement of the bridge.

Recommendation: Replace the first paragraph in Item 5 with the following two paragraphs.

> For single span, semi-integral bridges on a gradient, elasticized EPS shall be used at the upgrade abutment only, which will result in most movement going towards the upgrade abutment. For single span, semi-integral bridges with no grade differential, the designer shall arbitrarily specify which abutment will receive the elasticized EPS material or use engineering judgment if outside factors are present.
>
> For single span, full integral bridges, elasticized EPS material shall be used at both abutments.

Modification No. 3

Topic: Earth Pressure behind Abutments

Locations:

(a) Chapter 17, File No. 17.01-3, Item 6
(b) Chapter 17, File No. 17.02-6, P_h and P_f values
(c) Chapter 17, File No. 17.03-6
(d) Chapter 17, File No. 17.03-24

Application: All integral bridges (full integral and semi-integral, steel or concrete beams, with or without MSE walls, and for any wing wall configuration).

Current Status:

(a) The earth pressure behind the abutment backwall is determined using a K_p value of 4 when elasticized EPS is present or a K_p value of 12 when elasticized EPS is not present.
(b) P_h is computed as $P_h = \gamma_{soil}K_p\ (H_{Backwall} + \Delta h)$ and P_f is computed as $P_f = \gamma_{soil}K_p\ (H_{Backwall} + \Delta h + H_{ftg})$, with $K_p = 4$ when elasticized EPS is used.

Discussion: This research indicates that elasticized EPS reduces the maximum earth pressure behind the abutment to about 8 to 17 percent of the values when elasticized EPS is not present (Arenas, 2010). This is a very significant reduction, and it warrants widespread use of elasticized EPS behind abutments. The magnitude and distribution of the earth pressures behind the abutment change with the magnitude of thermal displacements, and they can be computed with the IAB v3 spreadsheet.

The research showed that the lateral earth pressures due to self-weight of the backfill are very low due to the ability of the elasticized EPS to accommodate lateral expansion of the backfill. This finding, combined with earlier research results (Reeves et al., 2001), indicates that the lateral earth pressures due to self-weight can be conservatively calculated using an at-rest lateral earth pressure coefficient of 0.5 for abutments with elasticized EPS. The increment of pressures due to thermal movement from IAB v3 should then be added to the at-rest pressures.

As an alternative to the procedure recommended here of adding the pressures from thermal displacements to the K_0 pressures, VDOT may want to consider adopting a conservative K value that envelopes pressures resulting from the recommended procedure. An advantage of doing this is that it simplifies the calculation. A disadvantage of doing this is that it will be more conservative than necessary. We have completed a parameter study using IAB v3 and found that a K value of 2.0 can safely be used to calculate lateral earth pressures for integral bridges with elasticized EPS at both abutments for any bridge configuration provided that the maximum thermal displacement at an abutment does not exceed 4.5 inches.

Because this research did not investigate single span bridges with semi-integral abutments, we do not recommend any changes to the existing guidelines for this case, which require that elasticized EPS be used only on one abutment, and that a passive lateral earth pressure coefficient, K_p, of 4.0 be used for both abutments.

Recommendations:

(a) Replace the first paragraph of File No. 17.01-3, Item 6 with the following.

> For single span, semi-integral bridges with elasticized EPS behind only one abutment, as indicated in Item 5, calculate lateral earth pressures behind both abutments using a passive lateral earth pressure coefficient, K_p, equal to 4.0.
>
> For all other integral bridges with elasticized EPS behind both abutments (see Item 5), calculate the at-rest lateral earth pressure acting on the abutment using an at-rest lateral earth pressure coefficient, K_0, of 0.5. For these bridges, use the IAB

v3 spreadsheet to compute the component of lateral earth pressure acting on the abutment due to thermal effects, and add this pressure to the at-rest lateral earth pressure. For integral bridges with a skew angle, the thermal component of earth pressure across the bridge calculated by IAB v3 varies with depth and lateral position across the abutment. If the variations in either direction are small, average values can be used.

(b) In File No. 17.02-6, replace the P_h and P_f definitions and calculations with the following:

P_t	Lateral earth pressure at the pavement surface
P_h	Lateral earth pressure at the base of the backwall (hinge location)
P_f	Lateral earth pressure at the base of the footing
$P_{2/3}$	Lateral earth pressure increment due to thermal movements at 2/3 of the abutment height (from IAB v3)
$P_{1/3}$	Lateral earth pressure increment due to thermal movements at 1/3 of the abutment height (from IAB v3)

Applying the IAB v3 spreadsheet to the conditions of the example problem as described on File Nos. 17.02-2 and 17.02-3, the values of $P_{2/3}$ and $P_{1/3}$ are:

Acute corner: $P_{2/3} = 53$ psf
$P_{1/3} = 148$ psf

Obtuse corner: $P_{2/3} = 58$ psf
$P_{1/3} = 133$ psf

Average values: $P_{2/3} = 56$ psf $= 0.056$ ksf
$P_{1/3} = 141$ psf $= 0.141$ ksf

$$P_t = \max\{0, 2P_{2/3} - P_{1/3}\}$$
$$= \max\{0, 2(0.056) - 0.141\}$$
$$= 0$$

$$P_f = K_0\gamma_{soil}\,(H_{Backwall} + \Delta h + H_{ftg}) + \max\{0, 2P_{1/3} - P_{2/3}\}$$
$$= 0.5\,(0.145)\,(6.33 + 0.4 + 3) + \max\{0, 2(0.141) - 0.056\}$$
$$= 0.705 \text{ ksf} + 0.226 \text{ ksf}$$
$$= 0.93 \text{ ksf}$$

$$P_h = (H_{Backwall}\,P_f + H_{ftg}P_t) / (H_{Backwall} + H_{ftg})$$
$$= (6.33(0.93) + 3(0)) / (6.33 + 3)$$
$$= 0.63 \text{ ksf}$$

Modification No. 4

Topic: Pile Moments

Location: Chapter 17, File No. 17.02-20 through File No. 17.02-27

Application: Full integral abutment bridges with steel or concrete girders and with foundation piling in MSE walls that have a "U-back" configuration.

Current Status: Currently in Chapter 17, piles are designed for axial capacity and axial-bending combined capacity. The guidelines in Chapter 17 are based on AASHTO's LFRD design method.

Discussion: The pile design is based on a trial-and-error method. At the beginning of this section, the pile size, type, orientation, and number of piles has been defined. The bridge designer can use the IAB v3 spreadsheet to compute moments due to thermal displacements in both lateral directions, i.e., transverse and longitudinal to the bridge alignment.

The AASHTO 2007 load factors that apply in this situation for earth pressures and for temperature effects are 1.35 and 1.2, respectively. Because the response to thermally induced displacements depends on the soil reactions throughout this system, we recommend that a load factor of 1.35 should be applied to all the loads, moments, and pressures computed by the IAB v3 spreadsheet to account for uncertainties and variability in soil response. Even when using this higher value of load factor, the factored loads and moments based on output from IAB v3 tend to be smaller than the values from the current procedures in Chapter 17 because IAB v3 takes into account the global displacement patterns that are induced in the abutment system, whereby the abutment movement displaces not only the pile caps and piles, but also the MSE wall backfill, reinforcing strips, and facing panels.

Another important outcome from using IAB v3 is that pile bending moments in the transverse direction are considered for skewed bridges, whereas they are not considered at all in the current procedure in Chapter 17. Thus, IAB v3 provides for more complete representation of the pile bending moments for skewed bridges. Because VDOT practice is to orient the piles for weak-axis bending in the direction of the bridge alignment, the transverse moments can be higher than the longitudinal moments for skewed bridges, as shown in the example below.

We also noticed that, on page 17.02-23, the calculation for the vector Q does not follow the normal rules for multiplication of scalar quantities times the vector M. In the existing example in Chapter 17, it appears that either all the entries for M should be the same, or all the values for Q should be zero except for the third value. In the following recommendations, we have applied the second approach, but VDOT should review this and implement whichever approach it determines is correct.

Recommendation: Adjust the procedure in Chapter 17 as follows:

- On page 17.02-22:

  Replace M_t with M_{t1} and M_{t2}, using the values provided by IAB v3:
  M_{t1} = 7.4 k-ft (moment in longitudinal direction)
  M_{t2} = 24.6 k-ft (moment in transverse direction)

- On page 17.02-23:

  Replace M_b with M_{b1} and M_{b2}, replace Q with Q_1 and Q_2, and replace M_u with M_{u1} and M_{u2}.

$$M_{b1} = \begin{pmatrix} 0 \\ 0 \\ M_{t1} \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 7.4 \\ 0 \end{pmatrix} k-ft$$

$$M_{b2} = \begin{pmatrix} 0 \\ 0 \\ M_{t2} \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 24.6 \\ 0 \end{pmatrix} k-ft$$

  The importance factor, η, has a value of 1.0. The AASHTO 2007 load factors that apply in this situation for earth pressures and for temperature effects are 1.35 and 1.2, respectively. Because the response to thermal induced displacements depends on the soil reactions throughout this system, a load factor of 1.35 is applied to all the loads, moments, and pressures computed by the IAB v3 spreadsheet to account for uncertainty and variability in soil response.

$$Q_1 = \eta\,\gamma 1\, M_{b1} = \begin{pmatrix} 0.0 \\ 0.0 \\ 10.0 \\ 0.0 \end{pmatrix} k-ft$$

$$Q_2 = \eta\,\gamma 1\, M_{b2} = \begin{pmatrix} 0.0 \\ 0.0 \\ 33.2 \\ 0.0 \end{pmatrix} k-ft$$

  M_{u1} = 8.9 k-ft (controlling longitudinal moment)
  M_{u2} = 29.5 k-ft (controlling transverse moment)

- On page 17.02-24:

  Add computation of M_x and replace M_n with M_{n1} and M_{n2}:

$$M_x = \left[1 - \left(1 - \frac{S_x}{Z_x}\right)\left(\frac{\lambda - \lambda_{pf}}{0.45\sqrt{\frac{E_s}{F_{yp}}}}\right)\right] F_{yp} Z_x =$$

$$\left[1 - \left(1 - \frac{43.4}{48.3}\right)\left(\frac{12 - 9.2}{0.45\sqrt{\frac{29{,}000}{50}}}\right)\right](50)(48.3) = 196\ k - ft$$

Evaluate M_{n1} and M_{n2} based on λ values as shown on page 17.02-24, and assign according to:

$M_{n1} = M_y$
$M_{n2} = M_x$

Make subsequent consequential changes to Chapter 17 based on the values of M_{n1} and M_{n2}.

- On page 17.02-25:

Check for capacity using M_{n1} and M_{n2}:
$M_{ux} = M_{u1}$ $\quad M_{nx} = M_{n1}$
$M_{uy} = M_{u2}$ $\quad M_{ny} = M_{n2}$

$$I_a = \frac{P_u}{2\ \phi P_n} + \left(\frac{M_{uy}}{\phi_b M_{ny}} + \frac{M_{ux}}{\phi_b M_{nx}}\right) = \frac{0.7}{2} + \left(\frac{10.0}{0.9\ (82.4)} + \frac{33.2}{0.9\ (196)}\right) = 0.67$$
$$I_b = \frac{P_u}{\phi P_n} + \frac{8}{9}\left(\frac{M_{uy}}{\phi_b M_{ny}} + \frac{M_{ux}}{\phi_b M_{nx}}\right) = 0.7 + \frac{8}{9}\left(\frac{10.0}{0.9\ (82.4)} + \frac{33.2}{0.9\ (196)}\right) = 0.99$$

$$\frac{P_u}{\phi P_n} = 0.7 > 0.2\ \Rightarrow I = I_b = 0.99$$

I < 1, and the design is satisfactory according to this criterion. Modify the remainder of the example accordingly, including the calculations for the P-delta effect.

Modification No. 5

Topic: Lateral Loads on Dowels and Piles. Lateral Force Acting on Bridge. Bridge Lateral Displacement.

Location: Chapter 17, File No. 17.07-1 through File No. 17.07-3 and File No. 17.08-8

Application: Full integral abutment bridges with steel or concrete girders and with foundation piling in MSE walls that have a “U-back” configuration.

Current Status: Chapter 17 computes lateral loads acting on piles (in the skew direction) for a skewed bridge where no lateral displacement is allowed.

Discussion: The existing equation derived in Chapter 17 was computed assuming that the bridge will not displace laterally. Thus, this equation is not appropriate for bridges that can experience lateral displacements. In addition, this section assumes that full passive earth pressure is developed behind the abutment, and as explained in Modification No. 3, this will lead to an over-estimate of the lateral load on the bridge.

When the bridge is not restrained from lateral displacements, the IAB v3 spreadsheet provides a better approach to compute lateral loads and displacements, including the lateral loads acting on piles and dowels. The results are a function of the type of pile, the magnitude of the thermal displacement, and the skew angle. The IAB v3 spreadsheet also provides the lateral displacement of the bridge.

The IAB v3 spreadsheet provides lateral loads in the direction normal to the bridge alignment. The equation in Chapter 17 provides lateral loads in the direction of the skew angle. If lateral loads are necessary in the skew direction, the longitudinal and transverse loads provided by IAB v3 spreadsheet can be projected in the skew direction.

Recommendation:

Use the IAB v3 spreadsheet to compute lateral forces acting on dowels and piles in the transverse direction, which is normal to the bridge alignment. These are the shear forces in the transverse direction on the result page of the IAB v3 spreadsheet.

The transverse displacement of the bridge is displayed at the end of the result page.

For the example in Chapter 17, the IAB v3 spreadsheet computes the following:

- The maximum transverse load acting on all the dowels in the abutment is 9 kips. Given that the abutment has 53 dowels, the maximum transverse load per dowel is 0.2 kips.
- The maximum transverse load acting on all the piles in the abutment is (-)22.8 kips. Given that the abutment has 5 piles, the maximum transverse load per pile is (-)4.6 kips.
- The maximum transverse displacement of the abutment is 0.13 in.

The resultant loads can be computed as the vector sum of the longitudinal and transverse loads from the IAB v3 spreadsheet.

For design of system components, the loads from IAB v3 should be multiplied by a load factor of 1.35.

Modification No. 6

Topic: Dowel Spacing (Dowel Forces)

Location: Chapter 17, File No. 17.02-34 and File No. 17.02-35

Application: Full integral abutment bridges with steel or concrete girders, with foundation piling in MSE walls that have a "U-back" configuration and a hinge connection at the pile cap.

Current Status: The number of dowels is determined for resisting the maximum shear force acting on the pile cap. The force acting on the pile cap, and therefore acting on the dowels, is derived from the passive earth pressure acting on the pile cap, and the reaction of the piles to thermal displacements. No consideration is given to axial loads or combined axial-bending loads in selecting the number of dowels.

Discussion: The dowel spacing is computed by dividing the dowel capacity by the lateral force per unit length, as determined according to the dowel spacing equation on page 17.02-35. In this equation, the controlling force is the passive earth pressure developed behind the pile cap. As discussed in Modification No 3, the earth pressure behind the pile cap is greatly reduced because of the use of elasticized EPS.

The IAB v3 spreadsheet can provide the longitudinal and transverse maximum shear forces acting on the dowels due to thermal movements. These thermally induced shear forces in the dowels can be conservatively added to the lateral force acting on the pile cap, similar to the approach on pages 17.02-34 and 17.02-35, but using the pile cap pressures from Modification No. 3. The values calculated by IAB v3 are for abutments constructed with elasticized EPS behind the abutment in accordance with VDOT guidelines. Because of soil-structure interactions associated with displacements of the abutment-EPS-backfill system, the shear loads computed in the dowels by IAB v3 are greatly reduced compared to the current calculation in Chapter 17. Consequently, axial and/or combined axial-bending loads may control dowel design.

Recommendation:

> Analyses of axial load and combined axial-bending load should be added to the design of dowels in Chapter 17. The procedures in Chapter 17 can be used to determine the axial loads in the dowels, and the IAB v3 spreadsheet can be used to determine the bending moment in the dowels. For the example in Chapter 17, the total bending moment carried by all the dowels is the vector sum of the longitudinal and transverse moments, which is $(1.7^2 + (-0.5)^2)^{0.5} = 1.8$ kip-ft. For the 62 dowels in the example abutment, this corresponds to 0.35 kip-in per dowel. Applying the importance factor ($\eta = 1.0$) and the load factor ($\gamma = 1.35$) gives the factored bending moment per dowel of 0.47 kip-in.
>
> After designing the dowels to carry the axial load and bending moment, the shear capacity of the dowels should also be checked. The shear loads in the dowels can be determined from the at-rest lateral earth pressure on the pile cap plus the shear

loads from the IAB v3 spreadsheet for thermal induced displacements. The following calculations are based on the dowel spacing of 9 inches (S_{dowel} = 9 in.) in the example abutment, but this spacing should be changed if the combined axial-bending load analysis establishes that a different dowel spacing should be used.

The shear load from the lateral earth pressure acting on the pile cap is determined using the previously computed values of P_h = 0.63 ksf and P_f = 0.93 ksf.

$V_{EP} = S_{dowels} H_{ftg}\left(P_h + P_f\right)/2$ Shear force in dowel due to lateral earth pressure on pile cap

$$V_{EP} = (0.75\text{ ft})(3\text{ ft})(0.63\text{ ksf} + 0.93\text{ ksf})/2$$

$$V_{EP} = 1.76\text{ kips}$$

The shear load from the thermal movements is obtained from the IAB v3 spreadsheet using the values for the longitudinal and transverse shear forces per dowel, which are 0.6 kips and 0.2 kips, respectively, for this example.

$V_{dowel} = \sqrt{\left(V_{EP} + V_{Long}\right)^2 + V_{Tran}^2}$ Total shear force in dowel

$$V_{dowel} = \sqrt{(1.76 + 0.6)^2 + 0.2^2} = 2.37\text{ kips}$$

Apply the importance factor (η = 1.0) and the load factor (γ = 1.35) to obtain the factored shear load per dowel.

$V_{u,dowel} = \eta\gamma V_{dowel}$ Factored shear force in dowel

$$V_{u,dowel} = (1.0)(1.35)(2.37) = 3.2\text{ kips}$$

Compare the factored shear force per dowel to the shear capacity of the dowel. Because $V_{u,dowel}$ = 3.2 kips < CAP_{dowel} = 16.2 kips, the shear capacity of the dowels is adequate.

Modification No. 7

Topic: MSE Wall Design

Location: Chapter 10, Item 2.2, 10.09-2

Application: Full integral abutment bridges with steel or concrete girders and with foundation piling in MSE walls that have a “U-back” configuration.

Current Status: No design consideration are present in this section regarding thermal forces acting on MSE wall.

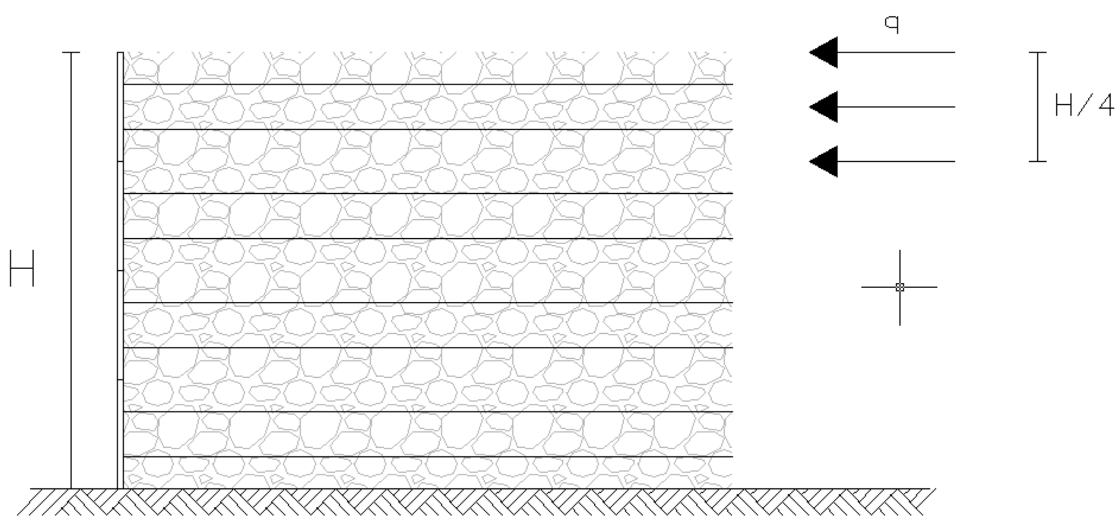
Discussion: When the superstructure of an Integral Abutment Bridge (IAB) is supported by piling extending through MSE wall backfill, designers should take into consideration the thermal effects, i.e., the effects of expansion and contraction of the bridge on the MSE wall reinforcing and panels. As the bridge expands and contracts, and the foundation piling displaces the backfill material, these movements impose increments of earth pressure on the front MSE wall panels, and they increase the tension in the reinforcement.

The load magnitudes depend on the thermal bridge displacement, the distance between the foundation piles and the MSE wall face, and the orientation and type of pile.

Recommendation:

The following loads imposed by thermal effects should be considered in the MSE wall design:

- The following figure shows the pressure increment due to thermal displacements that should be applied in addition to those pressures from standard practice for MSE wall design.



A homogeneous pressure of magnitude q acting on the upper quarter of the MSE wall should be added to those loads from standard practice. The magnitude of the load q can be computed using the IAB v3 spreadsheet. If the skew angle of the bridge is larger than 10 degrees, the pressure q should also be applied to the MSE wall side walls for a horizontal distance equal to the overall abutment height.

  - The value of q for the example in Chapter 17 is 26 psf, which should be applied along the upper quarter of the entire front wall, which is the upper

2.4 ft. Since the skew angle is 30°, this load should be also applied to the upper portion of the MSE side wall, for a distance of 9.3 ft from the front wall.

- Use the IAB v3 spreadsheet to compute the maximum strip tensile force (peak value). This load should be added to the loads imposed on the reinforcement strips from the weight of the backfill and the traffic surcharge determined according to standard practice for MSE wall design. Similar to the earth pressure on the MSE wall panels due to thermal effects, the maximum strip tensile force should be added only to those strips located in the upper quarter of the MSE wall. However, in this case, the increased tension only applies to the strips attached to the front MSE wall panel. The tensile forces in the strips computed by IAV v3 have units of pounds per square foot (psf). In order to apply these forces, the designer should multiply the pressure value by the tributary area of the MSE wall face for each strip.

  - The tensile force maximum value for the example in Chapter 17 is 38 psf. If the designer is using a vertical strip spacing of 2 ft and a horizontal strip spacing of 2.5 ft, the maximum tensile force due to thermal effect acting in the upper strips is 38 x 2 x 2.5 = 190 lbs. This load should be added to the strips directly under the abutment and in the upper quarter of the front MSE wall under the abutment. The total load acting on the strips should be compared to the strip capacity.

- Use the IAB v3 spreadsheet to compute the tensile force acting on strips at the connection with the MSE Wall. This load should be added to the loads due to self-weight and traffic determined according to standard practice for MSE wall design. This increment of tension at the reinforcing strip connections should be applied to the strips attached to the MSE front wall in the upper quarter of wall height. The total load acting on the connections should be compared to the connection capacity.

  - The strip tensile force at the connection computed by IAB v3 for the example in Chapter 17 is equal to the maximum tensile force value. Therefore, the tensile force at the connection with the MSE wall is 190 lbs (refer to previous hollow bullet for details). For other conditions, the maximum tensile force at the connection could be less than the maximum tensile force in the strip at some other location. The strip connection load from the IAB v3 spreadsheet should be added to the standard calculation of connection force for strips directly under the abutment and in the upper quarter of the front MSE wall under the abutment. Check that the strip connection capacity can accommodate the applied tension.

- For design of MSE system components, the wall pressures and strip tensile loads from IAB v3 should be multiplied by a load factor of 1.35.