

CHAPTER 6 – NUMERICAL INVESTIGATIONS OF INTEGRAL BRIDGE/SOIL INTERACTIONS

6.1. Introduction

Integral bridges are subjected to complex soil/structure interactions. A thorough understanding of these interactions is needed to provide a basis for expanding the current limits on the lengths of integral abutment bridges.

This chapter presents the findings of series of finite element analyses that were performed to investigate the significance of the interactions among the abutment, the approach fill, the foundation soil, and the piles. The effect of the approach fill on the stresses in the piles supporting the abutment, and the effects of the type of abutment (fully versus semi-integral) were examined in these analyses.

The possibility of using simple procedures for design of the piles was investigated. Discussions of the results of the analyses and recommendations for future research are presented at the end of this chapter.

6.2. Objectives of Numerical Analysis

The objectives of the research include investigation of the:

- Effect of the stiffness of the foundation soil on pile stresses,
- Effect of fully integral abutments on pile stresses,
- Effect of semi-integral abutments on pile stresses, and
- Possibility to develop a simplified method for design of piles supporting integral abutment bridges.

6.3. Expected Soil/Abutment/Pile Interactions

As the superstructure expands toward the approach fill, a series of interactions takes place between the following components of the bridge and its foundation:

- Abutment/approach fill,
- Approach fill/foundation soil,
- Foundation soil/pile, and
- Pile/abutment.

These interactions should be more fully understood in order to expand the current limits on the lengths of integral abutment bridges.

Abutment/approach fill interactions result in changes in the earth pressures acting on the bridge abutment. The magnitude and the mode of the abutment movement are primary factors that control the earth pressures. Earth pressures decrease as the bridge contracts, and increase when the bridge expands.

As the approach fill is pushed by the abutment, it tends to move the foundation soil in the same direction. This is beneficial as far as the pile stresses are concerned because the foundation soil acts as if it were softer because it is moving in the same direction as the piles. This results in lower stresses in the piles.

The type of foundation soil is important in determining the pile stresses. For conditions where a given amount of displacement is imposed at the tops of the piles, as is the case for piles supporting integral bridges, softer soils result in lower pile stresses than do stiffer soils. A computer program such as LPILE is useful for assessing the stresses resulting from imposed displacements.

The interactions between the abutment and the piles that support it also have an important influence on the pile stresses. Experiments were conducted to investigate this issue. The findings of the experimental program were presented in Chapter 5.

A combination of these factors result in interactions among the abutment, the approach fill, the foundation soil and the piles. These interactions can be modeled by conducting finite element studies. The results of the finite element analyses provide a basis for improved understanding of the behavior of integral bridges and their foundation.

6.4. Software Selection

The interactions between the bridge system and the approach system would be best modeled by a finite element program capable of solving three-dimensional problems. However, 3D finite element analyses would require more time and effort than was possible within the scope of this study. To give some understanding of the complex interactions described in the previous paragraphs, it was decided to use the computer programs SAGE and LPILE for this investigation. Description of the capabilities of SAGE and LPILE are presented below.

6.4.1. SAGE

Finite element analyses were performed using the finite element program SAGE 2.03 (Static Analysis of Geotechnical Engineering Problems) developed at Virginia Tech. SAGE is capable of analyzing 2D plane strain soil-structure interaction problems. Newton-Raphson iteration is used to solve the non-linear equations.

Element types include triangular, quadrilateral, beam-bar, Wilson, and zero-thickness interface elements. Soil behavior can be modeled by choosing from ten material models, including; Mohr-Coulomb, Drucker-Prager, Hyperbolic, and Cam Clay (Bentler et al., 1999).

6.4.2. LPILE

LPILE is a program developed by Ensoft, Inc. of Austin, TX for analyzing the behavior of piles under lateral loading. The program is based on the finite difference method, and approximates 3D soil/pile interaction through the use of nonlinear p-y curves.

Deflection, shear, moment, and soil response along the pile are computed. The boundary conditions at the pile head can be specified in terms of shear, moment, displacement, and rotational stiffness.

6.5. Bridge Geometry

A 300-ft long integral abutment bridge was selected for the parametric analyses. It was assumed that the bridge consists of W44x285 steel girders spaced 8 feet apart, with a 10-inch thick concrete deck, resting on 10-ft high 3.0-ft thick abutments, which are supported by HP10x42 steel piles, spaced 6 feet apart, as shown in Figure 6.1.

Two abutment types were considered: fully integral and semi-integral. Enlarged views of these abutments are depicted in Figure 6.2. The semi-integral abutment is similar to fully integral abutment, except for a lateral joint in the middle of the abutment. A dowel passes through this joint to prevent shear displacements between the top and bottom sections of the abutment.

The bridge was modeled as a plain strain problem, with symmetry around the centerline of the bridge. The finite element mesh used in the analyses is shown in Figure 6.3. Both the fully integral and the semi-integral abutments were modeled using the same mesh. As can be seen in Figure 6.3, the mesh is finer around the abutment, and is coarser

near the boundaries. Zero-thickness interface elements were used between the approach fill and the abutments.

Sections of the finite element mesh around the fully integral abutment and the semi-integral abutment are shown in large scale in Figures 6.4 and 6.5, respectively. The lateral joint in the semi-integral abutment was modeled by quadrilateral elements and beam-bar elements as shown in Figure 6.5.

6.6. Material Properties

Different types of models of nonlinear soil behavior are used in SAGE and LPILE. The parameters used in these analyses were obtained from published literature (Duncan et al., 1980, Reese and Wang, 1997).

6.6.1. SAGE

The bridge superstructure, the piles and the dowels of the semi-integral abutments were modeled as beam-bar elements with linear stress-strain properties. The abutment and the joint-filler in the semi-integral abutment were modeled using four-node quadrilateral elements with linear stress-strain properties. The approach fill and the foundation soil were modeled using four-node quadrilateral and three-node triangular elements with hyperbolic material properties. Table 6.1 and 6.2. summarize the material properties used in the analyses. The hyperbolic soil parameters representing dense to loose sand were selected from Duncan et al. (1980).

The behavior of the joint-filler was modeled by setting the values of modulus for these elements approximately equal to zero so that it does not contribute to the shear, and all the shear force is absorbed by the dowels.

6.6.2. LPILE

Table 6.3 summarizes the soil parameters used in LPILE. These values were obtained from the program manual (Reese and Wang, 1997). The soil parameters shown in Table 6.3 were used by LPILE to generate the p-y curves used in the analyses.

Table 6.1. Properties of structural components

Structural Component	Bridge beams	Pile	Dowels
EA (kips)	2.43×10^6	0.36×10^6	17.4×10^3
EI (kips-ft ²)	4.95×10^6	14.44×10^3	11.58
Spacing (ft)	8	6	1
EA per ft. (kips/ft)	~0*	60×10^3	17.4×10^3
EI per ft. (kip-ft ² /ft)	600×10^3	2.4×10^3	11.58
*Axial loads in the beams were not of concern (see section 6.8 for details)			

Table 6.2. Hyperbolic stress-strain and strength parameters for approach fill and foundation soils

Parameter	Loose Sand	Medium Dense Sand	Dense Sand
γ , Unit weight (pcf)	115	125	140
c, Cohesion	0	0	0
ϕ , Friction angle (degrees)	33	36	42
R_f , Failure ratio	0.7	0.7	0.7
K, Young's modulus coefficient	200	300	600
n, Young's modulus exponent	0.4	0.4	0.4
K, Bulk modulus coefficient	50	75	175
m, Bulk modulus exponent	0.2	0.2	0.2

Table 6.3. Parameters used to define p-y curves in LPILE

Parameter	Loose Sand	Medium Dense Sand	Dense Sand
γ , Unit weight (pcf)	115	125	140
c, Cohesion	0	0	0
ϕ , Friction angle (degrees)	33	36	42
k, coefficient of horizontal subgrade reaction (lb/in ³)	25	90	225

6.7. Assumptions and Sources of Errors in Numerical Modeling

A comparative study was made to determine the degree of correspondence between the results of laterally loaded pile analyses performed with SAGE and with LPILE. Three soil-conditions (dense, medium dense and loose sand) and two boundary conditions (fully fixed and partially fixed head) were considered. The properties of the steel HP10x42 piles and the soil used in the analyses are listed in Tables 6.1, 6.2, and 6.3.

A total of six analyses were conducted as tabulated in Table 6.4. The slope at the pile head was assumed to be either zero or 0.005, which brackets the range expected for most piles supporting integral abutment bridges.

Comparisons of the solutions by SAGE and LPILE for deflection, shear and bending moment are shown in Figures 6.6 and 6.7. Figure 6.6 compares results for fixed head piles in medium dense sand while Figure 6.7 compares results for partially fixed piles in medium dense sand. As can be seen in these figures, for a given displacement at the top of the pile, the maximum shear calculated by SAGE is about the same as that calculated by LPILE. The moments computed using SAGE are about 35% less than those computed using LPILE.

Similar comparisons were made for dense and loose sand. Table 6.4 shows that the results of the SAGE analyses compare reasonably well to the results of the LPILE analyses. It thus seems reasonable to conclude that two-dimensional finite element analyses can be used to investigate the soil-structure interaction effects in integral

bridges. Although the piles supporting the abutment must be represented as equivalent two-dimensional piles in such analyses, the computed results can be expected to be qualitatively the same, and quantitatively similar, to the actual three-dimensional behavior, at least as judged by the correspondence between the SAGE and LPILE results shown in Table 6.4.

Table 6.4. Comparison of Shear and Moment as calculated by SAGE and LPILE

Case No.	Soil Type	Top Slope (rad)	Top Deflection (in.)	Shear _{LPILE} / Shear _{SAGE}	Moment _{LPILE} / Moment _{SAGE}
D-FF	Dense	0	0.69	1.05	1.51
D-PF	Dense	0.005	0.69	0.81	1.45
MD-FF	Medium Dense	0	0.44	1.10	1.41
MD-PF	Medium Dense	0.005	0.52	0.87	1.52
L-FF	Loose	0	0.71	1.05	1.31
L-PF	Loose	0.005	0.70	0.87	1.37
D = dense sand, MD = medium dense sand, L = loose sand FF = fully fixed = zero rotation at the top of the pile PF = partially fixed: rotation = 0.005 radians at the top of the pile					

6.8. Parametric Analyses

Finite element analyses were conducted to study the following:

1. Effects of approach fill in the pile stresses for different soil conditions,
2. Effects of abutment type in the pile stresses,

The loads applied represent the forces exerted on the abutment by the superstructure (the girders and the deck) as the temperature increases or decreases and the superstructure expands or contracts. The stiff girders and the attached deck tend to restrain rotation of

the abutment, and including the flexural stiffness (EI) of the superstructure in the analyses models this important aspect of the structural behavior. However, because it was more convenient to perform the analyses by applying forces rather than displacements, the axial stiffness (EA) of the girders and the bridge deck were set equal (approximately) to zero. The axial forces were applied to the abutment along the neutral axis of the bridge girders.

The characteristics of the finite element model and results are thus:

- The applied force corresponds to the axial forces exerted on the abutment by the superstructure as temperatures increase or decrease,
- The resulting displacements and rotations of the abutment correspond to the actual displacements and rotations due to temperature increase and decrease, and
- The forces induced in the abutment, the approach fill, the foundation piles and the foundation soils show how the loads are carried by increased earth pressures in the approach fill and increased shear forces on the foundation piles.

6.8.1. Effects of Approach Fill

The effects of the approach fill on pile stresses were studied by conducting two sets of finite element analyses. The first set of analyses investigated the pile stresses with no approach fill. The second set of analyses investigated the pile stresses with an approach fill. Figure 6.8 shows the cross sections used in these analyses. Lateral forces were applied through the bridge beams such that the displacement at the pile head was the same for both sets of analyses. Any difference in the pile stresses was thus due to the approach fill.

The results of these analyses indicate that the approach fill significantly reduces the pile stresses. This beneficial reduction in the stresses occurs because the approach fill drags the foundation soil as it moves, resulting in less resistance of the foundation soil against the pile displacements. In other words, the foundation soil acts as if it were softer when the approach fill is in place. It would therefore be excessively conservative to

perform analyses of the lateral loads on the foundation piles without recognizing this effect.

Reductions in the maximum shear due to approach fill were calculated for three sand densities and were tabulated in Table 6.5. Reductions in shear are significant, ranging from 40% for loose sand to 64% for dense sand. The computed values of slope at the pile head are also shown in this table. It can be seen that the slope of the pile head increases as the foundation soil gets more dense. It appears that this occurs because the dense sand offers greater resistance to lateral displacement of the piles, and more pile head rotation is required to achieve the same pile head displacement.

Additional finite element analyses were conducted to compare the effects of bridge expansion and contraction on pile stresses. Lateral forces were applied to pull the abutment away from the approach fill, such that the pile head displaced about 0.68 inches. The foundation soil was assigned the properties of medium dense sand.

These analyses indicated a slightly smaller beneficial effect of the approach fill for the case where the bridge contracted. The reduction in the shear due to the presence of approach fill was 47% in this case, as compared to 51% in the case of expansion. The stresses in the pile were found to be about 5% higher for 0.68 inch movement of pile head away from the approach fill than for 0.68 inch movement of pile head towards the approach fill.

In conclusion, finite element analyses indicate that the presence of the approach fill significantly reduces the stresses in piles supporting integral bridges. Pile stresses are slightly higher for the contraction mode than for the expansion mode.

6.8.2. Effects of abutment type: fully vs. semi-integral

Finite element analyses were conducted to compare the behavior of fully integral and semi-integral abutments. The foundation soil was assigned the properties of medium dense sand.

Loads were applied through the bridge beams to induce 2 inches of displacement towards the approach fill in both cases.

Table 6.5. Reductions in maximum pile stresses due to approach fill

Foundation Soil	Displacement at pile head (in.)	Slope at pile head** (rad.)	Reduction in Shear*
Dense Sand	0.70	0.0065	64%
Medium Dense Sand	0.68	0.0056	51%
Loose Sand	0.70	0.0054	40%
* As compared to the analyses with no approach fill			
** For cases with approach fill.			

Figure 6.9 shows the displaced positions of the integral and the semi-integral abutments in medium dense sand. The initial and the displaced geometry of the semi-integral abutment are shown in Figure 6.10. As can be seen in Figure 6.9, the bottom of the semi-integral abutment rotates more than the top, which is restrained by the bridge beams. The rotation of the lower portion of the semi-integral abutment is controlled by the shear force in the dowels and the interactions among the pile cap, the soil, and the piles.

The larger slope at the tops of the piles under semi-integral abutments is beneficial to the pile stresses. Additionally, it can be seen in Figure 6.9 that piles supporting semi-integral abutments displace less than those supporting fully integral abutments. As a result of these effects, the computed pile stresses were about 10% lower for the semi-integral abutment.

The behavior of the semi-integral abutments was also explored in the contraction mode of the bridge by applying a lateral load through the bridge beams to pull the abutments away from the approach fill. A semi-integral and a fully integral abutment were pulled such that the tops of the abutments displaced 2 inches towards the bridge centerline. Figure 6.11 shows the displaced position of both abutments in medium dense sand. It can be seen that the bottom of the semi-integral abutment rotates more than the top, and that the displacement at the top of the piles is less than for the fully integral abutment, as was the case in the expansion mode. The initial and the displaced geometry of the semi-integral abutment are shown in Figure 6.12. The computed pile stresses were 40% smaller for the semi-integral abutment than for the integral abutment.

In conclusion, it appears that semi-integral abutments offer advantages over the fully integral abutments as far as the pile stresses are concerned. The advantages are much more significant in the contraction mode of the bridge.

6.9. Proposed Method to Account for Soil Structure Interaction Effects in Design of Piles Supporting Integral Abutment Bridges

Finite element analyses indicate that movements of the approach fill cause the foundation soil to behave as if it were softer. This is somewhat analogous to soil-pile-soil interaction in pile groups. As a result of this interaction, piles in a group carry smaller shear loads and are less severely stressed than are single piles subjected to the same displacement at the pile head. A conventional way of considering the pile group effects is to reduce the soil resistance using p-multipliers. A similar procedure can be used in the case of piles supporting integral bridges, as a means of accounting for approach fill/foundation soil interaction.

The following procedure was used to determine appropriate values of p-multiplier to account for the approach fill effect:

Step 1: A finite element analysis was performed to evaluate the shear, the displacement, and the slope at the pile head, with the approach fill in place.

Step 2: Using LPILE, the shear and the slope from step 1 were imposed at the head of a single pile.

Step 3: The value of the p-multiplier in LPILE was varied until the calculated displacement in this step becomes equal to the displacement in step 1 for the same pile head shear and slope.

Similar analyses were conducted for loose and dense sand. The values of the p-multiplier found in these analyses are shown in Table 6.6. As can be seen in this table, the reduction in stiffness varies from 0.08 for dense sand to 0.55 for loose sand. Because pile stresses increase with sand density, and decrease as the value of the p-multiplier

decreases, it can be seen that the beneficial approach fill effect is greatest for stiff soil conditions, where the pile stresses induced by a given amount of displacement would be greatest.

Table 6.6. Calculated p-multipliers to account for the interactions between the approach fill and the foundation soil

Foundation Soil	Displacement at pile head (in.)	Slope at pile head (rad.)	Calculated p-multiplier
Dense Sand	0.70	0.0065	0.08
Medium Dense Sand	0.68	0.0056	0.28
Loose Sand	0.70	0.0054	0.55

6.10. Summary of Findings

The finite element analyses described above show the importance of the interactions among the abutment, the approach fill, the foundation soil and the piles. The analyses indicate that appreciable rotations occur in integral abutments. These rotations are beneficial to the piles in two ways: (1) the slope at the pile head is greater than zero, which reduces the moments in the piles and (2) the displacement at the pile head is less than that at the top of the abutment, which reduces the shear and moment in the piles.

Interactions between the approach fill and the foundation soil create further favorable conditions with respect to pile stresses because the foundation soil behaves as if it were softer when it is displaced by the movement of the approach fill. The p-multiplier concept can be used to allow for the beneficial approach fill effect when computer programs such as LPILE are used for analysis and design of piles for integral bridges. Appropriate values of p-multiplier range from about 0.1 for stiff soil conditions to about 0.5 for soft soil conditions. If refinement of these factors appears warranted, 2D finite element analyses of the type described here could be used in conjunction with LPILE analyses.

The finite element analyses indicate that semi-integral abutments such as the one shown in Figure 6.2 offer benefits over fully integral abutments. The benefits of using semi-integral abutments in reducing the pile stresses are more pronounced in the contraction mode of the bridges than the expansion mode.

6.11. Recommendations for Future Work

It would be desirable to instrument abutments of integral bridges and piles supporting integral bridges to investigate the rotation behavior of semi-integral abutments, and to investigate pile stresses. Data from such tests would be very useful in validating the findings of this study.

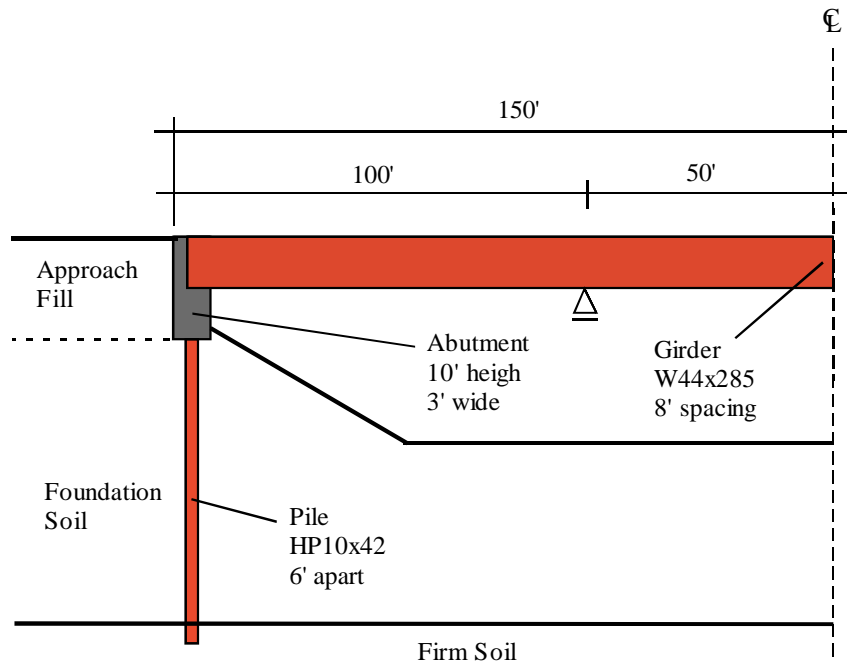


Figure 6.1. Geometry of bridge considered in finite element analyses

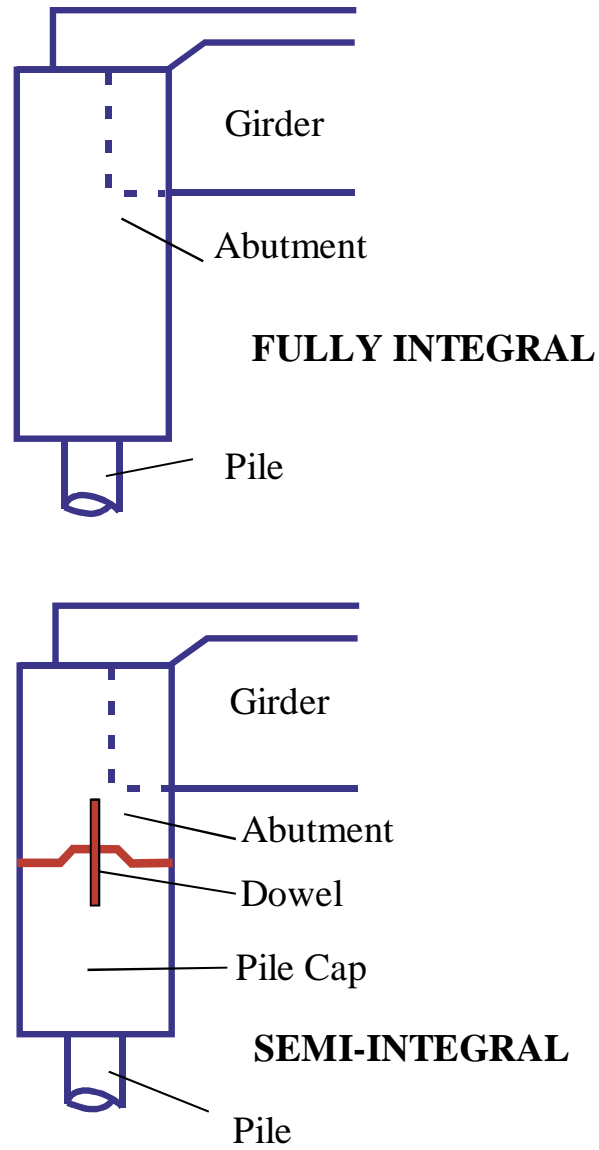


Figure 6.2. Enlarged views of fully-integral and semi-integral abutment details

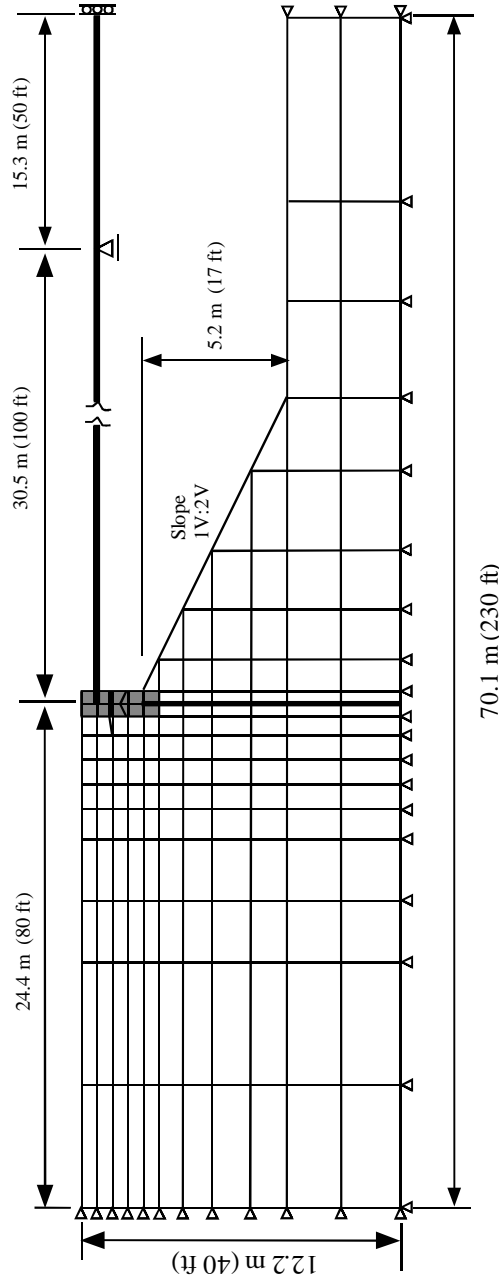


Figure 6.3. Finite element mesh used for the bridge analyzed

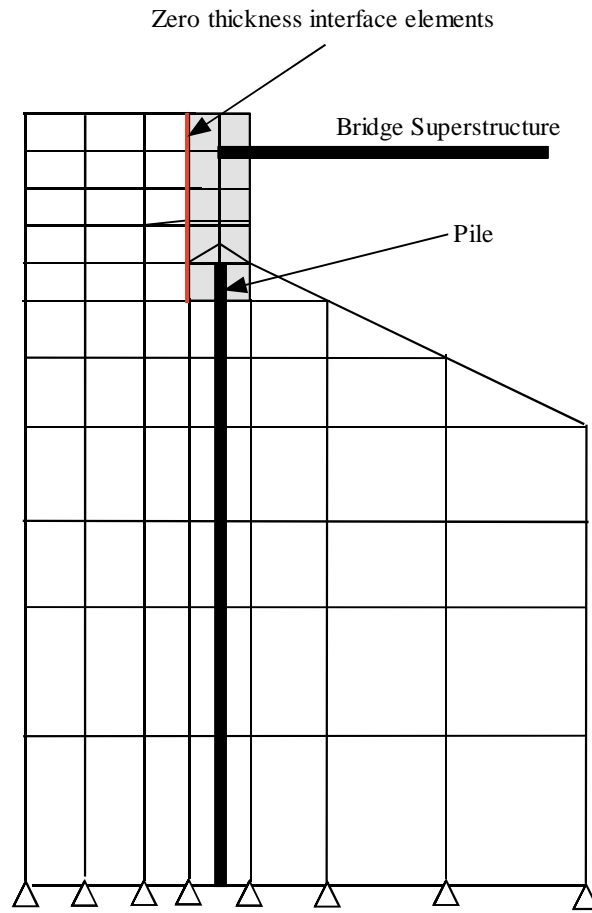


Figure 6.4. Finite element mesh of the area of the fully-integral abutment

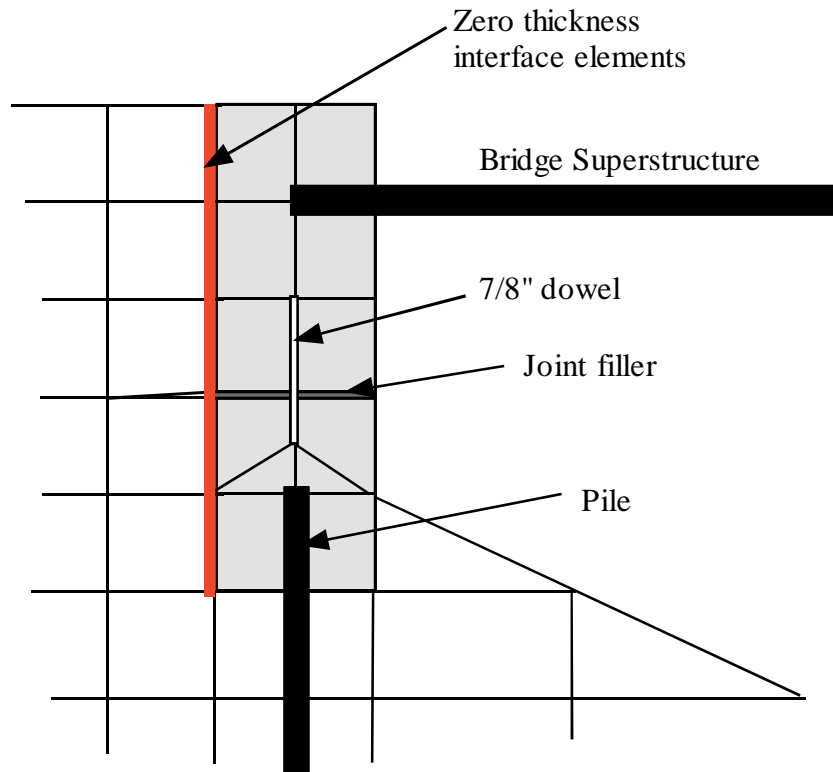


Figure 6.5. Finite element mesh of the area of the semi-integral abutment

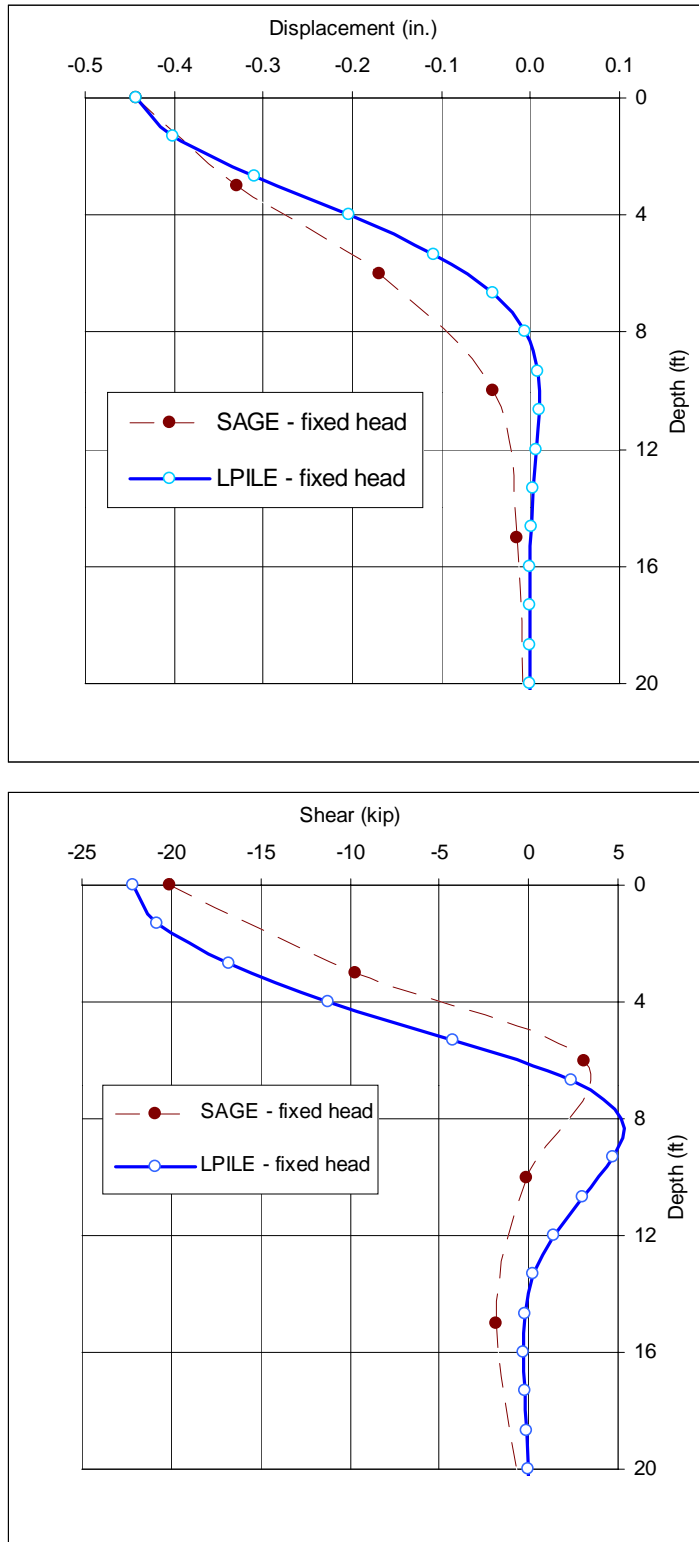


Figure 6.6. Comparison of results for SAGE and LPILE for a fully fixed head pile

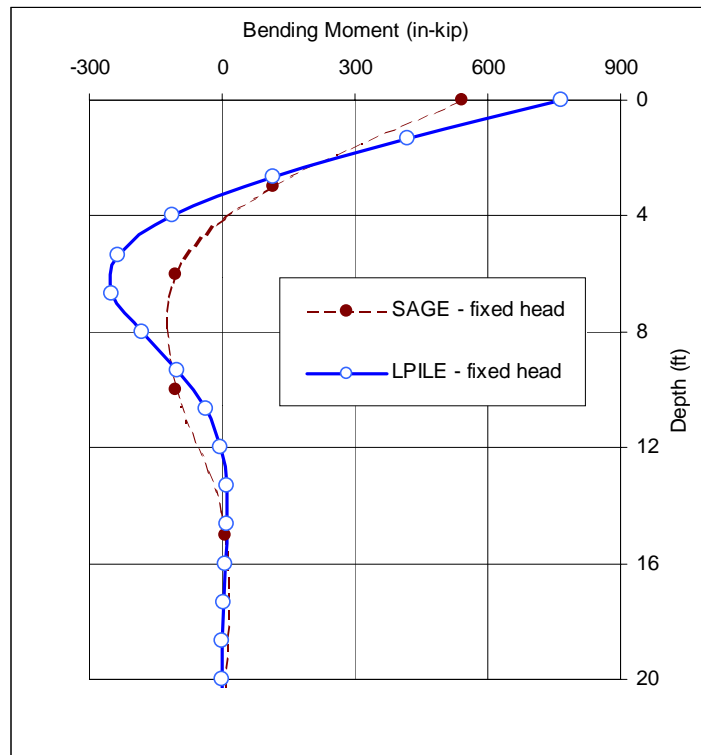


Figure 6.6 (Continued). Comparison of results for SAGE and LPILE for a fully fixed head pile

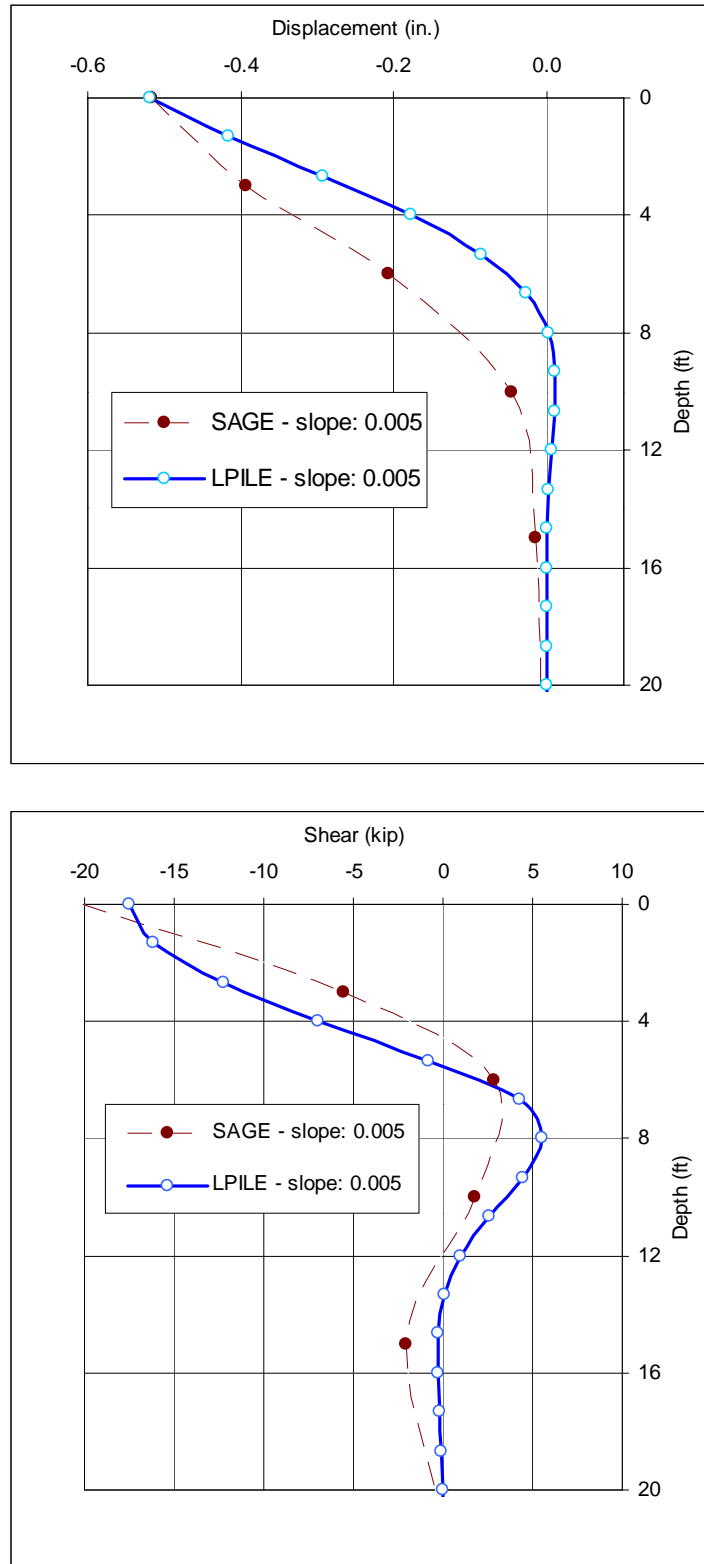


Figure 6.7. Comparison of results for SAGE and LPILE for a partially fixed head pile

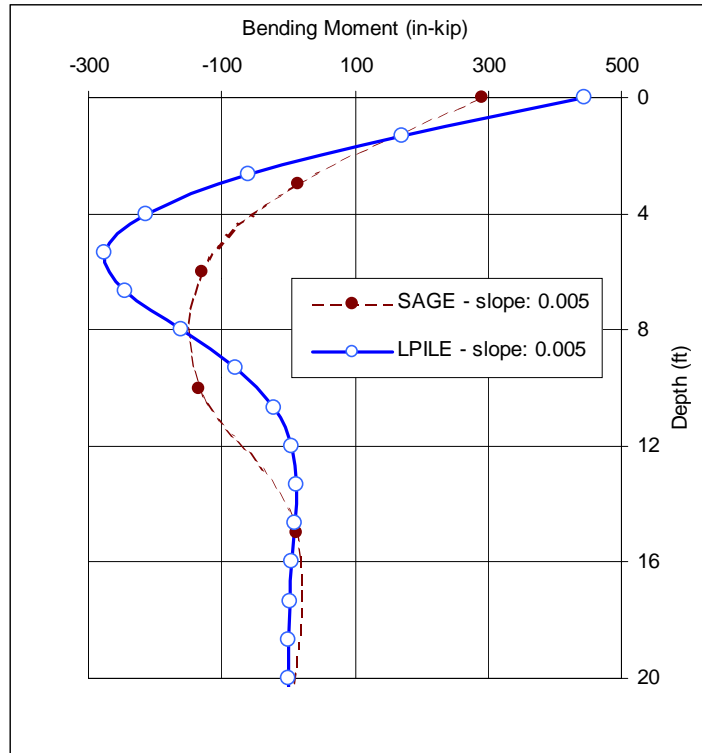
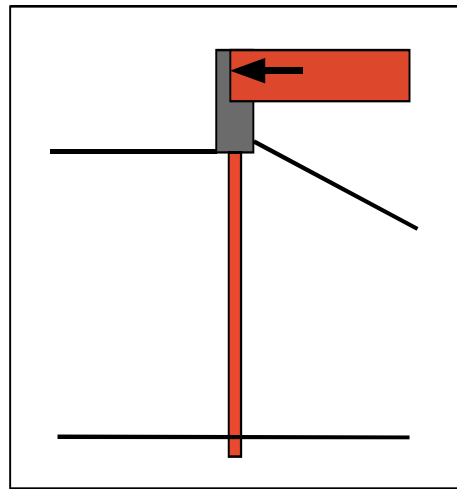
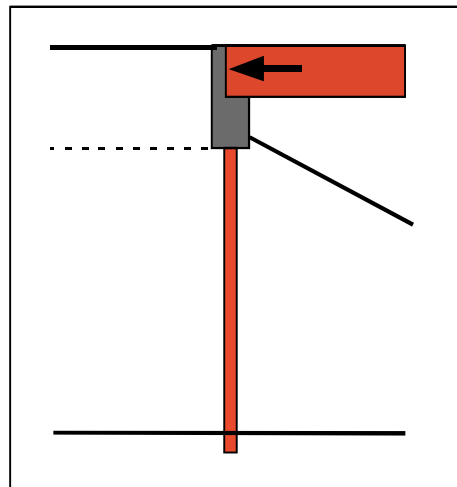


Figure 6.7 (Continued). Comparison of results for SAGE and LPILE for a partially fixed head pile



Bridge w/o approach fill



Bridge w/ approach fill

Figure 6.8. Sketches of the geometry of the bridge analyzed w/ and w/o the approach fill

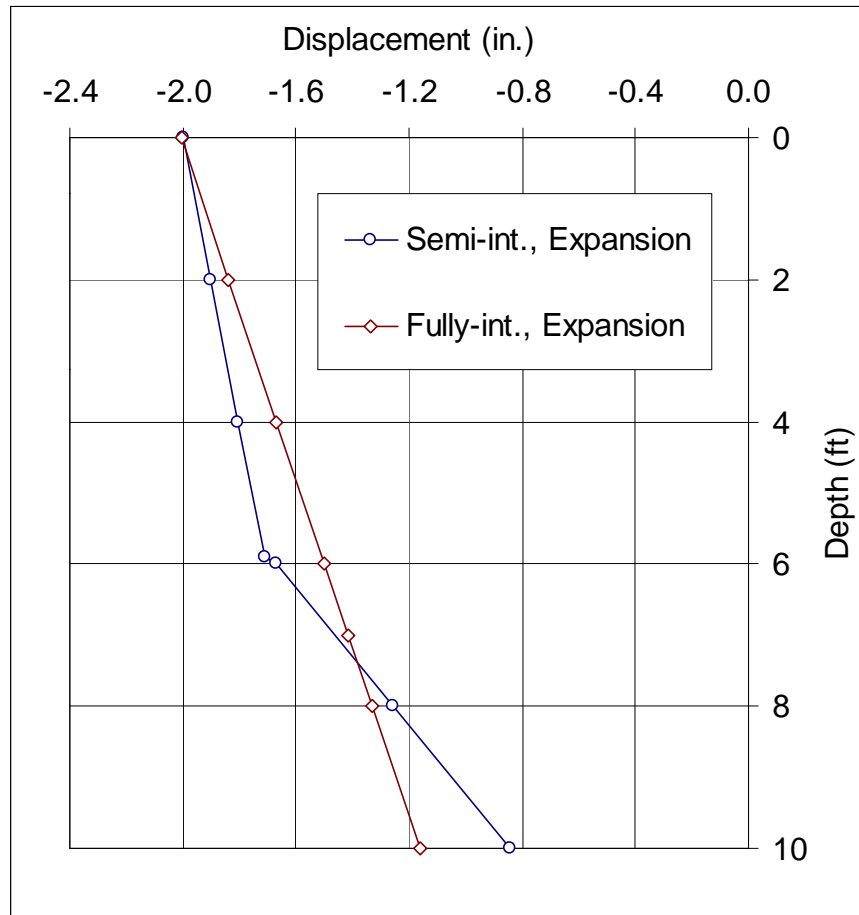


Figure 6.9. Displacement behaviors of fully- and semi-integral bridges in expansion mode of the bridge in medium dense sand

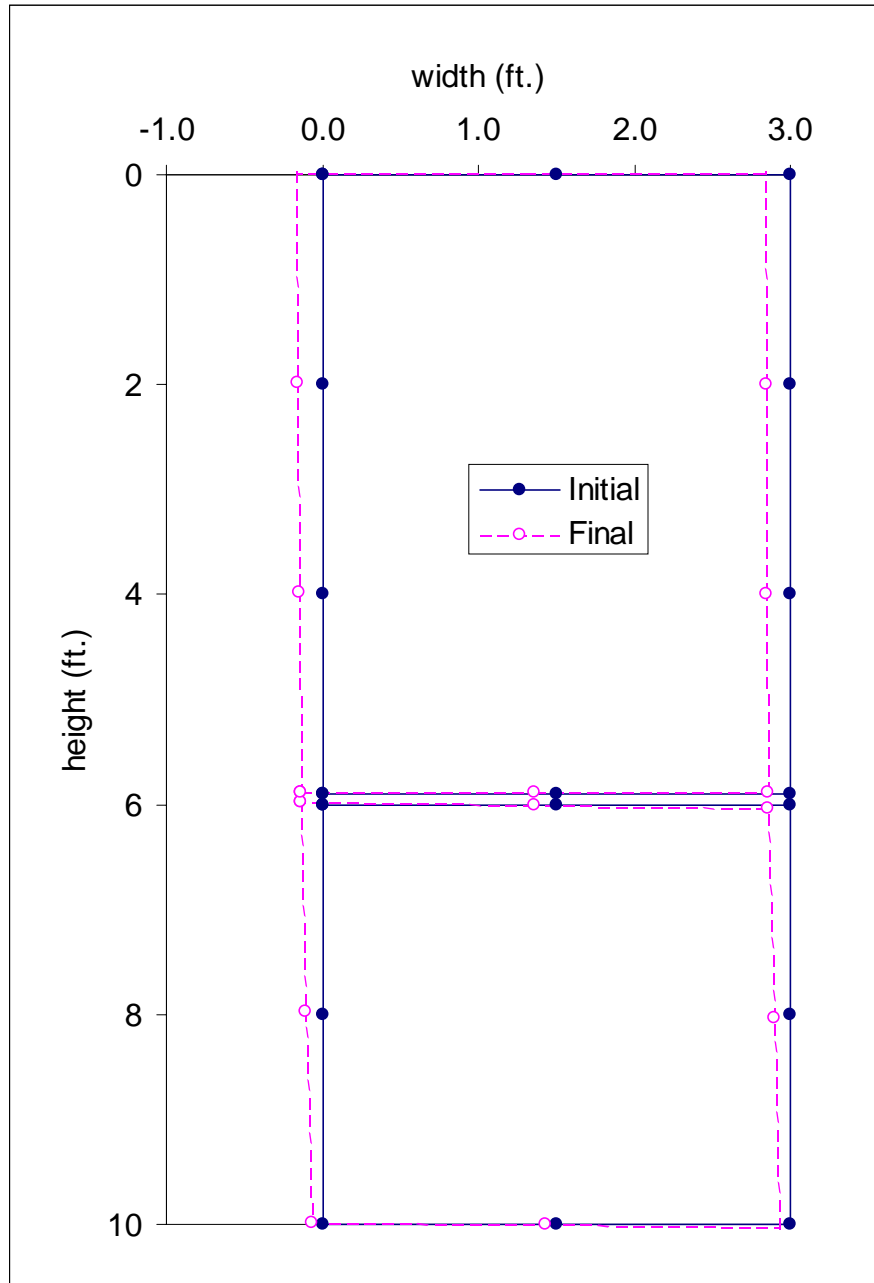


Figure 6.10. Initial and rotated shape of the semi-integral abutment in expansion mode of the bridge in medium dense sand (displacements shown to true scale)

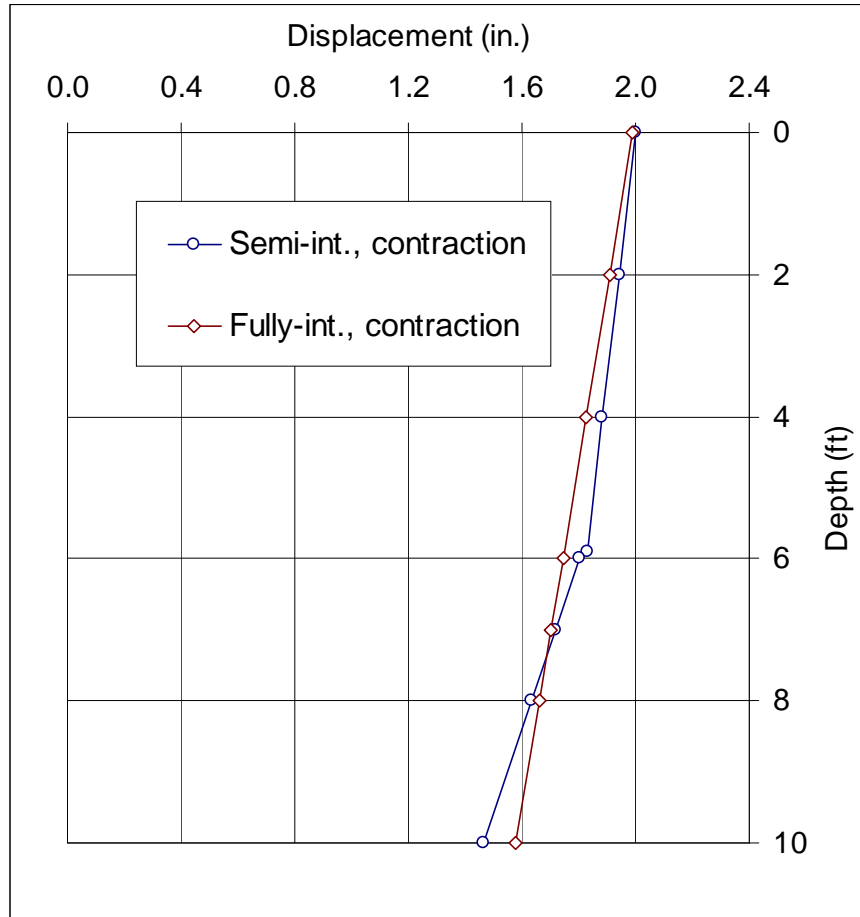


Figure 6.11. Displacement behaviors of fully- and semi-integral bridges in contraction mode of the bridge in medium dense sand

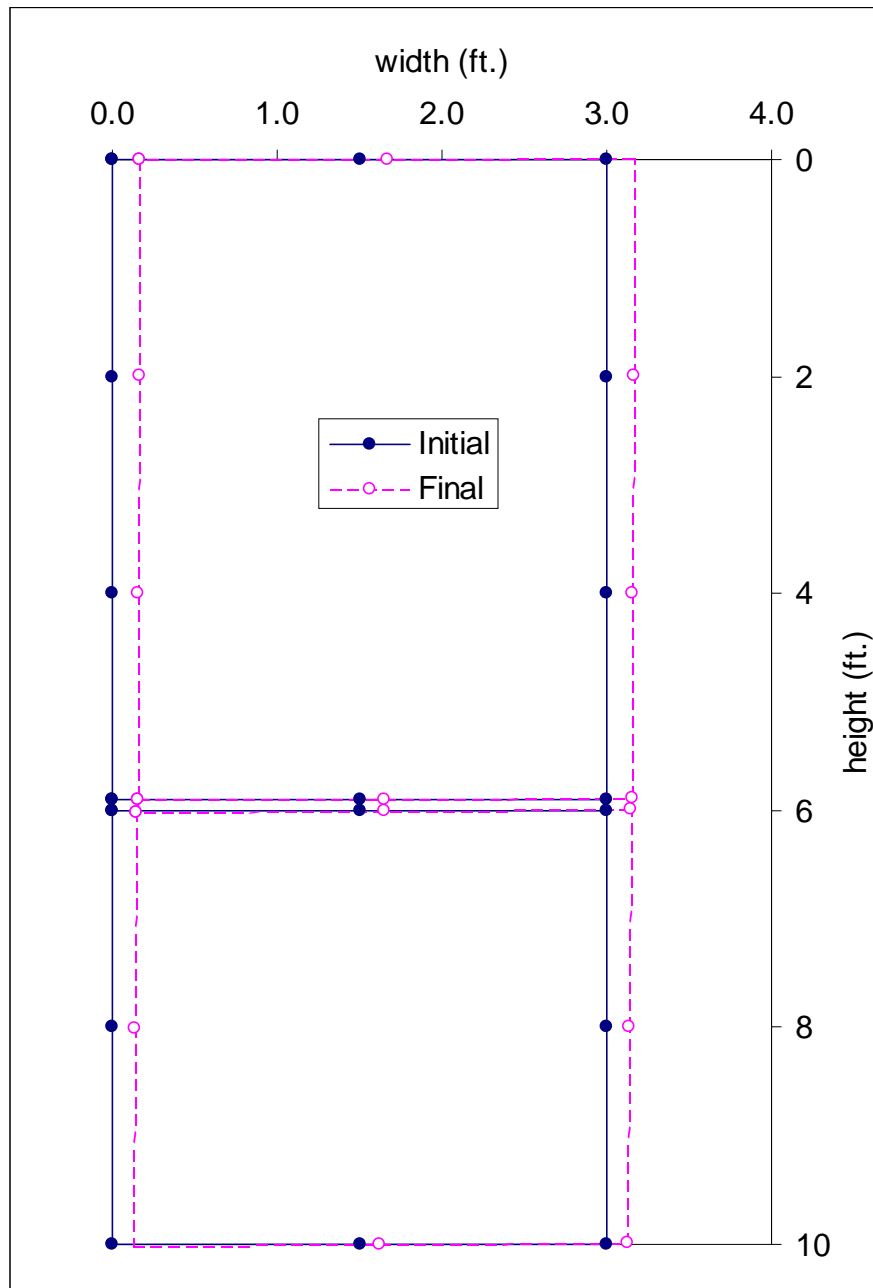


Figure 6.12. Initial and rotated shape of the semi-integral abutment in contraction mode of the bridge in medium dense sand (displacements shown to true scale)