Optimizing Steel Pile Design in Integral Abutment Bridges

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ABSTRACT

Integral abutment bridges are the excellent alternative to conventional bridges by eliminating the joints and reducing leakage between the girder ends and the abutment walls. Typical foundation types in integral abutment bridges include steel HP-driven piles, drilled shafts and precast concrete piles, among which steel HP piles are the most popular in the current bridge practices. Limited studies have been done to investigate the soil-pile-structure interaction steel HP piles to verify the steel HP pile orientations for optimized pile design. In this study, 3D finite element models are developed to investigate the soil-pile-structure interaction mechanism in the integral abutment bridge with steel HP piles oriented in different directions. The load cases include the strength limits and the service limits with the AASHTO HL-93 live load and temperature changes, as well as the extreme event limit under earthquakes. The steel pile structural capacity and deformation are analyzed and evaluated for different pile orientations. Design recommendations are proposed for steel HP pile optimization in integral abutment bridges according to quantitative analyses.

INTRODUCTION

Bridge deterioration is mainly caused by moisture exposure and water leakage through deck joints (Bao et al, 2021). Integral abutment bridges eliminate the deck joint at the girder ends by embedding the girder ends into the abutment end walls as shown in Figure 1, which provides better protection from water and salt damage, reduces the construction and maintenance costs and extends the service life of bridges (Kim et al, 2010; Kunin et al, 1999; Maruri et al, 2004).

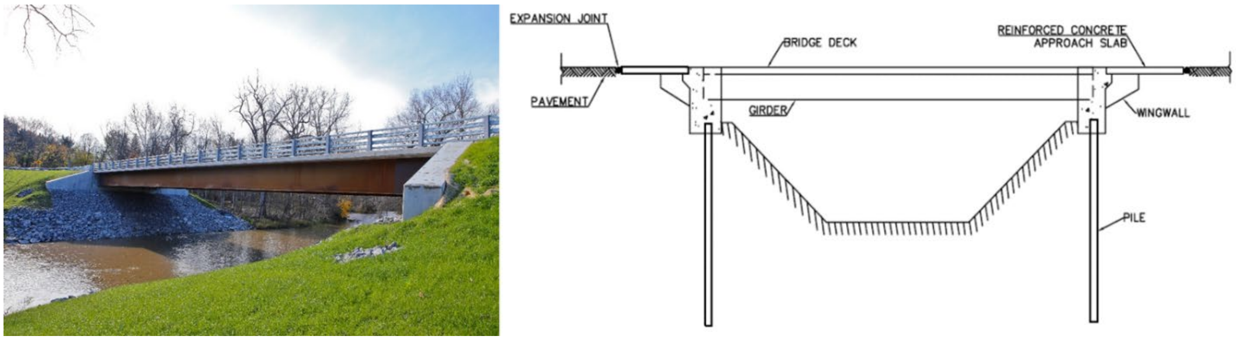

Figure 1: Integral Abutment Bridge

The current practices show forty-two states in the United States have adopted integral abutment bridges as shown in Figure 2. Each State Department of Transportation specifies the design parameters and limitations of integral abutment bridges in Bridge Design Manuals and Specifications. The main reasons why the eight States that currently do not use integral abutment bridges include poor soil conditions in some southern states, such as high-volume expansive clay and soft soils, and extreme cold weather with freezing temperature in Alaska to restrict the movement of integral abutment bridges (Bao et al. 2023).

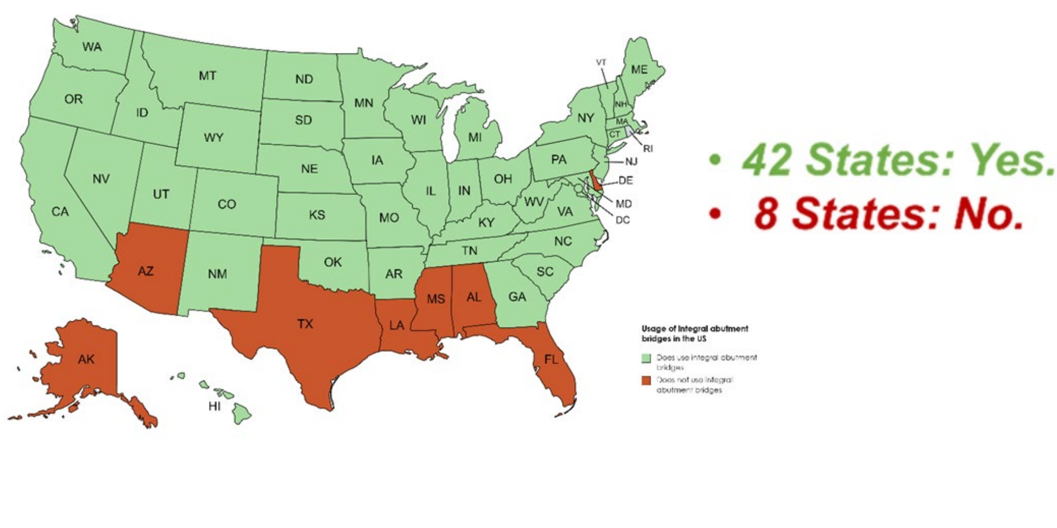

Figure 2: Integral Abutment Bridge Use in the United States (Bao et al, 2023)

The most popular foundation types used in integral abutment bridges are driven piles, drilled shafts and precast piles, as shown in Figure 3. Driven piles are special hot rolled H beams with the same thickness for flange and web. Driven piles have been used as bridge foundations due to their easy installation, easy splicing, easy connection to the superstructure, high bending moment capacity for lateral loads and controllable settlement.

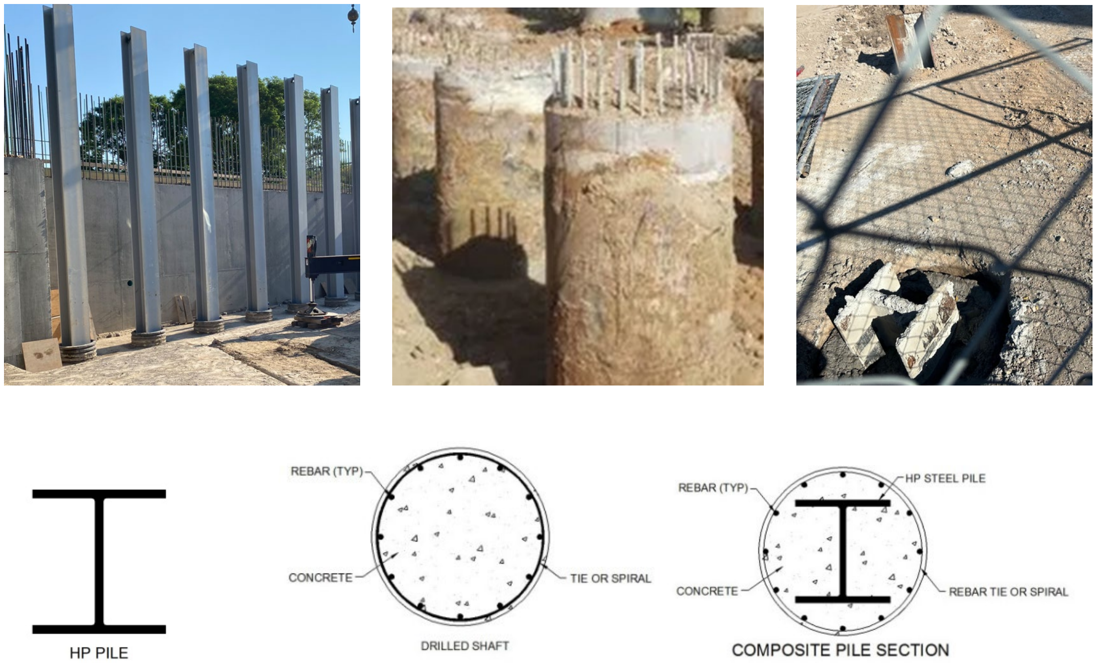

Figure 3: Deep Foundations in Integral Abutment Bridges

Drilled shafts have been a common alternative to driven piles in bridge construction under certain circumstances. Scour effects for bridges over water ways and large lateral loads from extreme events such as earthquake and flooding make drilled shafts suitable for bridge foundations. Moreover, a drilled shaft foundation is the preferred foundation type if a small foundation footprint is needed due to limited space. Composite piles are used when the driven piles alone are not adequate to support the lateral loads in adverse soil conditions. Concrete fill provides much higher buckling resistance to the pile and therefore increases the axial capacity as well as the shear and moment capacity of the pile. Composite piles usually have smaller diameters than the regular drilled shafts. Precast concrete piles are suitable to use as friction piles if driven into sand and clay, or to use as end bearing piles if driven through soft soil to hard strata. Precast piles are the preferred foundation type in marine environments due to their cost and high resistance to corrosion. Precast concrete piles usually are prestressed in order to increase the axial capacity and reduce the cracks.

Steel HP driven piles are the most commonly used foundation type in integral abutment bridges and this study will focus on steel HP driven piles, and investigate the effect of pile orientations on the structural behaviors of the piles. The bridge longitudinal direction refers to the direction parallel to the traffic flow, while the bridge transverse direction is perpendicular to the traffic flow. The HP pile orientations are not consistent among States. Some States make the HP pile orientation with the web parallel to the bridge longitudinal direction, while other States orient the

HP pile web parallel to the bridge transverse direction as shown in Figure 4. No consensus has been made with the HP pile orientation in integral abutment bridge practices across the US.

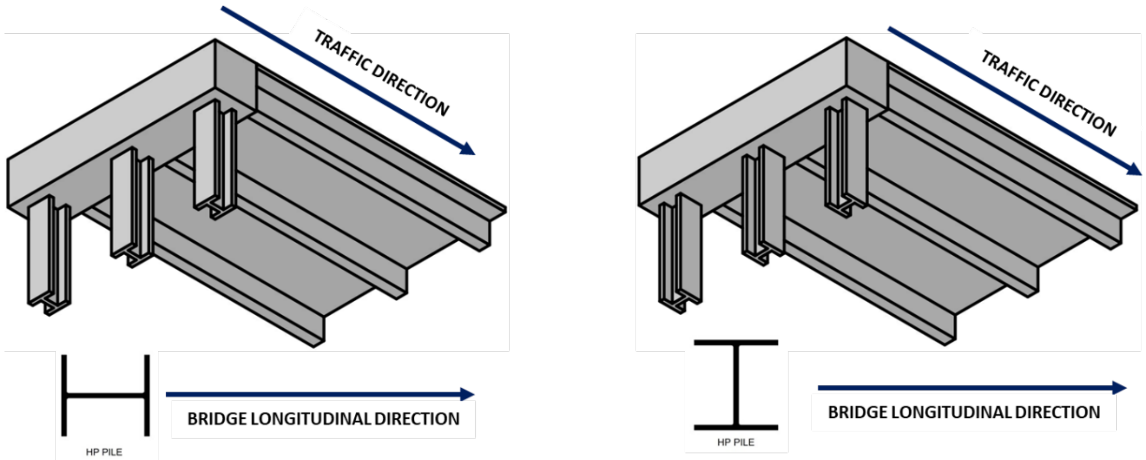

Figure 4: Steel HP Pile Orientations

BRIDGE MODELING AND ANALYSIS

The prototype bridge is a simple span steel girder bridge with fully integral abutments at the girder ends as shown in Figure 5. The simple span bridge is 39.6 meters (130 feet) long and 17.4 meters (57 feet) wide, and the superstructure of bridge consists of a 203 mm (8 inches) thick reinforced concrete deck and 6 I-plate steel girders spaced at 3.05 meters (10 feet) on center. The bridge has no skew and carry 4 lanes of traffic. The bridge foundation uses 6 HP 14x117 steel piles spaced at 3.05 meters at each abutment. The piles are 12.2 meters (40 feet) long.

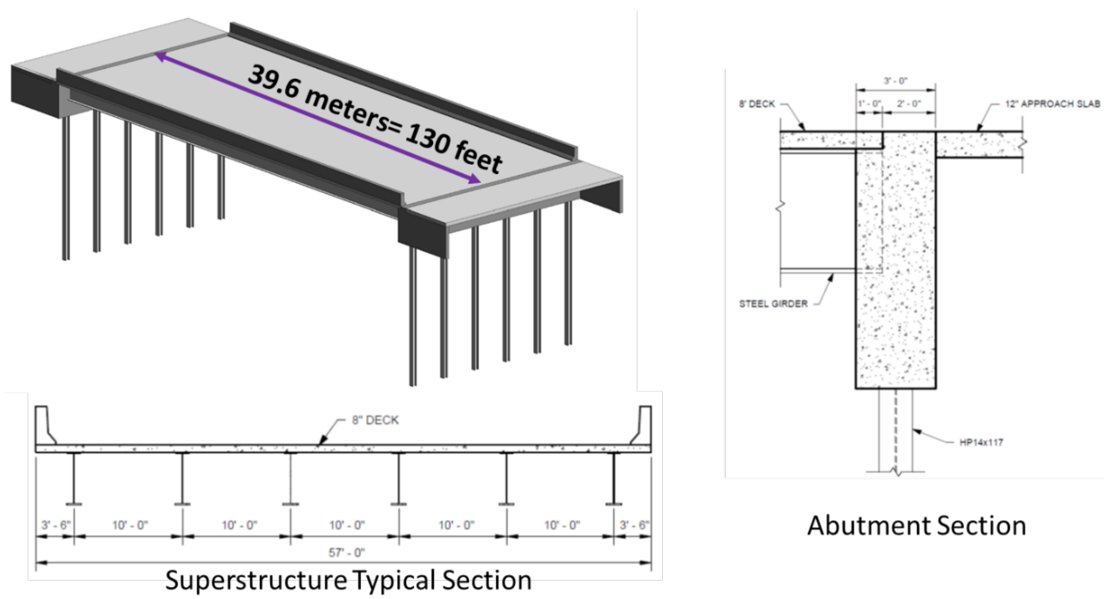

Figure 5: Bridge Model Description

The single-pile behavior is important to understand soil-pile-structure interactions in the bridge. The 3D single pile finite elements models using ANSYS were developed and analyzed as shown in Figure 6 (Bao et al, 2012 and Bao at el. 2013). The lateral loads on the top of pile were applied incrementally, and the shear force and deflection along the pile were recorded. The single pile analysis results were used to determine the soil spring stiffness along the pile in the 3D bridge models. The soil spring stiffness was obtained by dividing the pile lateral force by the corresponding displacement along the pile length. The calculated soil spring stiffness for the lateral force being applied parallel to the HP pile web was 18.6 KN/cm, and the soil spring stiffness for the lateral force parallel to the HP pile flanges was 15.3 KN/cm.

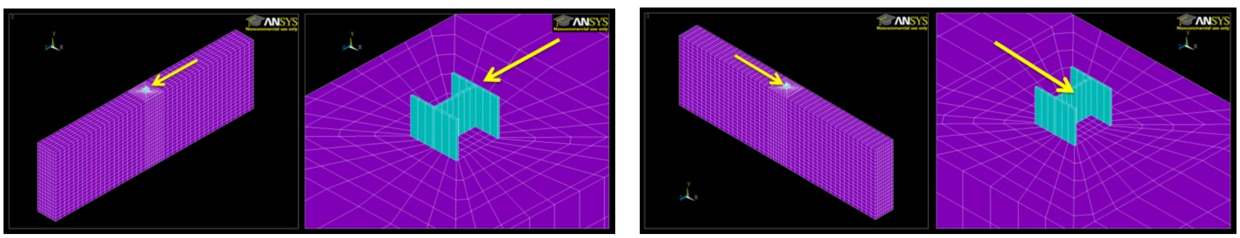

Figure 6: Single Pile Analysis in ANSYS

In the 3D bridge finite element models, linear Winkler springs are employed to model the backfill and foundation soil behavior, and these springs are applied at the back of abutment end-walls and along the piles as shown in Figure 7. The 3D bridge finite element models were developed using the structural analysis software STAAD.Pro. The piles are 12.2 meters (40 feet) long, and are fixed at the bottom ends to represent reaching the bedrock. Standard compacted granular soil backfill was used behind the abutment endwalls.

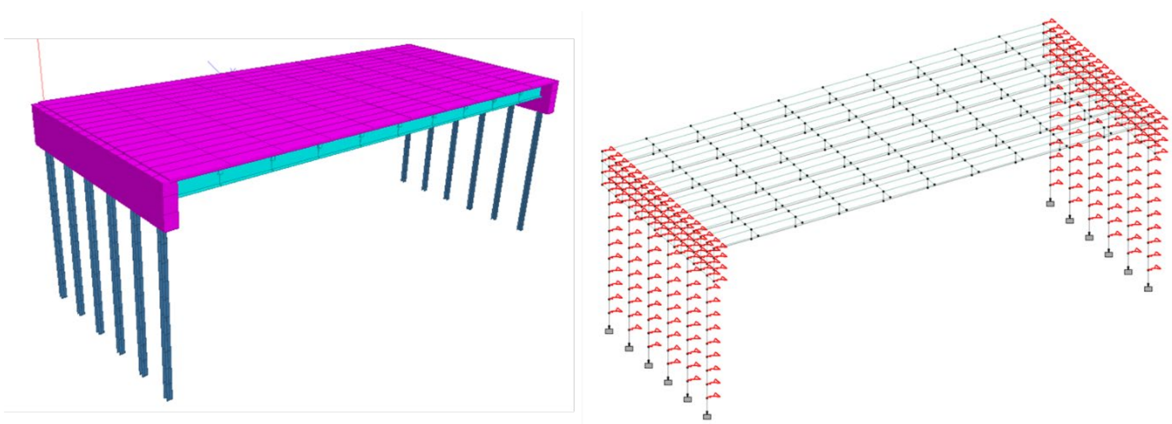

Figure 7: 3D Bridge Finite Element Model

The design live load applied on the bridge was the typical AASHTO HL-93 Live Load. The temperature range used in the analysis was 88°C (160°F). Two seismic load cases were considered according to AASHTO LRFD Bridge Design Specifications. Seismic Case 1: 100% earthquake load in the longitudinal direction + 30% earthquake load in the transverse direction.

Seismic Case 2: 30% earthquake load in the longitudinal direction + 100% earthquake load in the transverse direction. The governing forces were selected according to the load combinations specified in AASHTO LRFD Bridge Design Specifications.

Two geographical locations were selected according to two different seismic zones to investigate the effect of earthquake magnitude on pile orientations and behaviors. One location represented seismic zone 1, and used the seismic response coefficient $C_S = 0.15$, and the other location was selected in seismic zone 3 with the seismic response coefficient $C_S = 0.50$. No liquefaction concerns were considered in the seismic analysis.

RESULTS

Pile displacement is an important indicator of the bridge's performance under temperature loads, live loads and extreme events. Such as earthquake. The pile displacements under temperature and shrinkage, in seismic zone 1 and seismic zone 2 with different pile orientations are shown in Table 1, respectively.

Table 1: Steel HP Pile Top Displacements

Load Combo	HP Pile Web Orientation	Displacement Direction	Abut. Pile Displacement (cm)
Temperature	Longitudinal	Longitudinal	**2.9**
	Transverse	Longitudinal	**3.4**
Seismic Zone 1	Longitudinal	Longitudinal	3.0
		Transverse	**9.5**
	Transverse	Longitudinal	3.7
		Transverse	**5.1**
Seismic Zone 3	Longitudinal	Longitudinal	8.0
		Transverse	**29.9**
	Transverse	Longitudinal	10.8
		Transverse	**14.6**

Bridge piles are subject to significant lateral loads during earthquakes. The lateral loads on pile top will develop bending moments in the piles. Under the combined axial loads and bending moments, the piles are more susceptible to structural failure than the piles mainly in axial compression. Interaction equations for combined axial force and flexure are used to check the structural capacity of piles as shown in Eq.1 and Eq. 2 (AISC, 2017). An interaction number greater than one indicates structural deficiency. The lower value of the interaction number, the higher the pile structural capacity. The larger interaction number from the two seismic load cases governs the design.

If $\frac{Pu}{\emptyset Pn} \geq 0.2$:

$$Interaction\ Number = \frac{Pu}{\emptyset Pn} + \frac{8}{9}\left(\frac{Mux}{\emptyset Mnx} + \frac{Muy}{\emptyset Mny}\right) \leq 1 \qquad \text{Eq. 1}$$

Or, if $\frac{Pu}{\emptyset Pn} < 0.2$:

$$Interaction\ Number = \frac{Pu}{2*\emptyset Pn} + \left(\frac{Mux}{\emptyset Mnx} + \frac{Muy}{\emptyset Mny}\right) \leq 1 \qquad \text{Eq. 2}$$

Where:
$\emptyset$= Resistance factor specified by AASHTO LRFD Bridge Design Specification
P_u= Applied axial load
P_n= Nominal axial resistance
M_{ux}= Applied strong axis moment
M_{nx}= Nominal moment resistance in pile strong axis
M_{uy}=Applied weak axis moment
M_{ny}= Nominal moment resistance in pile weak axis

The interaction numbers of the steel HP piles with different orientations under earthquake loads in seismic zone 1 and zone 3, are listed in Table 2. The HP pile size used in the analysis was HP14x117, and yield strength of steel = 345Mpa (50 ksi). The axial compressive strength $\Phi*P_n$ of the pile HP14x117 was 6049 KN, the strong-axis bending strength $\Phi*M_{nx}$ of the pile was 965 KN-m and the weak-axis bending strength $\Phi*M_{ny}$ of the pile was 515 KN-m.

Table 2: Pile Structural Capacity Check – Interaction Number

Load Combo	HP Pile Web Orientation	Load Case	Pu (KN)	Mux (KN-m)	Muy (KN-m)	Interaction Number
Strength I	Longitudinal	HL-93 Live Load	1358	347	82	0.69
	Transverse	HL-93 Live Load	1358	85	241	**0.72**
Extreme Event: Seismic Zone 1	Longitudinal	Seismic Case 1	831	240	141	0.59
		Seismic Case 2	831	180	416	**1.06**
	Transverse	Seismic Case 1	831	162	164	0.56
		Seismic Case 2	831	486	111	**0.79**
Extreme Event: Seismic Zone 3	Longitudinal	Seismic Case 1	831	453	416	1.28
		Seismic Case 2	831	243	828	**1.93**
	Transverse	Seismic Case 1	831	488	193	0.95
		Seismic Case 2	831	1285	60	**1.52**

If the interaction number is greater than 1.0, increasing the size of piles and/or increasing the number of piles is needed to meet the design requirements until the interaction number is lower than 1.0. From Table 2, we can find that when the HP pile web is parallel to the bridge transverse direction, the interaction numbers are consistently lower than those of the pile web parallel to the bridge longitudinal direction under earthquake loadings.

CONCLUSION

The steel HP pile design can be optimized by selecting the right pile orientation. According to the quantitative analyses, we can draw the following conclusions for the steel HP piles in integral abutment bridges:

- The orientation of steel HP piles affect the pile structural capacity as well as the pile displacement in fully integral abutment bridges.
- For the bridges with the strength limits governing the design where the pile displacements are mainly caused by temperature and shrinkage, it is more economical to orient the steel HP pile web parallel to the bridge longitudinal direction (direction of traffic flow).
- In the seismic zones where the pile governing structural capacity and displacements are caused by extreme seismic events, it is more economical to orient the steel HP pile web parallel to the bridge transverse direction (perpendicular to the direction of traffic flow).

REFERENCES

American Association of State Highway and Transportation Officials, *AASHTO LRFD Bridge Design Specifications*, 7th Edition, 2016

American Institute of Steel Construction, *Steel Construction Manual*, 15th Edition, 2017.

Bao, A., Sichak, C., and Anthony, S. (2023). "A Case Study on Curved Fully Integral Abutment Bridge Thermal Deformation: I-390 over I-490", Paper ID: IBC 23-67, *Proceedings of 2023 International Bridge Conference*, June 12-14, 2023, National Harbor, MD.

Bao, A., Guillaume, C., Satter, C., Moraes, A., Williams, P., Kelly, T. and Guo, Y. (2021). "Testing and Evaluation of Web Bearing Capacity of Corroded Steel Bridge Girders", *Engineering Structures*, Vol 238, July 2021, 112276, ISSN 0141-0296. https://doi.org/10.1016/j.engstruct.2021.112276

Bao, A., Guillaume, C. and Moraes, A. (2019). "Shear Strength of Deteriorated Steel Girders in Multi-Girder Bridges", *Proceedings of the 10th International Structural Engineering and Construction Conference - Interdependence between Structural Engineering and Construction Management*, ISBN: 978-0-9960437-6-2, Chicago, IL, USA, May 20-25, 2019.

Bao, A., Gulasey, M., Guillaume, C., Levitova, N., Moraes, A. and Satter, C. (2018). "Structural Capacity Analysis of Corroded Steel Girder Bridges", *Proceedings of the 3rd International Conference on Civil, Structural and Transportation Engineering*, Niagara Falls, Canada, June 10-12, 2018.

Bao, Y., Lawrence, J., Hopson, V., and Puzio, M. (2014). "Optimization of Bridge Deep Foundation Design in Seismic and Tsunami Zone", *Proceedings of 2014 Structures Congress*, Boston, MA, April 3-5, 2014.

Bao, Y. and Rietz, A. (2013). "Seismic Soil-Structure Interaction in Fully Integral Abutment Bridges with HP Driven Piles", *Proceedings of 7th International Structural Engineering and Construction Conference*, Honolulu, HI, June 18-23, 2013.

Bao, Y. and Rietz, A. (2012). "Numerical Modeling of Dynamic Soil-Structure Interaction in Bridges with HP Driven Piles", *Proceedings of DFI 37th Annual Conference on Deep Foundations*, Houston, TX, October 16-19, 2012.

Civjan, S. A., Kalayci, E., Quinn, B. H., Breña, S. F. and Allen, C. A. (2013). "Observed integral abutment bridge substructure response", *Engineering Structures*. Vol. 56, p.p.1177-1191.

Fennema J.L., Laman J.A. and Linzell D.G. (2005). "Predicted and measured response of an integral abutment bridge", *Journal of Bridge Engineering*, Vol.10, Issue 6, p.p. 666–77.

Hoffman J. and Phares B. (2014). "Thermal load design philosophies for horizontally curved girder bridges with integral abutments", *Journal of Bridge Engineering*, Vol. 19, Issue 5.

Kalayci, E., Civjan, S.A., Breña, S.F. (2012). "Parametric study on the thermal response of curved integral abutment bridges" *Engineering Structures*, Vol. 43, 129-138, October 2012.

Kim, W., Laman, J.A. (2010). "Integral abutment bridge response under thermal loading", *Engineering Structures*, Vol. 32, Issue 6, p.p.1495–1508.

Kunin, J., and Alampalli, S. (1999). "Integral Abutment Bridges: Current Practice in the United States and Canada," Special Report 132, Transportation Research and Development Bureau, New York State Department of Transportation, Albany, New York.

Maruri, R., and Petro, S. (2004) "Integral Abutments and Jointless Bridges 2004 Survey Summary", Federal Highway Administration and Constructed Facilities Center at West Virginia University, Morgantown, West Virginia.

New York State Department of Transportation Bridge Manual, (2021).