Numerical Modeling of Dynamic Soil-Structure Interaction in Bridges with HP Driven Piles

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HP-Pile foundations are the most favorable type of foundations for bridges because of their constructability, versatility with regard to subsoil conditions, and settlement controllability. For many years, bridge engineers have puzzled over the most economical way to orient HP-Piles: Should the strong axis be oriented in the longitudinal direction or in the transverse direction? The accurate design of foundations may considerably reduce construction costs. In order to answer this question, 3-D finite element models will be set up to analyze the effects of pile orientation on bridge behavior. Because seismic loading usually controls the structural design in seismic zones, it is important to investigate the effects of pile orientation under such loading. HP-Piles are designed conservatively due to the uncertainty of the dynamic soil-structure interaction during earthquakes. For the bridge substructure, the soil's stiffness plays an important role in load distribution as the soil and piles act as a combined system to resist the seismic loading. The dynamic soil-structure interaction mechanisms of bridges in both the longitudinal and the transverse directions will be investigated through the use of 3-D finite element models. The numerical models will realistically simulate the soil-pile-abutment-wingwall-superstructure system subjected to seismic loads. Nonlinear soil springs will be employed to model the non-elastic soil behavior. The analysis will provide theoretical support to the design practice.

KEYWORDS: HP driven piles, finite element, pile orientation, soil-structure interaction

Introduction

As sustainability has asserted itself in the public's eye, bridge professionals have rushed to develop criteria for sustainable bridges. The three main categories that define and distinguish sustainable bridges are: lower energy input, increased durability, and simplified deconstruction. By optimizing the structural members, the engineer is able to reduce the material quantities for the bridge, effectively reducing the energy input for the bridge (Hunt; Whittemore). A deeper understanding of soil-foundation-structure mechanism will facilitate sustainable bridge design by lowering energy input and increasing the service life of bridges (Rietz et al.).

Due to the lack of knowledge on soil-structure interaction under earthquake loading, the real world design procedures are kept simple and conservative. HP steel pile foundations are the most favorable type of foundations for bridges because of their easy installation and controllable settlement. It has been proven that soil-structure interaction is beneficial to the behavior of structural systems (Li et al.). The soil's stiffness has a significant effect on load distribution when the soil, piles, abutment, and superstructure act as a combined system to resist the loading on the bridge. While some researchers have investigated the soil-structure interaction in the bridge longitudinal direction using various approaches, the interaction mechanism in the bridge transverse direction still remains unknown. There are more uncertainties in the bridge transverse direction because of the unconfined embankment where the mobilization of passive earth pressure is questionable. In this paper, the dynamic soil-structure interaction mechanisms of bridges in both the longitudinal and the transverse directions for a simple span bridge will be investigated. The analyses are performed using nonlinear finite element models in the computer program ANSYS (Bonić et al.). The numerical models will realistically simulate the soil-pile-abutment-wingwall-superstructure system. The effect of HP pile orientation on the bridge seismic behavior will also be investigated. Nonlinear Winkler springs will be employed to model the non-elastic backfill soil behavior, where the stiffness of springs is a function of the displacement or the rotation of the abutment wall. The analyses will provide theoretical support to the design practice.

The power of the finite element method lies in its versatility and ability to solve various physical problems. The analyzed domain can have arbitrary shapes, loads, and boundary conditions and the mesh can mix elements of different types, shapes, and material properties. Another attractive feature of the finite element method is the close physical resemblance between the actual structure and its finite element model (Bao). In this paper, 3D numerical models for the entire bridge and the abutment are set up respectively to explore the dynamic responses in simple span bridges. Contact elements are included in the numerical models to simulate the realistic contact surface between the concrete abutment walls and the soil embankment. A 3-D finite element analysis of a single pile is performed to determine the stiffness of the nonlinear Winkler soil springs.

Single Pile Analysis

HP steel piles are special hot rolled H beams with the same thickness for flange and web. The advantages of HP piles include easy installation, easy splicing and easy connection to the superstructure, high bending moment capacity for lateral loads, and high resistance to compression. HP piles are oriented such that the strong axis is parallel to the flanges and the weak axis perpendicular to the flanges. The purpose of the single pile analysis is to obtain the lateral soil spring stiffness along the pile subjected to lateral forces. Two 3-D finite element models were set up to investigate the soil-HP pile interaction in both the strong axis and the weak axis directions. In Model A, the lateral force is applied in the HP pile strong axis direction, as shown in Figure 1, and in Model B, the lateral force is applied in the HP pile weak axis direction, as shown in Figure 2. The dimensions of the soil domain are 66 ft (length) × 6 ft (width) × 20 ft (deep). Drucker-Prager (DP) plastic soil constitutive model is used in the finite element analysis, and the soil model parameters are listed in Table 1. The size of the HP pile used in the analysis is HP14×89, and key geometric features are listed in Table 2.

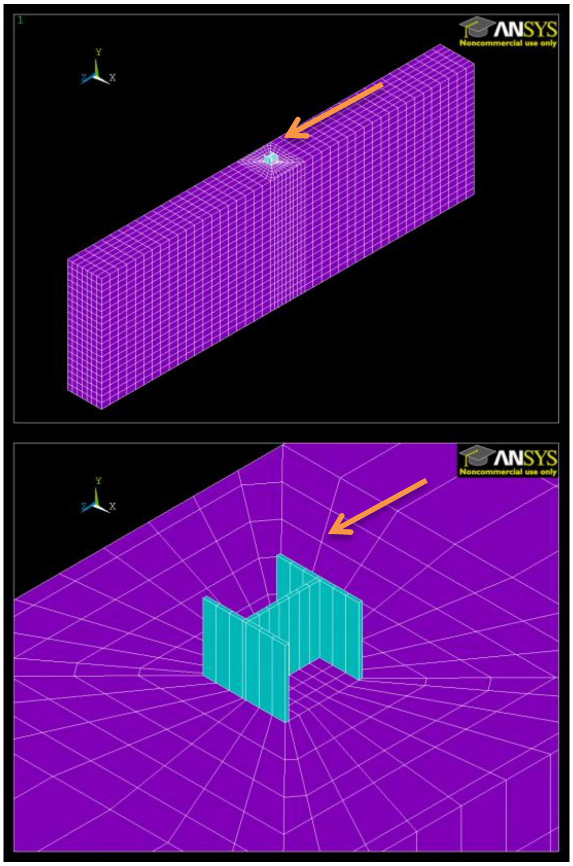

Figure 1: Model A - Lateral force being applied in the strong axis of the HP pile

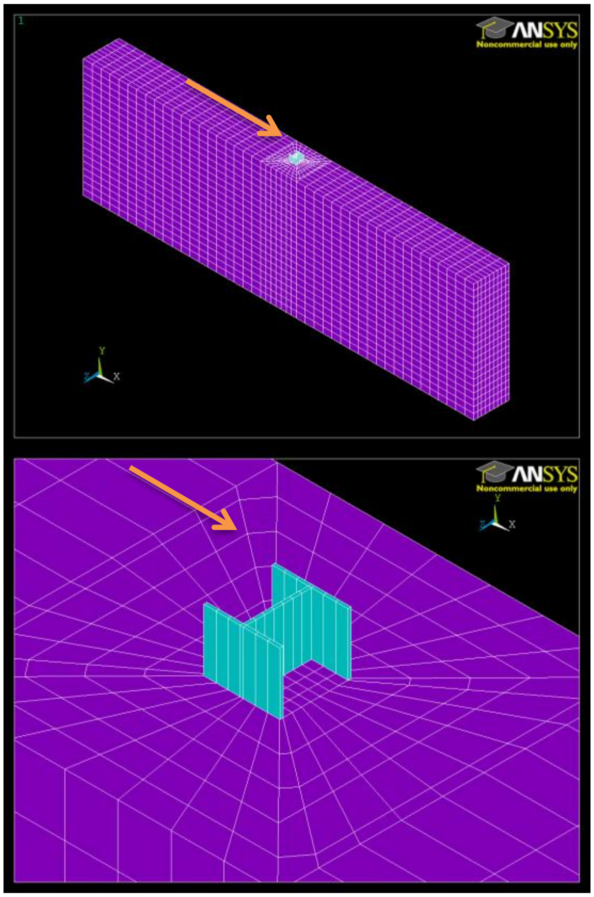

Figure 2: Model B- Lateral force being applied in the weak axis of the HP pile

Table 1: Soil Model Parameters

Soil Properties					
Soil Model	Young's Modulus, E	Poisson's Ratio, ν	Cohesion, C	Friction Angle, ϕ	Dilatancy Angle, θ
	kip/in.^{2}		kip/in.^{2}	Degrees	Degrees
Linear	10	0.3			
Nonlinear	10	0.3	0.003	30	10

For Model A, the pile is 20 feet long, and a lateral force of 4.2 kips is applied to the top of the HP pile, with the pile strong axis parallel to the direction of the force. The pile shear force and deflection along the pile height are shown in Figure 3 and Figure 4, respectively. The equivalent soil spring stiffness along the pile is illustrated in Figure 5.

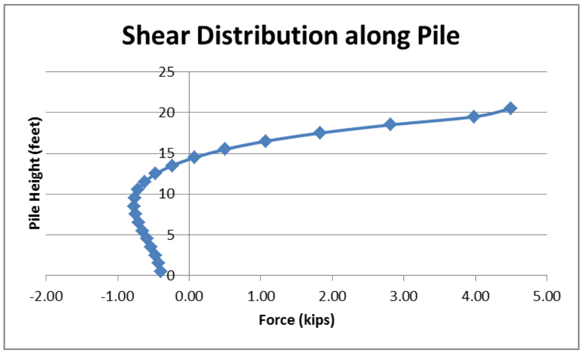

Figure 3: Model A – Pile Shear Force

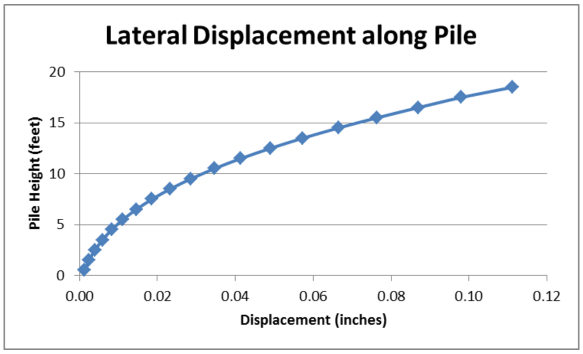

Figure 4: Model A – Pile Deflection

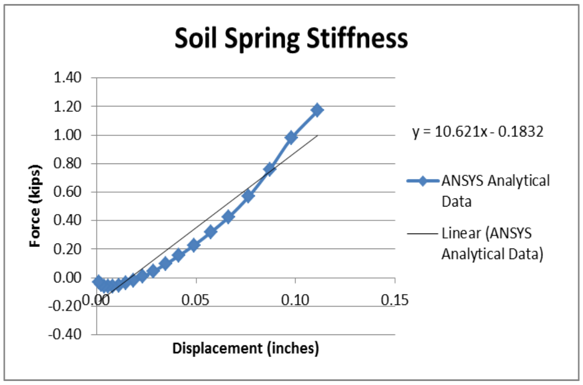

Figure 5: Model A – Equivalent Soil Spring Stiffness

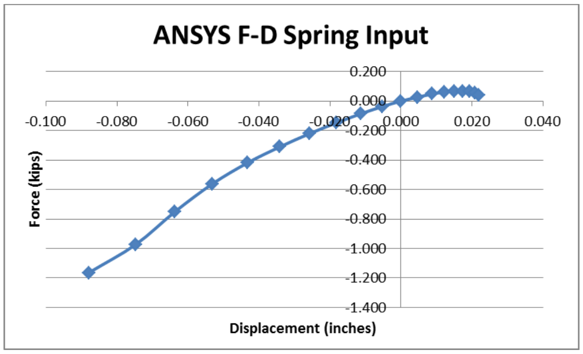

Figure 6: Model A – ANSYS Model Spring Input

Table 2: HP14×89 Steel Pile Geometry

Shape	Area, A	Depth, d	Web	Flange		Nominal Weight	Axis X-X				Axis Y-Y			
			Thickness, t_w	Width, b_f	Thickness, t_f		I	S	r	Z	I	S	r	Z
	in.^{2}	in.	in.	in.	in.	lb/ft	in.^{4}	in.^{3}	in.	in.^{3}	in.^{4}	in.^{3}	in.	in.^{3}
HP14 x 89	26.1	13.8	0.615	14.7	0.615	89	904	131	5.88	146	326	44.6	3.53	67.7

In Figure 5, the soil spring stiffness was obtained by dividing the soil lateral force by the pile deflection along the pile height. The equivalent soil spring stiffness was calculated by linearizing the soil spring stiffness curve. From Figure 5, the equivalent soil spring stiffness for lateral force being applied parallel to the HP pile strong axis is 10.62 kip/in. Figure 6 shows the force-deflection curve input for the nonlinear Winkler springs used to simulate the soil interaction with the HP pile foundations.

Model B was set up to investigate the soil spring stiffness in the HP pile weak axis direction. In Model B, the pile is 20 feet long, and a lateral force of 4.2 kips parallel to the pile weak axis is applied to the top of the HP pile. The pile shear force and deflection along the pile are shown in Figure 7 and Figure 8, respectively. The equivalent soil spring stiffness along the pile is plotted in Figure 9.

From Figure 9, the equivalent soil spring stiffness for the lateral force being applied parallel to the HP pile weak axis is 8.75 kip/in. By comparing Figure 9 with Figure 5, we find that the HP pile orientation does have an effect on the soil spring stiffness. Figure 10 shows the force-deflection curve input for the nonlinear Winkler springs used to simulate the soil interaction with the HP pile foundations in the direction of the pile weak axis.

According to the single pile analysis, we found that for the HP driven pile, the equivalent soil spring stiffness of the pile strong axis is 21% higher than that of the pile weak axis. The higher soil spring stiffness is due to lower deflection of the pile and higher level of soil mobilization in the passive soil pressure zone.

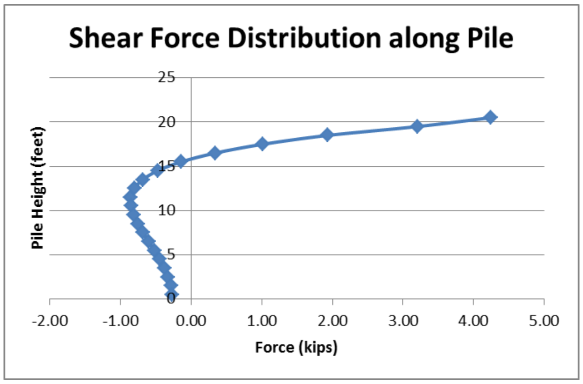

Figure 7: Model B – Pile Shear Force

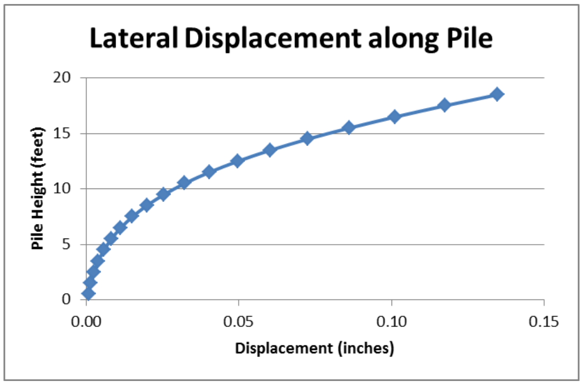

Figure 8: Model B – Pile Deflection

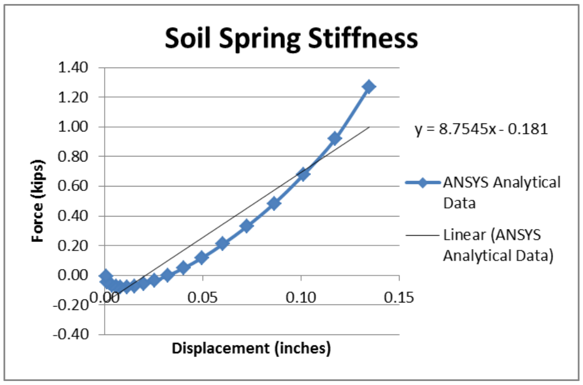

Figure 9: Model B – Equivalent Soil Spring Stiffness

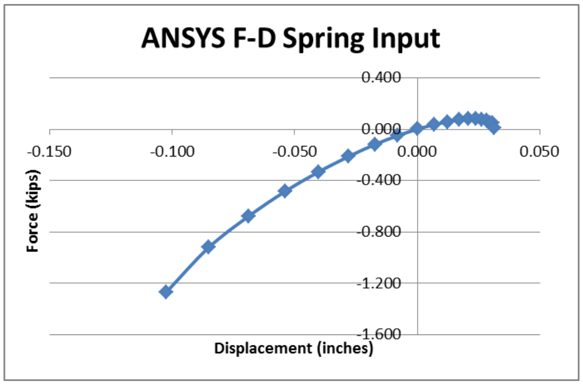

Figure 10: Model B – ANSYS Model Spring Input

Simple Span Bridge Analysis

The simple span bridge has a span length of 180 feet. The bridge is 40 feet wide and carries three lanes traffic. The superstructure of the bridge consists of an 8 inch thick cast-in-place concrete deck and 5 I-plate girders. The integral abutment includes end wall, wingwalls, pile cap and HP driven piles. The end wall is 2 feet wide and 12 feet deep, each wingwall is 1 foot thick and 15 feet long and the pile cap is 2 feet wide and 3 feet deep. The bridge foundation uses 5 HP14×89 steel piles spaced 9 feet on center in each abutment and the piles are 50 feet long. The simple span bridge finite element model is shown in Figure 11. Nonlinear Winkler springs are employed to model the non-elastic backfill soil behavior, and these springs are applied along the piles and at the boundaries of soil domains as well to simulate realistic boundary conditions. Contact elements are included in the numerical models to simulate the realistic contact surface between the concrete abutment walls and the soil embankment. Four groups of numerical models are set up to explore dynamic responses in the simple span bridge as listed in Table 3. The bridge longitudinal direction refers to the direction parallel to the flow of traffic, and bridge transverse refers to the direction perpendicular to the flow of traffic. The total service dead load on the bridge is 1500 kips and AASHTO HL-93 live loads are applied to all the bridge models. Two seismic load cases are considered according to AASHTO LRFD Bridge Design Specifications. Case 1: 100% earthquake load in the longitudinal direction + 30% earthquake load in the transverse direction. Case 2: 30% earthquake load in the longitudinal direction + 100% earthquake load in the transverse direction. The 100% earthquake load is determined by multiplying the bridge total dead load by a factor of 0.30. In the numerical simulation, 100% earthquake load is input as a 450-kip lateral load and 30% earthquake load is input as a 135-kip lateral load. AASHTO LRFD load combinations are used to identify the governing load case for the HP pile deign. The effect of HP pile orientation on the bridge dynamic behavior is investigated. The material properties for the simple span bridge models are listed in Table 4.

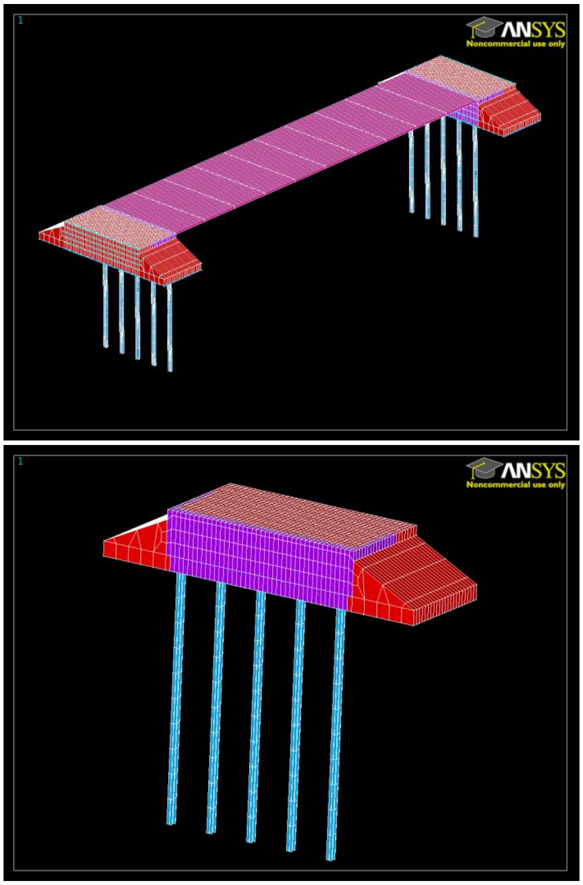

Figure 11: 3D Simple Span Bridge Finite Element Model in ANSYS

For each bridge model, the pile deflection, shear force and bending moment in both longitudinal direction and transverse direction are plotted are compared.

Table 3: Simple Span Bridge Numerical Model Descriptions

	Vertical Loads		Earthquake Load		HP Pile Strong Axis Orientation
	Dead Load	Live Load	Longitudinal	Transverse	
Model B1	1500 kips	HL-93	450 kips	135 kips	Longitudinal
Model B2	1500 kips	HL-93	450 kips	135 kips	Transverse
Model B3	1500 kips	HL-93	135 kips	450 kips	Longitudinal
Model B4	1500 kips	HL-93	135 kips	450 kips	Transverse

Table 4: Material Properties for Simple Span Bridge Models

Component	HP Piles		Endwalls, wingwalls, and pile caps		Backfill Soil				
Material	Steel		Concrete		Soil (Drucker Prager Soil Model)				
Material Properties	Elastic Modulus (ksi)	Poisson's Ratio	Elastic Modulus (ksi)	Poisson's Ratio	Elastic Modulus (ksi)	Poisson's Ratio	Cohesion (ksi)	Friction Angle (degrees)	Dilatancy Angle (degrees)
	29000	0.3	4000	0.2	10	0.3	0.003	30	10

Pile deflection is an important index to evaluate the pile's performance under earthquake. The pile deflections in the bridge longitudinal direction and transverse direction for Model B1 through Model B4 are plotted in Figure 12 and Figure 13, respectively. The maximum pile top displacement for each model is listed in Table 5.

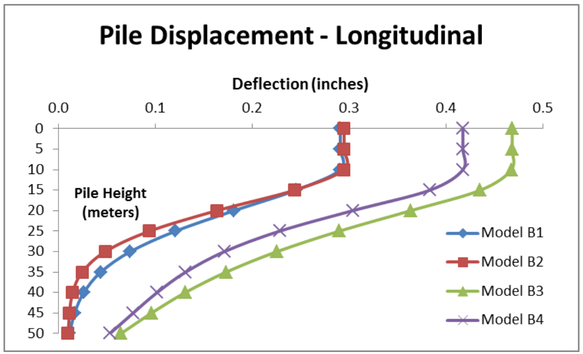

Figure 12: Pile Deflection-Longitudinal

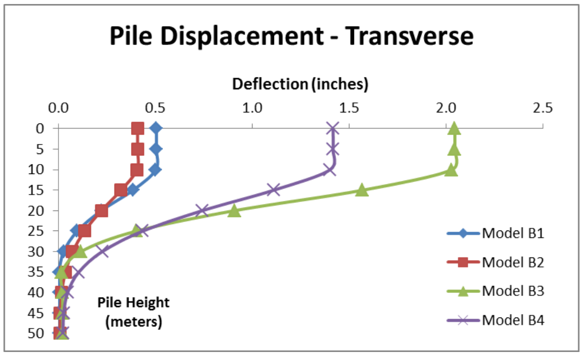

Figure 13: Pile Deflection-Transverse

Table 5: Pile Top Lateral Displacement

Model Number	Pile Top Lateral Displacement (inches)	
	Longitudinal Direction	Transverse Direction
B1	0.308	0.482
B2	0.299	0.384
B3	0.364	1.83
B4	0.363	1.312

Table 5 shows that pile orientation has a significant effect on the pile displacement in the bridge transverse direction. By comparing Model B1 with B2, both of which are subjected to the same loading, the difference in pile displacements in the longitudinal direction is only 3%, whereas the difference in the transverse direction is 26%. Model B2 has 26% less transverse displacement than Model B1. The same trend is shown in Model B3 and B4. Model B4 has about 40% less transverse displacement than Model B3, while the displacements in the longitudinal direction are almost identical. The results clearly indicate that orienting the HP strong axis in the bridge transverse direction can significantly reduce the bridge displacement under seismic loads.

The pile shear forces in the bridge longitudinal direction and the transverse direction are shown in Figure 14 and Figure 15, respectively. Figure 16 and Figure 17 show the moment along the pile in the bridge longitudinal direction and transverse direction, respectively.

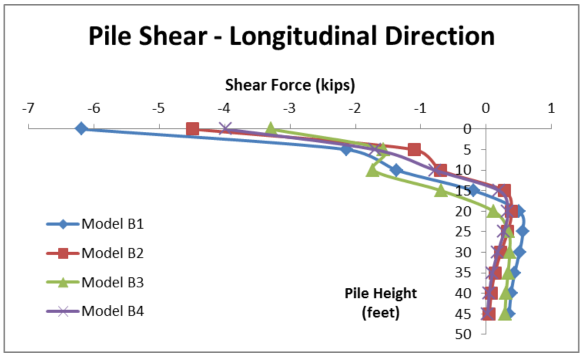

Figure 14: Pile Shear Force-Longitudinal

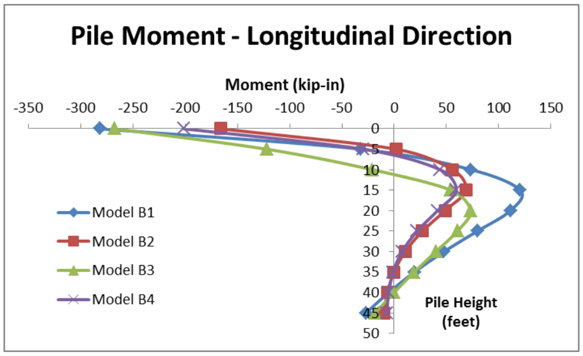

Figure 16: Pile Moment-Longitudinal

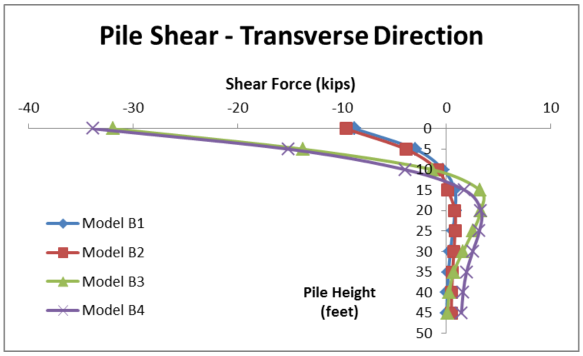

Figure 15: Pile Shear Force-Transverse

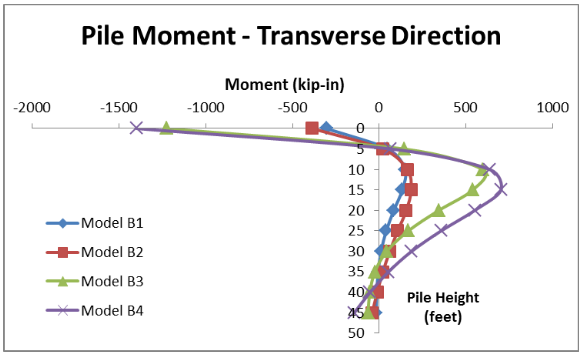

Figure 17: Pile Moment-Transverse

Table 6: Seismic Force Distribution for Simple Span Bridge Models

	Longitudinal Direction					Transverse Direction				
Model Number	Earthquake Load	Pile Load		Soil Load		Earthquake Load	Pile Load		Soil Load	
	kips	kips	%	kips	%	kips	kips	%	kips	%
B1	450	46.09	10.24	403.92	89.76	135	56.92	42.16	78.08	57.84
B2	450	29.89	6.64	420.11	93.36	135	66.33	49.13	68.67	50.87
B3	135	25.16	18.64	109.84	81.36	450	238.81	53.07	211.19	46.93
B4	135	24.26	17.97	110.74	82.03	450	216.17	48.04	233.83	51.96

Shear force distribution is critical to understand soil-structure interaction. According to Figure 14 and Figure 15, the seismic force distribution for Model 1 through Model 4 is summarized in Table 6. From Table 6, we find that the backfill soil plays an important role in seismic load distribution in both the longitudinal and transverse directions. In the longitudinal direction, the backfill soil takes roughly 80% to 90% of the total seismic load. In the transverse direction, the soil takes roughly 50% of the seismic for all four of the models. The HP piles have more effect on carrying loads in the transverse direction. The piles carry about 50% of the seismic load in the transverse direction, whereas in the longitudinal direction, the piles take less than 20% of the seismic load. The piles play a more important role in the transverse direction than in the longitudinal direction.

From the ANSYS analysis, the maximum factored axial load on each pile caused by vertical loads is 226 kips. For each load case, the interaction of the combined axial load and bi-axial bending moment of the pile is checked according to AASHTO LRFD requirement. For the HP14×89 pile, the design axial load capacity is 708 kips, and design bending moment capacity about the strong axis is 6264 kip-in and design bending moment capacity about the weak axis is 3084 kip-in. The maximum moment demands are obtained from Figure 16 and 17. The interaction of combined axial and flexure for each model is listed in Table 7.

Table 7: Combined Axial and Flexure Interaction for HP Pile

Model	HP Pile Strong Axis Orientation	Axial Load Pu (kip)	Moment-Strong Axis Mux (kip-in)	Moment-Weak Axis Muy (kip-in)	Axial Capacity ΦPn (kip)	Moment Capacity ΦMnx (kip-in)	Moment Capacity ΦMny (kip-in)	Interaction Number
B1	Longitudinal	226	375	299	708	6264	3084	0.32
B2	Transverse	226	394	211	708	6264	3084	0.29
B3	Longitudinal	226	294	1176	708	6264	3084	0.59
B4	Transverse	226	1404	212	708	6264	3084	0.45

An interaction number being greater than one indicates that the pile fails structurally. For the same loading conditions, the interaction number of Model B2 is 10% lower than that of Model B1, and the interaction number of Model B4 is 31% lower than that of Model B3. Therefore, when the HP pile strong axis is oriented in the transverse direction, the piles have a more favorable interaction number than when the piles are oriented in the longitudinal direction.

Conclusions

Our research findings show that:

1. The HP pile orientation has a significant effect on soil spring stiffness along the pile. The soil spring stiffness in the pile strong axis is higher than that in the pile weak axis. From the analysis, the soil spring stiffness in the pile strong axis is 21% higher than that in the pile weak axis.
2. Backfill soil plays an important role in seismic load distribution in the bridge longitudinal direction as well as in the transverse direction. It is beneficial to consider soil-structure interaction to facilitate sustainable design of HP pile foundation in bridges.
3. Orienting the HP pile strong axis to the bridge transverse direction significantly reduces the pile displacement in the transverse direction with minor effect on the pile displacement in the longitudinal direction. Orienting the HP pile strong axis to the bridge transverse direction benefits the overall performance of the bridge under earthquakes.
4. According to the combined axial load and flexure interaction check, it is more economical to orient the pile strong axis parallel to the bridge transverse direction.

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