SEISMIC SOIL-STRUCTURE INTERACTION IN FULLY INTEGRAL ABUTMENT BRIDGES WITH HP STEEL PILES

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This paper presents the results of 3D nonlinear finite element modeling of seismic soil-foundation-structure interaction in fully integral abutment bridges using HP steel piles as bridge foundations. The soil's stiffness has a significant effect on load distribution when the soil, HP piles, abutment, and superstructure act as a combined system to resist seismic forces on the bridge. Due to the lack of knowledge on dynamic soil-structure interaction during earthquakes, the real world design procedures are kept simple and conservative. A deeper understanding of soil-foundation-structure interaction mechanism will facilitate sustainable bridge design by optimizing the sizes of structural members and increasing the service life of bridges. In this paper, the seismic soil-structure interaction mechanisms are investigated for the bridge longitudinal direction as well as for the bridge transverse direction. Both simple span and two-span bridges are analyzed using the finite element program ANSYS. The research findings will provide the theoretical support to sustainable bridge design by optimizing the size and orientation of HP steel piles in fully integral abutment bridges.

Keywords: integral bridge, finite element, soil-structure interaction, HP piles

1. Introduction

A fully integral abutment bridge is a structure where the superstructure is directly connected to the substructure. The superstructure and substructure move into and away from the backfill when subject to lateral loading. Integral abutment bridges are more economical over their life span due to less construction cost and easier maintenance. Soil-foundation-structure interaction is beneficial to the behavior of integral abutment bridges subjected to seismic forces. HP steel piles are special hot rolled H beams with the same thickness for flange and web. HP piles have many advantages over drilled shafts, including: easy installation, easy splicing, easy connection to the superstructure, high bending moment capacity for lateral loads, high resistance to compression and controllable settlement. It has been proven that soil-structure interaction is beneficial to the behavior of structural systems (Bao *et al* 2012, David *et al* 2011, Jeremic *et al* 2004 and Li *et al* 2004). 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. Due to the lack of knowledge on dynamic soil-structure interaction during earthquake loadings, the real world design procedures are kept simple and conservative. A deeper understanding of soil-foundation-structure interaction mechanism is necessary to quantify the soil resistance and facilitate sustainable bridge design by reducing the structural member sizes and increasing the service life of bridges. While some researchers have investigated the soil-structure interaction in the bridge longitudinal direction using various approaches (Kwon *et al* 2006 and Saadehvaziri *et al* 2000), the interaction mechanism in the bridge transverse direction still remains unknown (Bao *et al* 2012 and Rietz *et al* 2012). 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 are investigated. The 3D numerical models realistically simulate the soil-substructure-superstructure bridge system.

Simple span bridges and two-span bridges account for the majority of highway bridges in the United States due to their cost and adequacy to carry two-way highway traffic. Optimizing the design of simple span and two-span bridges is critical to reducing the total cost of infrastructure. In this paper, both simple span and two-span bridges are analyzed using the finite element program ANSYS. The research findings will provide recommendations for sustainable design of bridges in terms of optimizing the size and orientation of HP steel piles.

Because performing full scale physical experiments on bridges is expensive and sometimes impossible, finite element modeling has been adopted in recent decades to conduct research on large scale structures including bridges due to the rapid growth of computing hardware and software. 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 and Sture 2010 and 2011). In this paper, 3D finite element models for the simple span and the two-span bridges are set up to explore the dynamic responses of these bridge types subjected to seismic loads.

2. Simple Span Bridge Analysis

2.1 *Model Description*

The simple span bridge has a span length of 45.7 meters, is 12.5 meters wide, and carries three lanes of traffic. The bridge has no skew. The superstructure of the bridge consists of a 203 mm thick cast-in-place concrete deck and 5 I-plate girders spaced at 2.8 meters. The integral abutment includes the end wall, wingwalls, pile cap and HP driven piles. The end wall is 0.6 meters wide and 3.7 meters deep, each wingwall is 0.3 meters thick and 4.6 meters long and the pile cap is 0.6 meters wide and 0.9 meters deep. The bridge foundation uses 5 HP12×74 steel piles (AISC 2011) spaced every 2.8 meters on center in each abutment and the piles are 15.2 meters long. The finite element model of the simple span bridge is shown in Figure 1. 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 to simulate realistic boundary conditions. Drucker-Prager (DP) soil constitutive model is used to model the granular soil embankment in the finite element analysis. Contact elements are included in the numerical models to simulate the realistic contact surface between the concrete abutment walls and the soil embankment. The total service dead load on the bridge is 5560 KN and an AASHTO (American Association of State Highway and Transportation Officials) HL-93 live load is also applied to the bridge models. Two seismic load cases are considered according to AASHTO LRFD Bridge Design Specifications: 100% earthquake load in the longitudinal direction + 30% earthquake load in the transverse direction and 30% earthquake load in the longitudinal direction + 100% earthquake load in the transverse direction. 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 100% earthquake load is determined by multiplying the bridge dead load by the seismic response coefficient 0.3. In the numerical experiments, 100% earthquake load is input as a 1668 KN lateral load and 30% earthquake load is input as a 500 KN lateral load. Four groups of numerical models are set up to explore the dynamic responses in the simple span bridge as listed in Table 1. AASHTO LRFD load combinations are used to identify the governing load case for the HP pile design [1]. 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 2. Winkler springs are employed to simulate the soil lateral resistance along the piles as well as at the soil embankment boundaries.

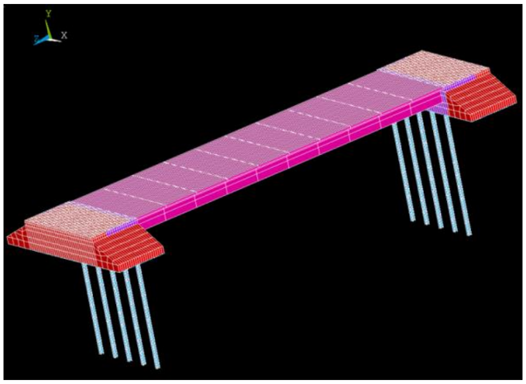

Figure 1. 3-D Simple Span Bridge Model in ANSYS

Table 1: Simple Span Bridge Numerical Model Description

Model Number	Earthquake Load (KN)		HP Pile Strong Axis Orientation
	Longitudinal	Transverse	
B1	1668	500	Longitudinal
B2	1668	500	Transverse
B3	500	1668	Longitudinal
B4	500	1668	Transverse

Table 2: Material Properties for Bridge Finite Element Models

Component	Material	Elastic Modulus (KN/mm^2)	Poisson's Ratio
HP Piles	Steel	200	0.3
Abutment Walls	Concrete	27.6	0.2
Backfill Soil	Soil	0.034	0.4

Soil Drucker-Prager Model		
Cohesion (KN/mm^2)	Friction Angle (degree)	Dilatancy Angle (degree)
0.003	30	10

2.2 *Results*

The maximum pile top displacement for each simple span bridge model is listed in Table 3 and the seismic force distribution for each model is listed in Table 4. Figure 2 and Figure 3 show the bending moments in the piles of the four models.

Moving load analysis is employed in the bridge finite element models to obtain the maximum axial load in the piles. AASHTO LRFD load combinations are used to find the governing scenario for design. From the moving load analysis, the factored axial load on each abutment pile caused by vertical loads is 854 KN. 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 HP12×74 pile, the design axial load capacity is 1975 KN, the design bending moment capacity about the pile strong axis is 499 KN-m, and the design bending moment capacity about the pile weak axis is 256 KN-m. The interaction of combined axial load and flexure interaction for each model of the simple span bridge is listed in Table 5.

Table 3: Pile Top Lateral Displacement - Simple Span Bridge

Model Number	Pile Top Lateral Displacement (mm)	
	Longitudinal	Transverse
B1	12.2	12.9
B2	14.1	10.5
B3	2.7	36.6
B4	6.6	28.0

Table 4: Seismic Force Distribution - Simple Span Bridge

Model	Longitudinal Direction		Transverse Direction	
	Pile Load	Soil Load	Pile Load	Soil Load
B1	28.9%	71.1%	69.3%	30.7%
B2	25.1%	74.9%	74.0%	26.0%
B3	19.4%	80.6%	72.0%	28.0%
B4	16.1%	83.9%	76.0%	24.0%

Table 5: Combined Axial and Flexure Interaction for HP Pile - Simple Span Bridge

Model	Interaction Number
B1	0.62
B2	0.62
B3	0.83
B4	0.74

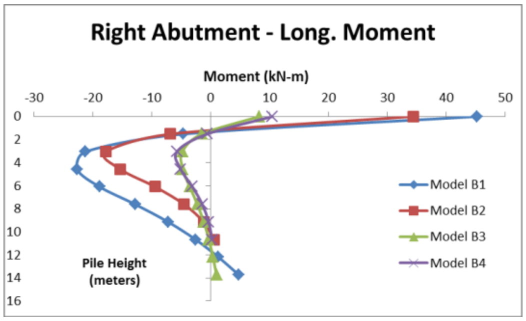

Figure 2. Abutment Pile Bending Moment – Longitudinal

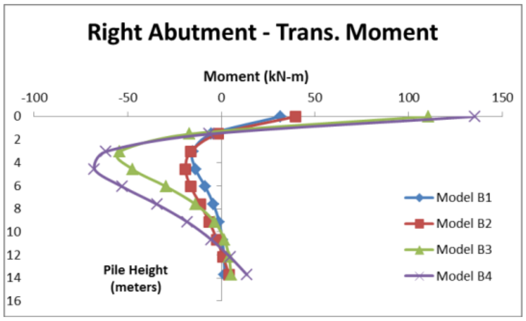

Figure 3. Abutment Pile Bending Moment – Transverse

2.3 *Discussion*

Model B1 and Model B2 are subjected to the same earthquake loads, but the pile orientation is different. Model B1 has the pile strong axis oriented in the bridge longitudinal direction, while Model B2 has the pile strong axis oriented in the bridge transverse direction. Model B3 and Model B4 are each subjected to the same earthquake loads. Model B3 has the pile strong axis oriented in the bridge longitudinal direction, while Model B4 has the pile strong axis oriented in the bridge transverse direction.

According to Table 3, the longitudinal displacement difference between Model B1 (12.2 mm) and Model B2 (14.1 mm) is 17%, and the difference in the transverse direction is 24% (12.9 mm for Model B1 vs. 10.5 mm for Model B2). The same trend is shown in Model B3 and B4. Model B4 (28.0 mm) has about 31% less transverse displacement than Model B3 (36.6 mm). The maximum displacement of the two earthquake load cases governs the performance based design of the bridge. Our analysis shows that the pile displacement in the bridge transverse direction governs and the results indicate that orienting the HP strong axis in the bridge transverse direction can effectively reduce the overall bridge displacement under seismic loads.

Table 4 shows that the backfill soil plays an important role in seismic load distribution in both the longitudinal and transverse directions in the simple span bridge models. In the longitudinal direction, the backfill soil takes roughly 70% to 80% of the total seismic load. In the transverse direction, the soil takes roughly 25% to 30% of the seismic loads. The piles carry about 70% of the seismic load in the transverse direction, whereas in the longitudinal direction, the piles take less than 30% of the seismic load. The results show that the piles dominate in the bridge transverse direction and the soil resistance dominates in the longitudinal direction. The higher soil resistance in the longitudinal direction comes from the infinite soil mass behind the bridge.

Figure 2 and Figure 3 compare the bending moments in the abutment piles. The pile takes higher bending moment in the strong axis direction than the weak axis direction when the bridge is subjected to the same magnitude of earthquake force.

Table 5 is to investigate the effect of pile orientation on the structural behavior of HP pile. An interaction number indicates the degree to which a pile will fail structurally when subjected to combined axial load and bending moment. If the interaction number of a pile is greater than one, it means that the pile is not adequate to resist the given loads. The greater interaction number of the two seismic design load cases governs the pile design. For HP pile strong axis being oriented parallel to the bridge longitudinal direction, the interaction number of Model B1 equals to 0.62 and the interaction number of Model B3 equals to 0.83, and therefore 0.83 governs for this case. For HP pile strong axis being oriented parallel to the bridge transverse direction, the interaction number of Model B2 equals to 0.62 and the interaction number of Model B4 equals to 0.74, and thus 0.74 controls. By comparing the interaction numbers for the different pile axis orientations, 0.74 vs. 0.83, it is obvious that the pile has more structural capacity when the HP pile strong axis is oriented in the bridge transverse direction.

3. Two-Span Bridge Analysis

3.1 *Model Description*

The two-span bridge is 91.4 meters long and has two equal spans with the span length of 45.7 meters each. The bridge is 12.5 meters wide and carries three lanes of traffic. The superstructure of the bridge consists of a 203 mm thick cast-in-place concrete deck and 5 I-plate girders spaced at 2.8 meters. The abutments have the same configuration as the simple span bridge. The multi-column pier has three 1200 mm square reinforced concrete columns with a pier cap. The columns are 6.1 meters tall. The pier foundation uses double row HP piles with a reinforced concrete pile cap. There are 14 total HP12×74 steel piles at the pier laid out in two rows of 7 piles each. The piles at the pier are 12.2 meters long. The pier piles are spaced 1.8 meters on center in each row and the spacing between the two rows is 1.2 meters. The finite element model of the two-span bridge is shown in Figure 4. The loads on the two-span bridge models are listed in Table 6.

Table 6: Two-Span Bridge Numerical Model Description

Model Number	Earthquake Load (KN)		HP Pile Strong Axis Orientation
	Longitudinal	Transverse	
B1	3336	1001	Longitudinal
B2	3336	1001	Transverse
B3	1001	3336	Longitudinal
B4	1001	3336	Transverse

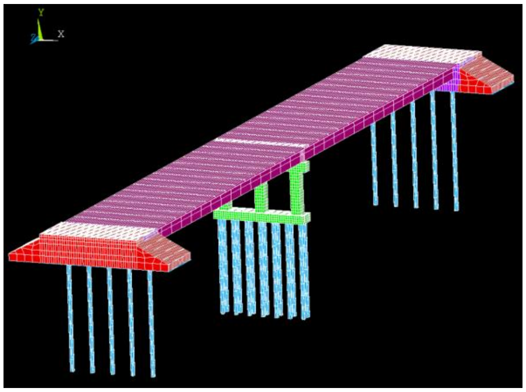

Figure 4. 3-D Two-Span Bridge Model in ANSYS

3.2 *Results*

The maximum pile top displacement of the two-span bridge is listed in Table 7 and the seismic force distribution for each model is listed in Table 8. The interaction numbers of combined axial load and flexure for the abutment piles and pier piles are listed in Table 9. Figure 5 to Figure 8 plot the bending moments along the piles in Model B1 through Model B4 for the two-span bridge.

Table 7: Pile Top Lateral Displacement - Two-Span Bridge

Model	Pile Top Lateral Displacement (mm)			
	Abutment		Pier	
	Long.	Tran.	Long.	Tran.
B1	19.4	14.7	16.9	11.8
B2	19.7	11.4	17.8	8.9
B3	9.3	40.5	7.7	36.3
B4	9.2	29.6	7.4	25.1

Table 8: Seismic Force Distribution - Two-Span Bridge

Model	Longitudinal Direction			Transverse Direction		
	Abut. Pile	Pier Pile	Soil	Abut. Pile	Pier Pile	Soil
B1	22.5%	31.0%	46.5%	36.9%	48.9%	14.2%
B2	17.3%	24.6%	58.0%	38.1%	46.8%	15.2%
B3	17.2%	24.3%	58.5%	36.3%	50.0%	13.6%
B4	16.8%	23.2%	60.1%	38.9%	49.1%	12.0%

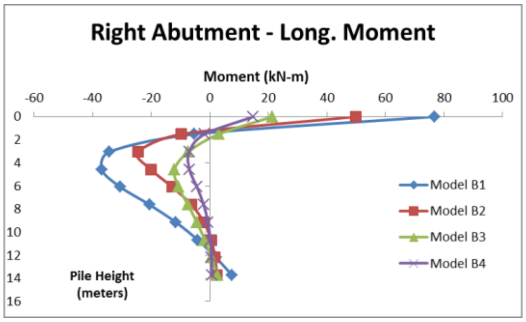

Figure 5. Two-Span Bridge Abutment Pile Moment – Longitudinal Direction

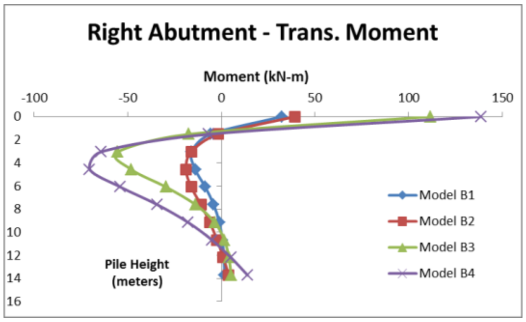

Figure 6. Two-Span Bridge Abutment Pile Moment – Transverse Direction

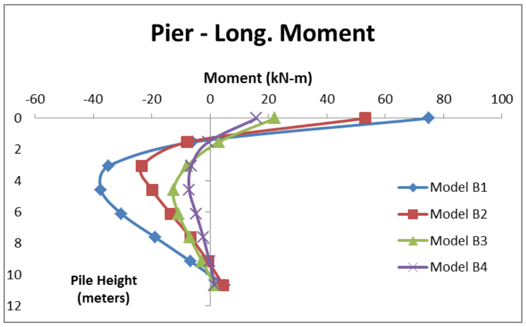

Figure 7. Two-Span Bridge Pier Pile Moment – Longitudinal Direction

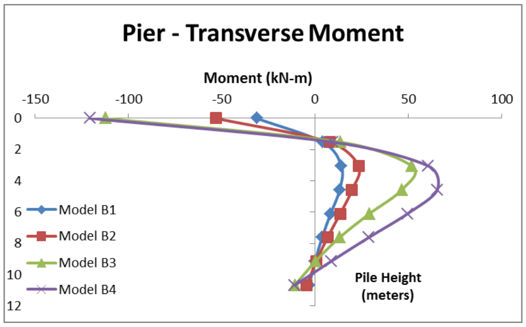

Figure 8. Two-Span Bridge Pier Pile Moment – Transverse Direction

Table 9: Combined Axial and Flexure Interaction for Piles in Two-Span Bridge Models

Model	Abut. Pile	Pier Pile
	Interaction Number	Interaction Number
B1	0.58	0.60
B2	0.58	0.60
B3	0.76	0.79
B4	0.63	0.63

3.3 *Discussion*

Table 7 shows that pile orientation has a more significant effect on the pile displacement in the bridge transverse direction than the longitudinal direction. From Table 7, Model B1 and Model B2, both of which are subjected to the same loads, the differences between longitudinal direction pile displacements for both abutment piles and pier piles are within 3%, whereas Model B2 has 29% less transverse displacement than Model B1 for the abutment piles (11.4 mm vs. 14.7 mm) and Model B2 has 34% less transverse displacement than Model B1 for the pier piles (8.9 mm vs. 11.8 mm). The same trend is shown in Model B3 and Model B4, both of which are subjected to the same earthquake load. Model B4 has about 36% less transverse displacement than Model B3 for the abutment piles (29.6 mm vs. 40.5 mm) and has 44% less transverse displacement than Model B3 for the pier piles (25.1 mm vs. 36.3 mm). Our analyses shows that the pile displacement in the bridge transverse direction governs, and therefore orienting the HP pile strong axis in the bridge transverse direction helps controlling bridge lateral displacement and improve the overall performance of bridges during earthquakes. Table 8 shows that the backfill soil plays an important role in seismic load distribution in both the longitudinal and transverse directions in the two-span bridge. In the longitudinal direction, the backfill soil takes roughly 50% to 60% of the total seismic load. In the transverse direction, the soil takes about 12% to 15% of the total seismic loads. The soil carries a larger portion of the load in the longitudinal direction. The HP piles play a more significant role in carrying loads in the transverse direction. The piles carry about 85% of the total seismic load in the bridge transverse direction, whereas in the longitudinal direction, the piles take less than 40% of the total seismic load.

Figure 5 and Figure 6 compare the bending moments along the abutment pile and Figure 7 and Figure 8 compare the bending moments along the pier pile for the two-span bridge models B1 through B4. From the results, we can find that the pile takes higher bending moment in the pile strong axis direction than the weak axis direction. This is because the pile has larger moment inertia about the strong axis.

Like the simple span bridge models, we checked the interaction numbers to investigate the structural adequacy of the HP piles. Table 9 lists the interaction numbers of the abutment pile and the pier pile. Comparing Model B2 with Model B1, both of which are subjected to the same loads, we find that Model B2 and Model B1 have very similar interaction numbers for both the abutment pile and the pier pile. This means that if the earthquake load is primarily in the bridge longitudinal direction, the pile orientation has little effect on the pile structural behavior. However, when we compare the interaction numbers of Model B4 with Model B3, we find that the interaction number of Model B4 is 21% lower than that of Model B3 for the abutment pile (0.63 vs. 0.76) and the interaction number of Model B4 is 25% lower than that of Model B3 for the pier pile (0.63 vs. 0.79). The results indicate that if the earthquake load is primarily in the bridge transverse direction, the pile has more structural capacity when the HP pile strong axis is oriented in the bridge transverse direction. In seismic zone, bridges should be designed to resist the seismic loads in both the longitudinal and the transverse direction, and the worst scenario governs the bridge design. Therefore, orienting the HP pile strong axis parallel to the bridge transverse direction benefits the overall pile structural behavior.

4. Conclusions

In this paper, we investigate seismic soil-structure interaction in simple span and multi-span bridges using 3D nonlinear finite element analysis. Our research findings show that:

1) Backfill soil plays an important role in seismic load distribution in both simple span bridges and two-span bridges. It is beneficial to consider soil-structure interaction to facilitate sustainable design of HP pile foundations in bridges.
2) Investigation of seismic load distribution shows that the piles take a larger portion of the load in the bridge transverse direction, whereas the soil takes a higher portion of the load in the bridge longitudinal direction.
3) Orienting the HP pile strong axis parallel to the bridge transverse direction significantly reduces the pile displacement in the bridge transverse direction, and therefore benefits the overall performance of the bridge subjected to seismic loads.
4) According to the combined axial load and flexure interaction check, the piles provide more structural capacity if the HP pile strong axis is parallel to the bridge transverse direction. Therefore, it is more economical to orient the pile strong axis parallel to the bridge transverse direction.
5) Abutment backfill soil has a more significant effect on seismic load distribution in simple span bridges than in multi-span bridges.

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