Optimization of Bridge Deep Foundation Design in Seismic and Tsunami Zone

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ABSTRACT

Bridge's response to extreme loading conditions such as earthquakes and tsunamis is critical to allow for continued evacuation and an effective emergency response. In this paper, dynamic responses and soil-foundation-structure interaction of bridges during earthquakes and tsunamis are analyzed by 3D nonlinear finite element modeling. This paper presents the research results of simple-span and two-span bridges with fully integral abutments and the deep foundation type focused on is HP steel piles. The effect of pile orientations on the bridge behavior is studied. The results show that it is more economical to orient the HP pile's web parallel to the bridge transverse direction.

Keywords: bridge, earthquake, tsunami, HP pile

1. INTRODUCTION

Critical and essential highway bridges need to remain operational after a disaster to allow for continued evacuation and an effective emergency response, therefore the bridge's response to extreme loading conditions is critical. Bridge damage caused by tsunamis following earthquakes has received more and more attention due to the recent increase in high magnitude earthquakes. Figure 1 shows tsunamis can cause significant scouring of the backfill soil behind the bridge abutment (CAESAR, 2011). The scour of backfill soil will cause further damage of bridges during strong aftershocks. During the 2011 Great East Earthquake, as many as 300 bridges in East Japan were damaged or totally destroyed (Yashinsky, 2012). The 7.0 Magnitude Haiti 2010 Earthquake produced deadly tsunami shortly after the earthquake and at least 52 aftershocks measuring 4.5 Magnitude or greater had been recorded. In addition to abutment scouring, tsunami waves can also cause scouring around piers and pile foundations. This risk is substantially higher for bridges that span a waterway. Tsunamis have the ability to completely scour the abutment backfill away, which could have serious implications in the event of a series of earthquakes, or a delayed aftershock of significant magnitude. Therefore, it is important to understand how well a bridge is able to withstand seismic loads without the aid of abutment backfill.

Figure 1: Bridge Damages during Earthquake and Tsunami (CAESAR, 2011)

The implications of the findings from recent earthquakes and tsunamis include (Buckle et al, 2012; David et al, 2011; Francis, 2006; Iemura et al, 2005 and 2007; Jeremic et al, 2004; Kwon et al, 2006; Lau et al, 2011; CAESAR, 2012; Saadeghvaziri, 2000 and Yashinsky, 2012):

1) Deep foundations need to go deep enough underground to provide suitable levels of stability in earthquake-tsunami conditions.
2) Effective methods of protecting abutment backfill need to be developed in order to prevent the scouring of all of the backfill material.
3) Bridges in potential tsunami zones should be constructed to withstand any type of earthquake / tsunami loadings without the aid of abutment backfill.
4) Each of the improvements mentioned above need to be cost effective.

A fully integral abutment bridge has the superstructure 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 considered more economical over their life span due to lower construction cost and easier maintenance. Research findings also show that fully integral abutment bridges perform better against the impact of tsunamis than bridges without integral abutment connections. The integral connection prevents the superstructure from being washed off of the abutment.

Simple span 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 traffic. Optimizing the design of simple span and two-span bridges is critical to reducing the total cost of infrastructure. HP steel piles are widely used as bridge foundations in the United States. HP piles are special hot rolled H beams with the same thickness for flange and web, as shown in Figure 3.

Figure 3: HP Steel Pile

2. 3-D NUMERICAL MODELING

It is costly and sometimes impossible to perform full scale physical experiments on bridges; therefore, finite element analysis has been used to model large scale structures including bridges due to recent rapid growth of computing techniques (Bao et al, 2011). In this research, 3-D finite element models of bridges are set up to explore the dynamic responses of fully integral abutment bridges subjected to seismic loads and the effect of tsunami scour on bridge abutments and pier foundations is studied. Finite element analysis programs ANSYS and STAAD are used as the tools for numerical simulations.

The prototype simple span bridge and its numerical model are shown in Figure 3. The simple span bridge has a span length of 45.7 meters and overall width of the bridge is 11.2 meters. The bridge has no skew and carries 3-lane traffic. The superstructure of bridge consists of a 20.3 cm thick reinforced concrete deck and 5 I-plate steel girders spaced at 2.8 meters on center, which are directly connected to the abutment wall. The abutment wall is 60 cm thick and the wingwalls are 30 cm thick. The bridge foundation uses 5 HP 14x102 steel piles (AISC, 2011) spaced at 2.8 meters at each abutment. The piles are 15.3 meters long.

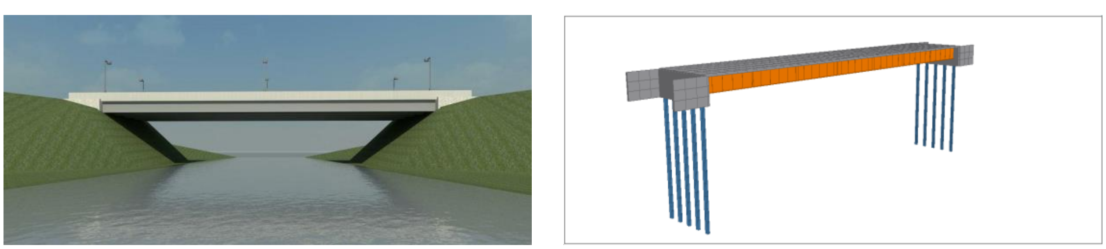

Figure 3: Simple Span Bridge and 3D Finite Element Model

The prototype two-span bridge and its numerical model are shown in Figure 4. The total length of the bridge is 91.4 meters and has two equal spans of 45.7 meters each.

The overall width of the bridge is 11.2 meters and carries 3-lane traffic. The superstructure of bridge consists of a 20.3 cm thick reinforced concrete deck and 5 continuous I-plate steel girders spaced at 2.8 meters on center. The abutment has the same configuration as the simple span bridge. The foundation piles at the abutments use 5 HP 14x117 (AISC, 2011) spaced at 2.8 meters on center. The multi-column pier has 3 columns and uses 2 rows of HP 14x102 piles, 7 piles spaced at 1.8 meters on center each row. The piles are 15.3 meters long at the abutments and 12.2 meters long at the pier.

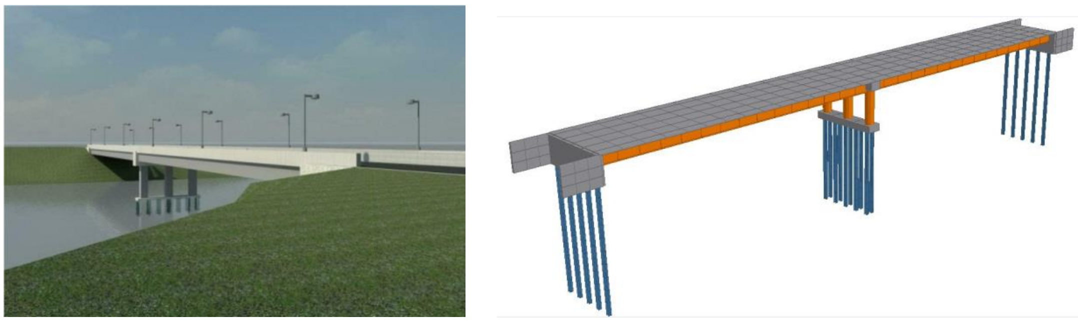

Figure 4: Two-Span Bridge and 3D Finite Element Model

Seismic load is applied in two orthogonal directions, and two seismic load cases are considered according to AASHTO LRFD Bridge Design Specifications (2010, 2009). Load case 1: 100% earthquake load in the longitudinal direction + 30% earthquake load in the transverse direction and load case 2: 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.

Winkler soil springs are applied along the piles as well as at the boundaries of backfill soil to simulate the realistic soil-foundation-structure system in bridge systems. The soil spring stiffness is determined using 3-D single pile analysis in ANSYS. Drucker-Prager (DP) soil constitutive model is used to model the granular soil embankment. Contact elements are included in the numerical models to simulate the realistic contact surface between the concrete abutment walls and backfill soil. The load on pile top is applied incrementally, and the pile shear force and deflection along the pile is recorded at each step. The soil spring stiffness is obtained by dividing the soil lateral force by the pile deflection along the pile (Bao et al, 2012, 2013). The soil spring stiffness in the pile weak axis is obtained by the same approach.

3. RESULTS

3.1 Simple Span Bridge Results

Stage 1: The structural behavior of the bridge during a major earthquake without tsunami scour is studied. In the numerical experiments, the bridge is identified as a critical bridge and is located at site class C. The earthquake spectral response acceleration at short periods S_S equals to 1.25, and the earthquake spectral response acceleration at 1-second periods S_1 is equal to 0.5. The calculated seismic response coefficient C_S is 0.5 and the acceleration coefficient S_{D1} is equals to 0.433. The bridge is assigned to seismic zone 3 based on the S_{D1} value according to AASHTO LRFD Bridge Design Specifications (2010). The total earthquake load on the bridge is calculated by multiplying C_S by the bridge's equivalent weight of the superstructure. The response modification factor R is taken as 1.0 and the resistance factor for moments is 1.25 for seismic zone 3 (AASHTO, 2010, 2009). With the assistance of abutment backfill soil, the seismic load on the bridge superstructure transfers to the foundation piles as well as to the backfill soil. The total seismic load and load distribution in two orthogonal directions between piles and backfill soil is listed in Table 1.

Table 1: Seismic Load Distribution in Simple Span Bridge

Load Case	Seismic Load		HP Pile Web Orientation	HP Piles Contribution		Backfill soil Contribution	
				Shear Force	%	Shear Force	%
1	L	3028 KN	L	648 KN	21	2380 KN	79
			T	559 KN	18	2469 KN	82
	T	908 KN	L	336 KN	37	572 KN	63
			T	423 KN	47	481 KN	53
2	L	908 KN	L	253 KN	28	654 KN	72
			T	182 KN	20	726 KN	80
	T	3028 KN	L	1134 KN	37	1894 KN	63
			T	1436 KN	47	1592 KN	53

L: Bridge longitudinal direction
T: Bridge transverse direction

Stage 2: Numerical experiments are conducted on the bridge model during aftershocks of significant magnitude without the resistance of abutment backfill to account for tsunami scour. The scour effects are realistically simulated by reducing the stiffness of soil springs. The backfill soil spring stiffness is set to be zero to model the loss of backfill soil due to tsunami scour. In the aftershock simulation, the seismic response coefficient C_S is 0.3 and the acceleration coefficient S_{D1} is equals to 0.258. The bridge in this stage is in seismic zone 2. According to AASHTO LRFD

Bridge Design Specification, the response modification factor R for critical bridges in seismic zone 2 is taken as 1.5 (AASHTO, 2010, 2009).

Bridge displacement is an important indicator of the bridge's performance during earthquakes. The pile displacements in Stage 1 and Stage 2 are shown in Table 2.

Table 2: Simple Span Bridge Pile Displacements

Stage	HP Pile Web Orientation	Displacement Direction	Abut. Pile Displacement (cm)
Stage 1	L	Longitudinal	8.4
		Transverse	**20.7**
	T	Longitudinal	9.3
		Transverse	**17.3**
Stage 2	L	Longitudinal	21.8
		Transverse	**33.2**
	T	Longitudinal	22.0
		Transverse	**33.3**

The structural capacity of the pile can be checked by using the interaction equation of combined compression and flexure. The interaction number comes from Equation (1) or Equation (2) that develops a relationship between the axial force and bending moment.

If Pu/∅Pn≥0.2:

$$\frac{Pu}{\emptyset Pn} + \frac{8}{9}\left(\frac{Mux}{\emptyset Mnx} + \frac{Muy}{\emptyset Mny}\right) \leq 1 \qquad \text{Equation (1)}$$

Or, if Pu/∅Pn<0.2

$$\frac{Pu}{2*\emptyset Pn} + \left(\frac{Mux}{\emptyset Mnx} + \frac{Muy}{\emptyset Mny}\right) \leq 1 \qquad \text{Equation (2)}$$

Where:
∅= Resistance factor
Pu= Applied axial load
Pn= Nominal axial resistance
Mux= Applied strong axis moment
Mnx= Nominal moment resistance in pile strong axis
Muy=Applied weak axis moment
Mny= Nominal moment resistance in pile weak axis

If the interaction number of a pile exceeds one, it means that the pile is inadequate to resist the given loads and represents structural failure. The summary of the interaction numbers of the abutment pile is listed in Table 3.

Table 3: Pile Structural Capacity Check – Interaction Number

Stage	HP Pile Web Orientation	Load Case	Pu (KN)	ΦPn (KN)	Mux (KN-m)	ΦMnx (KN-m)	Muy (KN-m)	ΦMny (KN-m)	Interaction Number
Stage 1	L	1	903	6143	325	961	107	532	0.61
		2	903	6143	91	961	362	532	**0.85**
	T	1	903	6143	160	961	194	532	0.60
		2	903	6143	542	961	56	532	**0.74**
Stage 2	L	1	903	6143	344	769	87	426	0.73
		2	903	6143	103	769	289	426	**0.89**
	T	1	903	6143	102	769	290	426	**0.89**
		2	903	6143	342	769	87	426	0.72

3.2 Two-Span Bridge Results

The two-span bridge is classified as a critical bridge and is in the same seismic zones as the simple span bridge. The seismic load distribution in the two-span bridge during a major earthquake without tsunami scour is listed in Table 4.

Table 4: Seismic Load Distribution in Two-Span Bridge

Load Case	Seismic Load		HP Pile Web Orientation	Abutment Piles		Pier Piles		Backfill soil	
				Shear Force	%	Shear Force	%	Shear Force	%
1	L	5881 KN	L	1358 KN	23	1056 KN	18	2380 KN	59
			T	1095 KN	18	860 KN	15	3925 KN	67
	T	1764 KN	L	494 KN	28	564 KN	32	706 KN	40
			T	582 KN	33	635 KN	36	547 KN	31
2	L	1764 KN	L	406 KN	23	318 KN	18	1040 KN	59
			T	300 KN	17	265 KN	15	1199 KN	68
	T	5881 KN	L	1762 KN	28	1880 KN	32	2329 KN	40
			T	1861 KN	32	2081 KN	35	1939 KN	33

Table 5 summarizes the pile top lateral displacements of the abutment pile and the pier pile during the major earthquake (Stage 1) and during the aftershock without abutment backfill soil (Stage 2).

Table 5: Two-Span Bridge Pile Top Displacements

Stage	HP Pile Web Orientation	Displacement Direction	Abut. Pile Displacement (cm)	Pier Pile Displacement (cm)
Stage 1	L	Longitudinal	13.2	9.7
		Transverse	**29.3**	**20.7**
	T	Longitudinal	14.8	11.1
		Transverse	**23.9**	**18.6**
Stage 2	L	Longitudinal	16.0	21.8
		Transverse	**28.9**	**24.1**
	T	Longitudinal	25.0	**21.7**
		Transverse	**26.7**	16.9

The structural capacity of the abutment pile and the pier pile is checked by the interaction numbers for combined axial force and flexure. The results are listed in Table 6 and Table 7 for the abutment pile and the pier pile, respectively.

Table 6: Two-Span Bridge Abutment Pile Structural Capacity Check

Stage	HP Pile Web Orientation	Load Case	Pu (KN)	ΦPn (KN)	Mux (KN-m)	ΦMnx (KN-m)	Muy (KN-m)	ΦMny (KN-m)	Interaction Number
Stage 1	L	1	761	7055	624	1185	132	644	0.84
		2	761	7055	178	1185	553	644	**1.06**
	T	1	761	7055	225	1185	376	644	0.83
		2	761	7055	761	1185	110	644	**0.87**
Stage 2	L	1	761	7055	489	948	108	515	0.78
		2	761	7055	146	948	362	515	**0.91**
	T	1	761	7055	124	948	384	515	**0.93**
		2	761	7055	412	948	116	515	0.71

Table 7: Two-Span Bridge Pier Pile Structural Capacity Check

Stage	HP Pile Web Orientation	Load Case	Pu (KN)	ΦPn (KN)	Mux (KN-m)	ΦMnx (KN-m)	Muy (KN-m)	ΦMny (KN-m)	Interaction Number
Stage 1	L	1	681	6143	268	961	132	532	0.58
		2	681	6143	79	961	438	532	**0.96**
	T	1	681	6143	176	961	190	532	0.60
		2	681	6143	591	961	57	532	**0.78**
Stage 2	L	1	681	6143	300	769	88	426	0.65
		2	681	6143	89	769	293	426	**0.86**
	T	1	681	6143	97	769	273	426	**0.82**
		2	681	6143	323	769	81	426	0.67

4. DISCUSSION

It is important to understand the soil-structure interaction mechanism during earthquakes. Table 1 and Table 4 show seismic load distribution between piles and abutment backfill soil in the simple span bridge and the two-span bridge, respectively. For the simple span bridge, we find that the abutment backfill takes about 80% of the total seismic load in the bridge longitudinal direction and absorbs 50% – 60% seismic load in the bridge transverse direction in simple span bridge. In the two-span bridge, the abutment backfill takes about 60% of the total longitudinal seismic load and 40% of the transverse load. The abutment backfill plays a more important role in the bridge longitudinal direction than in the transverse direction.

Many damages during earthquakes are caused by excessive displacement. Such damages include large cracks and superstructure sliding off the joint seats. It is very important to control the bridge displacement within an acceptable range in bridge seismic design. Table 2 shows the abutment pile displacements in the simple bridge longitudinal and transverse directions and compares the pile displacements for two different HP pile orientations. The larger of the longitudinal and transverse displacement should be used to check against a limiting value specified in design codes in bridge design. From Table 2, we can find that HP pile orientation has a significant effect on bridge displacements. According to the analysis, if the HP pile web is parallel to the bridge longitudinal direction, the governing displacement equals to 20.7 cm. If orienting the HP pile web parallel to the bridge transverse direction, the maximum displacement is 17.3 cm, which is about 15% less displacement than the other pile orientation. Table 2 also shows the pile displacements during the aftershock in the simple span bridge. In this case, the controlling displacements are almost same for the two different pile orientations, both of which are 33 cm. Table 5 shows the pile displacements in the two-span bridge. We can find that pile orientation affects the displacement of the abutment pile as well as the pier pile. During Stage 1, which represents the major earthquake without backfill scour, the governing displacements of the abutment pile are 29.3 cm and 23.9 cm for the HP pile web parallel to the bridge longitudinal direction and transverse direction, respectively. The pier pile has a governing displacement of 20.7 cm if the pile web is along the bridge longitudinal direction and 18.6 cm for the pile web parallel to the bridge transverse direction. In Stage 2, the pile displacements have the same trend as that in Stage 1. All the results indicate that orienting the pile’s web parallel to the bridge transverse direction can reduce the overall bridge displacements.

Bridge piles are subject to significant lateral loads during earthquakes. The lateral loads develop moments in the piles. Under the combined axial loads and bending moments, the piles are more susceptible to structural failure than the piles subjected to mainly axial loads. Interaction equations for combined axial force and flexure are used to check the structural capacity of piles. An interaction number that is greater than one indicates structural failure of the pile. The lower value of the interaction number, the higher the structural capacity of the pile. The larger interaction number from the two seismic load cases governs the design. Table 3 checks the interaction number of the abutment pile in the simple span bridge. In Stage 1, the pile has a lower interaction number if the HP pile web is parallel to the bridge transverse direction (0.74 vs. 0.85). In Stage 2, the governing interaction numbers for the two pile orientations are both 0.89. Table 6 listed the interaction numbers for the abutment pile in the two-span bridge and Table 7 shows the interaction numbers of the pier pile. During Stage 1, the results clearly show that orienting the pile web parallel to the bridge transverse direction can significantly reduce the interaction number of the pile and thus increase its structural capacity. The abutment pile has the interaction number of 1.06 (indicating failure) vs. 0.87 for the HP pile's web parallel to the bridge longitudinal orientation and transverse orientation, respectively, and the pier pile has the interaction number of 0.96 vs. 0.78. In Stage 2, both the abutment pile and the pier pile pass the structural capacity check, and pile orientation slightly affects the pile's interaction number (0.91 vs. 0.93 for the abutment pile and 0.86 vs. 0.82 for the pier pile).

5. CONCLUSION

In this paper, dynamic responses and soil-foundation-structure interaction mechanism in fully integral abutment bridges during earthquakes and tsunamis are investigated by 3D nonlinear finite element modeling. The research findings can provide theoretical support to sustainable design of bridges to survive a disaster by lowering energy input and increasing their service life. The following conclusions can be drawn from the analyses:

1) Abutment backfill soil plays an important role to absorb earthquake load in both longitudinal and transverse directions if no tsunami scour occurs.
2) Considering abutment backfill soil resistance in the regions with few tsunami hazards will significantly reduce the seismic loads on pile foundation, therefore, it benefits bridge pile design by reducing the sizes of piles.
3) Bridge piles can survive during an aftershock of significant magnitude without the assistance of abutment backfill if the piles are designed properly. Such designs

include adequate embedment into the bedrock and secure connections between the pile and the pile cap.

4) It is more economical to orient the HP pile web parallel to the bridge transverse direction, because such orientation can reduce the overall pile displacements as well as increase the structural capacity of the piles.

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