RESPONSE OF BRIDGE STRUCTURES TO SPATIALLY VARYING AND SITE-AMPLIFIED GROUND MOTIONS

Nawawi Chouw[1] and Hong Hao[2]

[1] *Department of Civil and Environmental Engineering, University of Auckland, Auckland, New Zealand*
[2] *School of Civil and Resource Engineering, University of Western Australia, Crawley, WA, Australia*
n.chouw@auckland.ac.nz, hao@civil.uwa.edu.au

ABSTRACT :

The paper addresses the pounding response of two adjacent bridge structures. The influence of non-uniform soil conditions on the development of ground motions at local sites and the consequence of spatial variation of the amplified ground movements on pounding response are considered. In this study the ground motions of the bedrock are simulated stochastically based on the new Australian design spectrum. The bridge structures, footings and subsoil are described using a combined finite element and boundary element method. The results show the importance of site amplification of the ground motions. The unequal site amplification can strongly contribute to the relative response between the bridge structures and consequently their pounding potential. As expected different soil conditions will provide different pounding response behaviour. In order to estimate pounding damage potential of bridge girders it is strongly recommended that soil-structure interaction and actual site amplification of local ground motions should be taken into account in the analysis.

KEYWORDS: Spatial variation, pounding, soil-structure interaction, non-uniform soil, bridge response, expansion joint

1. INTRODUCTION

Relative responses between adjacent structures have caused damage in the past earthquakes, e.g. the 1995 Kobe earthquake in Japan (Park et al., 1995), the 1999 Chi-Chi earthquake in Taiwan (JSCE, 1999), the 2006 Yogyakarta earthquake in Indonesia (Elnashai et al., 2007), the most recent earthquakes on 12 May 2008 in Sichuan province in China and on 14 June 2008 in Iwate and Miyagi regions.

In the case of buildings, pounding damages occur because of insufficient separation between the buildings. In the past decades many investigations have been performed to determine the required separation distance to avoid pounding and mitigation measures to reduce pounding effect. Pounding effect reduction measures and minimum separation distances have also been specified in many design specifications, e.g. UBC (1999), Chinese seismic design code (2005), recommendation of New Zealand Society for Earthquake Engineering (2006) and Australian standards (2007).

In the case of bridges, relative girder movements can cause pounding damages and unseating of the bridge deck that can lead to collapse of bridge span. Investigations on consequences of girder relative movements mainly focused on the required seat length and mitigation measures to prevent girder collapses, e.g. Hao (1998), DesRoches and Muthumar (2002), Zhu et al. (2002 and 2004), Wang (2007) and Chouw and Hao (2008a).

The most common measure to prevent bridge girder collapses is to adjust the fundamental frequency of the adjacent bridge structures that they have the same or at least very similar dynamic properties. Both bridge structures will then respond to the incoming seismic waves in phase, and relative girder movement can be reduced or avoided. This design philosophy is implemented in many design specifications, e.g. AASTHO (1998), CALTRANS (2001) and JRA (2004). In most of the studies it is assumed that the bridge structures experience the same ground excitations and have fixed base. Investigations that consider the spatial variation of seismic motions and soil-bridge structure interaction are still limited, e.g. Hao and Chouw (2006 and 2008a, 2008b).

Separation distance between bridge girders to avoid poundings is so far not an option, because the gap between bridge girders of conventional bridges is only a few centimetres. Recently, a new mitigation measure using modular expansion joints has been proposed by the authors (Chouw and Hao, 2008b). By introducing several intermediate small gaps the expansion joint can then have in total a large gap, enough to cope with the largest expected relative movement. Consequently, pounding damages during strong earthquakes can be avoided.

The development of ground motions at bridge local sites depends not only on the seismic wave propagation and the wave properties but also on local soil conditions. If local soil is soft, amplification can be expected. The influence of non-uniform ground conditions on ground motions have been considered in recent studies (Hao and Chouw, 2006 and Bi et al., 2008). In this study the simultaneous effect of unequally site-amplified local ground motions and soil-structure interaction on pounding responses of two adjacent bridge segments is considered.

2. BRIDGE STRUCTURES WITH NON-UNIFORM SOIL CONDITION

Figure 1 shows the considered bridge structures. Their material properties are given in Table 2.1. The local soil conditions considered in this study are listed in Table 2.2. In the case of soil 1 and 2 it is assumed that both sites have a soft soil layer of the thickness of 5 m and 11 m, respectively. In the case of soil 3 the left and right bridge sites have a soft soil layer of 11 m and 5 m, respectively. Below these soft soil layers bedrock is assumed.

It is assumed that the gap between the girders is 3 cm, and the structural members as well as the supporting ground remain elastic. In the analysis the bridge structures with their footings and the ground are modeled using a combined finite element and boundary element method.

To describe the radiation damping due to propagation of waves in the subsoil from vibrating bridge footings and to incorporate pounding effect including frequency-dependent soil stiffness correctly, the analysis is performed alternately in Laplace and time domains. It is assumed that the supporting bedrock is a half space. The soft layers have a shear wave velocity of 100 m/s, Poisson's ratio of 0.33 and a density of 2000 kg/m^3. The material damping of soil is neglected in this study. For simplicity it is assumed that the multiple piers of each bridge segment are modeled as one pier. However, the fundamental frequencies of the left and right bridge segments remain the same and have the respective values of 2.14 Hz and 0.9 Hz. The fundamental frequency ratio is then 0.42. Details of this numerical algorithm for describing non-linear soil-structure interaction are given in Chouw (1994) and Chouw and Hao (2008a).

Table 2.1 Structural properties of the bridges

	Left bridge structure				Right bridge structure			
	Length (m)	Mass (10^3 kg/m)	EA (10^8 kN)	EI (10^8 kNm^2)	Length (m)	Mass (10^3 kg/m)	EA (10^8 kN)	EI (10^8 kNm^2)
Girder	73.1	75.5	63.42	50.49	126.9	108.75	63.42	50.49
Pier	12.2	5.26	1.407	1.546	18.3	7.89	2.111	2.32
Footing	9	91.5	768.6	1024.8	9	91.5	768.6	1024.8

Table 2.2 Soil conditions at local sites of left and right bridge segments

Soil	Left site	Right site
1	5 m soft layer	5m soft layer
2	11 m soft layer	11 m soft layer
3	11 m soft layer	5 m soft layer

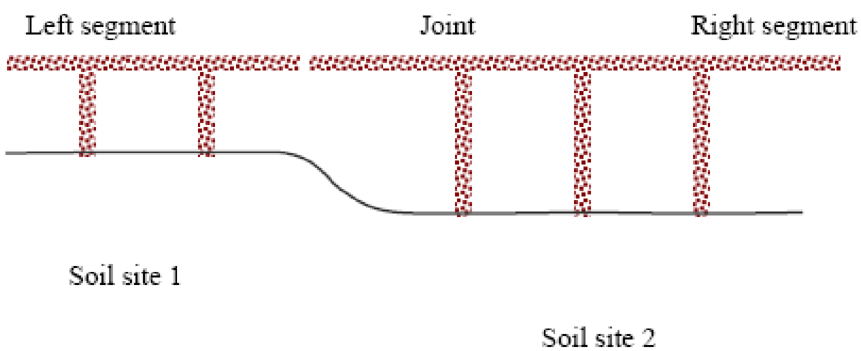

Figure 1. Two adjacent bridge segments with a gap of 3 cm

In this study it is assumed that the ground motions correspond to the new Australian design spectrum for the rock site conditions and normalized to 0.1 g (Australian Standards, 2007). The spatially varying bedrock movements below the bridge sites are simulated stochastically using an empirical coherency loss function based on recorded strong motion time histories in the SMART-1 array (Hao et al., 1989). It is assumed that the apparent wave velocity is 500 m/s, and the ground motions at considered bedrock locations with a distance of 100 m are intermediately correlated.
To consider the amplification effect of the local sites it is assumed that the seismic waves propagate upward to the ground surface following one dimensional wave propagation behaviour. The derivation of the spatially varying ground motions is given in Hao and Chouw (2006). Details about development of the coherency loss function and numerical procedure regarding stochastically simulated ground motions are given in Hao (1989).
In upper and lower parts of Figure 3 the simulated time histories of ground displacements at respectively the left and right bridge segment sites are compared for three different considered soil conditions. The solid black and grey lines are ground motions of the deep and shallow soft soil layer, respectively. The dotted lines are the ground displacements of the deep soft layer at the left bridge site and of the shallow soft soil at the right bridge site.
The propagating waves in deep soft soil layer are more significantly amplified than those in shallow soft layers. The black and dotted lines in the upper figure have respectively the maximum values of 9.34 cm and 9.53 cm at around 17.7 s, while the shallow soil (grey line) has the maximum value of 5.96 cm. The stronger site amplification at the right local site can be also observed in the lower figure (black line at 8.7 s). The maximum ground displacements at both bridge sites are listed in Table 2.3.

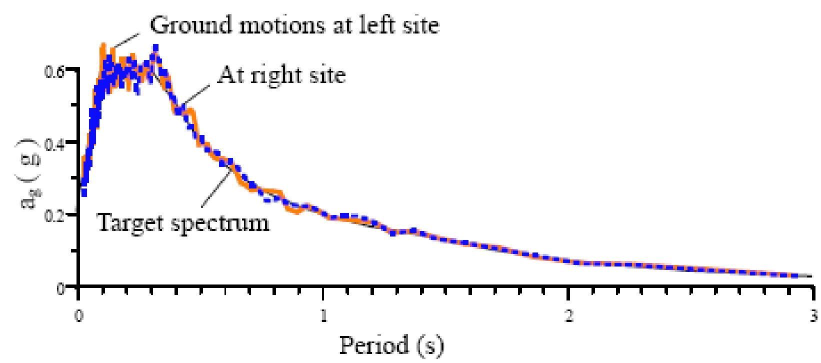

Figure 2. Australian design spectrum and response spectra of the simulated intermediately correlated ground acceleration with the apparent wave velocity of 500 m/s

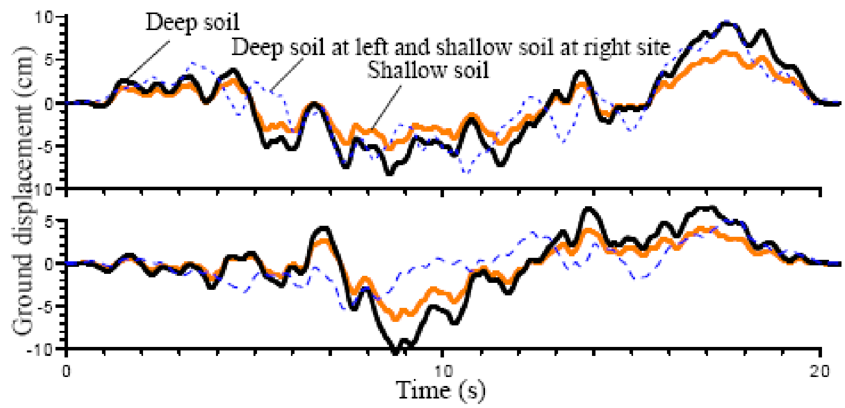

Figure 3. Influence of site amplification on the development of ground displacements at local sites

Table 2.3 Maximum ground displacement (cm) at bridge sites

Soil	Left site	t (s)	Right site	t (s)
1	5.96	17.73	- 6.55	8.79
2	9.34	17.67	-10.42	8.71
3	9.53	17.63	-5.38	7.47

3. POUNDING RESPONSES

Pounding response depends strongly on the development of relative movements of adjacent bridge girders. Relative movements occur when both adjacent bridge structures have different dynamic properties; ground excitations at both bridge sites are not the same; bridge structures interact with the supporting local soil unequally; or a combination of these conditions take place. In this study the spatial variation of surface ground motions is caused by non-uniform bedrock movements and amplification of propagating waves because of soft soil layer at local sites. Figure 4 shows the development of pounding forces between adjacent bridge girders depending on the considered local soil conditions. A comparison of the results indicates that a combined soil and structural effect should be considered in estimating pounding induced damages.

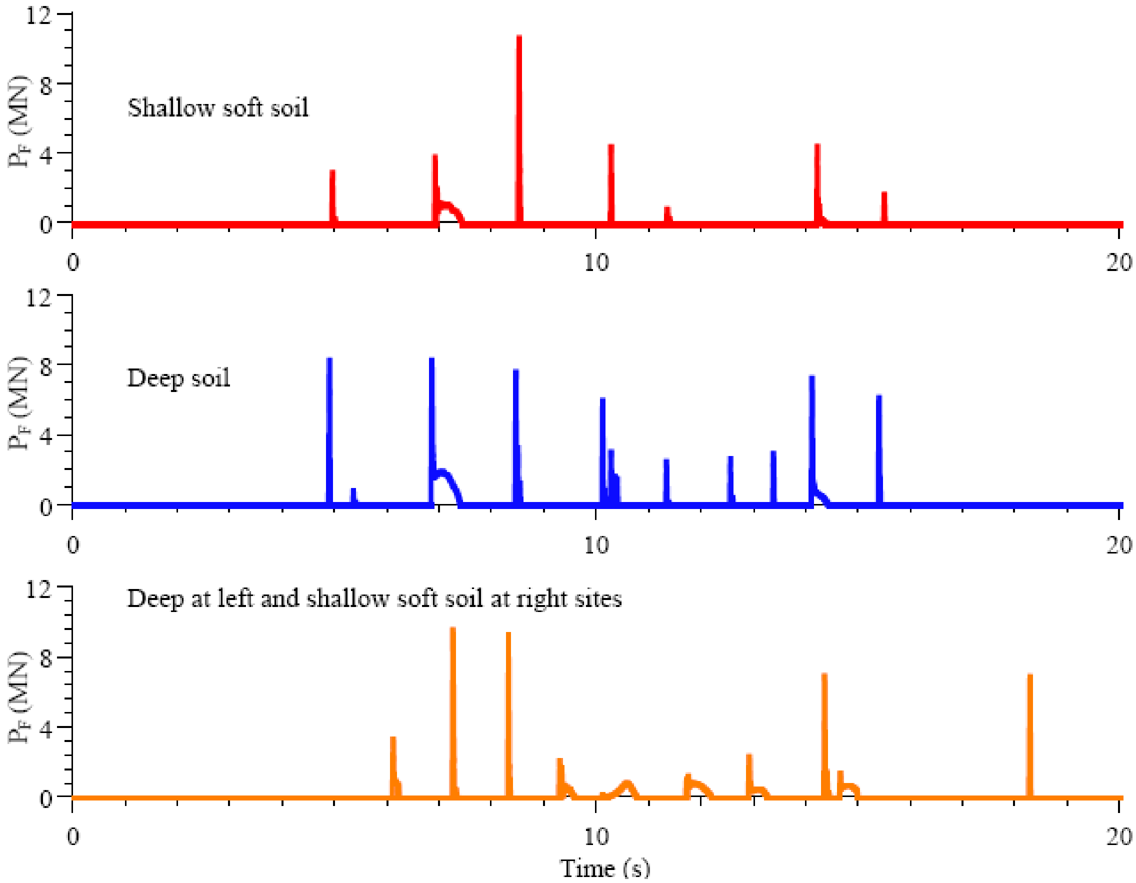

Figure 4. Influence of local bridge site condition on pounding force development

Table 3.1 Maximum pounding force (MN)

Soil	P_F	t (s)
1	10.7	8.50
2	8.33	6.84
3	9.6	7.24

Table 3.2 Maximum bending moment at bridge pier support (MNm)

Soil	M_l	t (s)	M_r	t (s)
1	89	7.72	112	7.66
2	143	7.64	199	7.90
3	94.6	5.28	113	16.8

Although soil condition 1, shallow soft soil layer, has smallest maximum ground displacement and the smallest number of pounding occasions compared to the case of soil condition 2, the bridge structures experience the largest pounding force of 10.7 MN at 8.5 s (Table 3.1 and uppermost figure). However, pounding damages can, but not necessarily always, be caused by the largest pounding forces. The number of strong poundings can sometime cause most girder damages. In such a case deep soft soil site has the largest damage potential (compared middle with other figures).

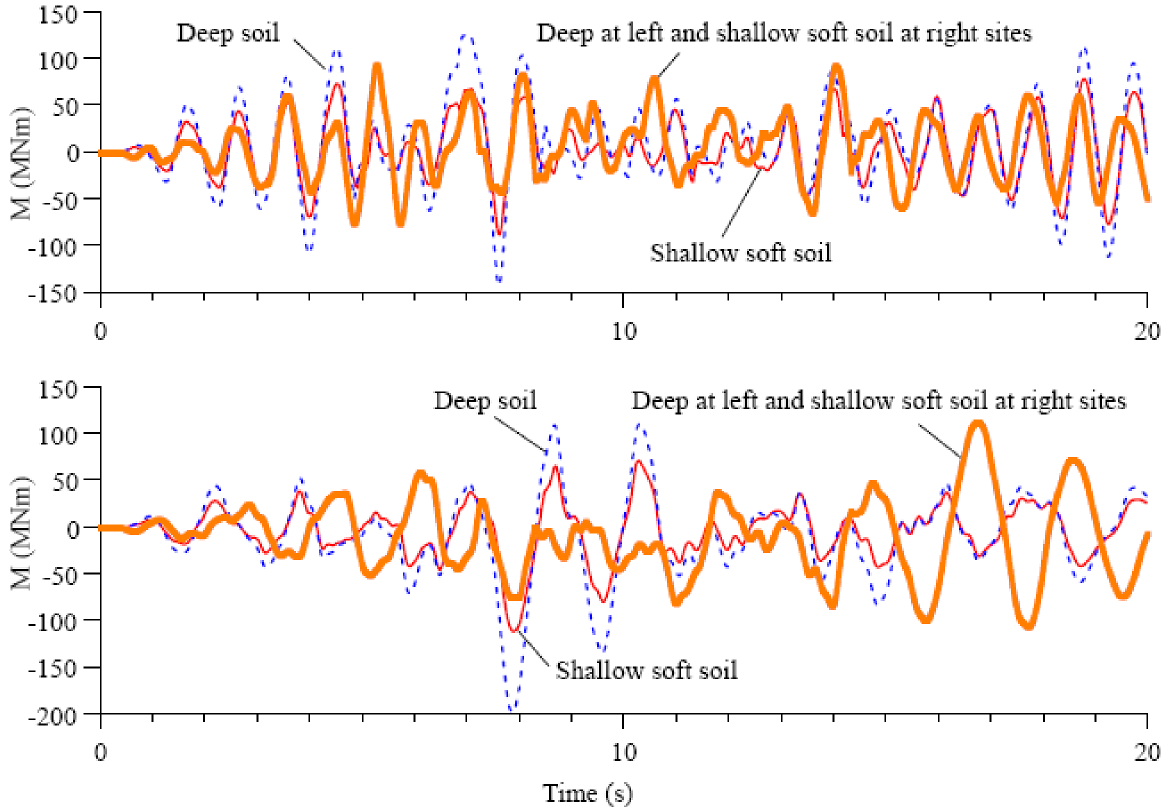

Figure 5. Influence of local soil conditions on bending moment development at bridge pier supports

The upper and lower figures show respectively the time histories of the bending moments including pounding effect at pier supports of the left and right bridge segments. Since the results depend additionally on the gap size between the girders, a general conclusion of the influence of local soil amplification therefore cannot be derived so easily. In the considered cases the deep soft soil causes the largest bending moment at both pier supports. Table 3.2 gives the maximum bending moments with their time of occurrences.

4. CONCLUSIONS

In this preliminary investigation local site effect on the development of spatially varying ground motions and their consequence for pounding response of two adjacent bridge segments are considered. Below the soft soil surface layers bedrock is assumed. The bedrock movements are stochastically simulated based on the new Australian design spectrum. The bridge structures and subsoil are described using a combined finite element and boundary element method.
The results confirmed that soft soil layer at bridge sites can significantly amplify the pounding damage potential of bridge girders. In the considered cases deep soft soil caused the largest bending moment at the bridge piers. However, in order to obtain more general conclusions further studies are necessary, because they are determined by the combined influence of several factors, non-uniform local sites, unequal soil-structure interaction, different dynamic structural properties of adjacent bridge segments, gap size and distance between considered adjacent sites.

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