16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 1465 (Abstract ID)

Registration Code: S-A1458623725

EFFECT OF POUNDING AND SOIL-STRUCTURE INTERACTION ON THE SEISMIC RESPONSE OF SKEWED BRIDGE

C. Kun[1], L. Jiang[2] and N. Chouw[3]

[1] *PhD student, Department of Civil and Environmental Engineering, the University of Auckland, Auckland, New Zealand. Email: ckun005@aucklanduni.ac.nz*

[2] *Professor, National Engineering Laboratory for Construction Technology of High Speed Railway, the Central South University, China. Email: lzhjiang@csu.edu.cn*

[3] *Associate Professor, Department of Civil and Environmental Engineering, the University of Auckland, Auckland, New Zealand. Email: n.chouw@auckland.ac.nz*

Abstract

The seismic vulnerability of skewed bridges has been found to be caused by several factors, including the skew angle of the bridge, pounding between adjacent superstructures, and soil-structure interaction (SSI). In this paper, a straight and 30˚ skewed bridge-abutment model were considered to investigate the effects of skew angle on the seismic response of the bridge. The influence of pounding and SSI were also investigated. The bridge segments were allowed to collide with the abutments and spaced apart so that collision does not happen. The bridge was also fixed on the shake table and founded on sand to study the effects of SSI. This paper focused on the bending moments of the bridge pier and in-plane rotations of the bridge girder. It was found that pounding reduced the bending moments of bridges by up to 23%. When pounding was not considered, the bending moment of the skewed bridge was 0.60 times that of the straight in the fixed base case, but was 1.20 times that of the straight when SSI was introduced. The maximum rotation induced in the bridge girder of the skewed bridge in the SSI case was 2.25 times that of the fixed base case when pounding was not considered. When pounding was introduced, SSI did not have much effect on the maximum rotation induced.

Keywords: skewed bridge; pounding; soil-structure interaction; shake table test

1. Introduction

The need for construction of skewed bridges could arise from several reasons such as the presence of obstacles, bridges spanning over complex intersections, and space or terrain restrictions. They have been found to be more prone to damage during seismic events, as was seen during the 1971 San Fernando earthquake [1], 1994 Northridge earthquake [2], 1995 Kobe earthquake [3], and the 2010 Chile earthquake [4].

Damage to bridges, and in worse cases, collapse of bridges could cause loss of functionality and loss of lives. Some studies have found one of the primary causes to be pounding at the location of the bridge expansion joint. Pounding happens when adjacent superstructures move out-of-phase from each other and closes the size of the gap provided. These out-of-phase movements could be due to several reasons like the spatial variation of ground motions, adjacent superstructures with different fundamental frequencies, and soil-structure interaction (SSI), or a combination of these factors [5].

The vulnerability of skewed bridges has been associated to the rotations induced by the bridge girder, especially when pounding occurs. Some studies have been done to investigate the torsional response of skewed bridges. Maragakis[6] studied the rigid body motions of short-spanned skewed bridges, focusing on the in-plane rotations. The study found that the rigid body motions of skewed bridges arise from the skew of the bridge deck and impact between the deck and abutments.

Another study by Wakefield *et al.* [7] shows that the dynamic response of the short and stiff skewed bridges is dominated by rigid body motions, including rotations if the bridge deck is not rigidly connected to the abutments. Their findings also match with observations of failures from the 1971 San Fernando earthquake. Deepu *et al.* [8] found that an increase in skew angle causes the structure to become stiffer and has larger responses compared to a straight bridge of the same dimensions.

The effects of SSI on the response of structures have been vigorously debated since the past, where some researches claim SSI to be detrimental to the response of structures [9, 10, 11], and others claiming otherwise [12, 13]. Conventionally, the latter assumption that SSI is beneficial in reducing structural responses has been adopted.

Most of the studies on skewed bridges have been conducted numerically or analytically. Experimental investigations have been scarce, and none of them has included the effects of pounding and SSI. In this study, a 1:20 scale bridge-abutment model was constructed and a series of shake table tests were carried out. A straight bridge and 30˚ skewed bridge were used to investigate the effects of skew angle on the bridge response. To study the influence of SSI, a rigid sand box was used to simulate the bridge being founded on sand.

2. Methodology

2.1 Prototype and model

A 100 m segment of the Newmarket Viaduct Replacement Bridge was chosen as the prototype bridge. The dimensions of the bridge are shown in Table 1.

Table 1 – Dimensions of the Newmarket Viaduct Replacement Bridge

Parameter	Dimensions
Pier-to-pier distance	50 m
Pier height	15.5 m
Pier width	3.44 m
Pier thickness	1.48 m
Seismic mass	1.9 tons
Longitudinal frequency	0.98 Hz

The bridge was scaled based on the principles of similitude outlined by Dove and Bennett [14]. The length and time scale factors obtained were 20 and 1, respectively. The dimensions of the straight bridge model are shown in Table 2.

Table 2 – Dimensions of straight bridge model

Parameter	**Scale factor**
Bridge span	5000 mm
Pier height	775 mm
Pier width	100 mm
Pier thickness	6 mm
Seismic mass	487 kg
Longitudinal frequency	0.98 Hz

2.3 Ground motion

The ground motion used in this study was stochastically simulated based on the New Zealand design spectrum for shallow soil conditions and was subsequently scaled according to the aforementioned scale factors. The acceleration time history of the ground motion applied was shown in Fig. 1.

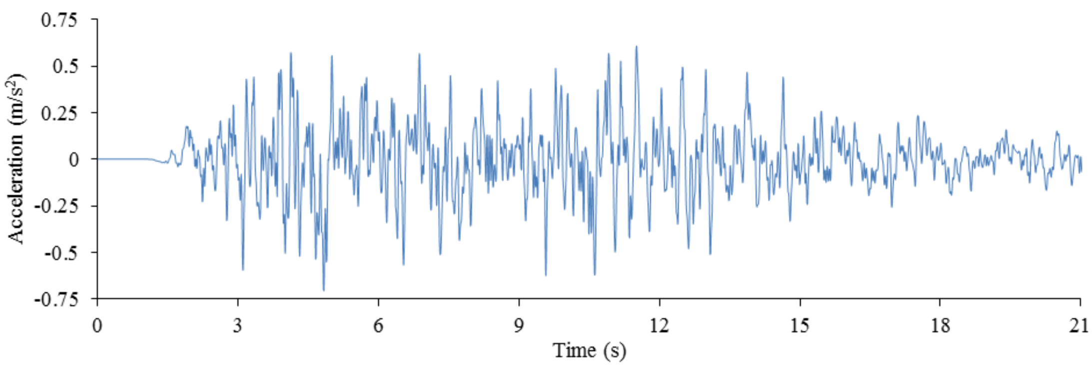

Fig. 1 – Acceleration time history of ground motion applied to model

2.4 Bridge setup

The straight and skewed bridges were fixed on the shake table or placed on compacted sand. The bridge and abutments were allowed to collide in the case where pounding was considered, and were arranged or spaced sufficiently apart when pounding was not considered. Fig. 2 shows the setup of the straight bridge for SSI case when pounding was not considered. The bridge segment and abutments experience uniform ground motions.

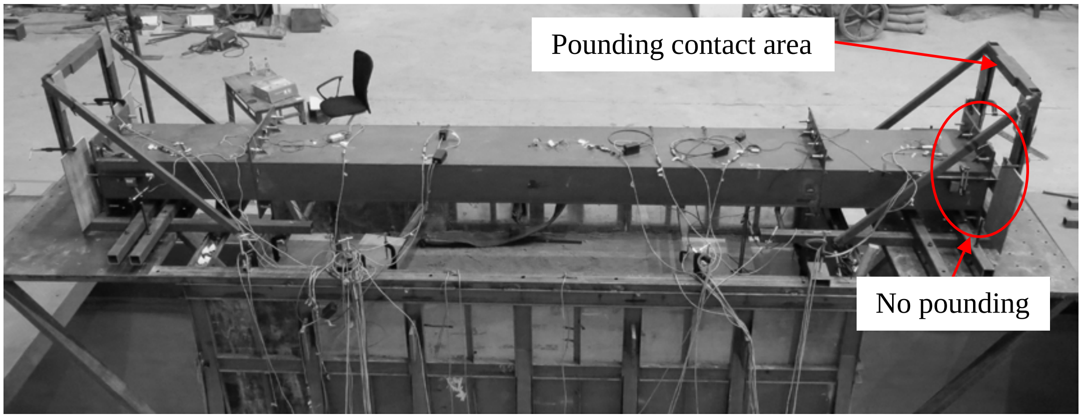

Fig. 2 – Setup of straight bridge for SSI case without considering pounding

3. Results and discussion

3.3 Bending moment development of bridge pier

The bending moment developed in the pier of the straight bridge was compared in Fig. 3 for the fixed base and SSI cases without considering pounding. It can be seen that SSI was beneficial in reducing the bending moment from about 24.58 Nm to 18.87 Nm, by about 23%.

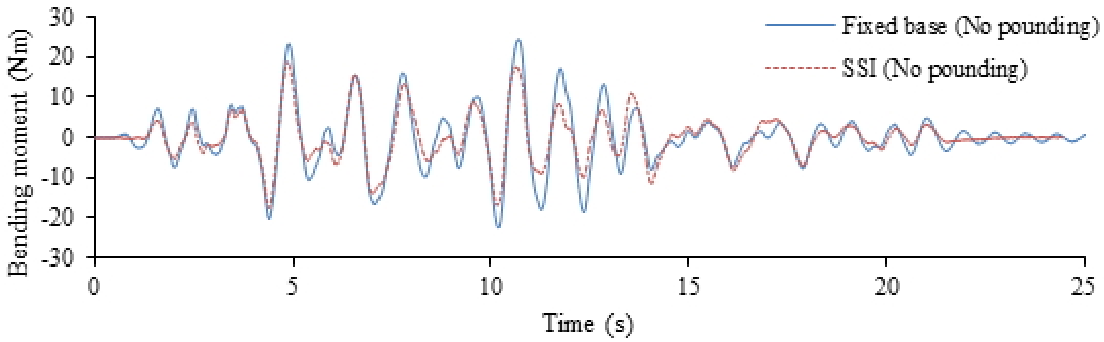

Fig. 3 – Bending moment of straight bridge for fixed base and SSI case without considering pounding

However, when pounding was considered, the influence of SSI on the magnitude of bending moment was not as significant. The restriction of girder movement due to pounding with adjacent abutments limits the bending of the bridge pier in both the fixed base and SSI cases. When the bridge was fixed on the shake table, the maximum bending moment was 8.4 Nm, whereas when it was founded on sand, a slight increase in the maximum bending moment to 9.41 Nm was observed.

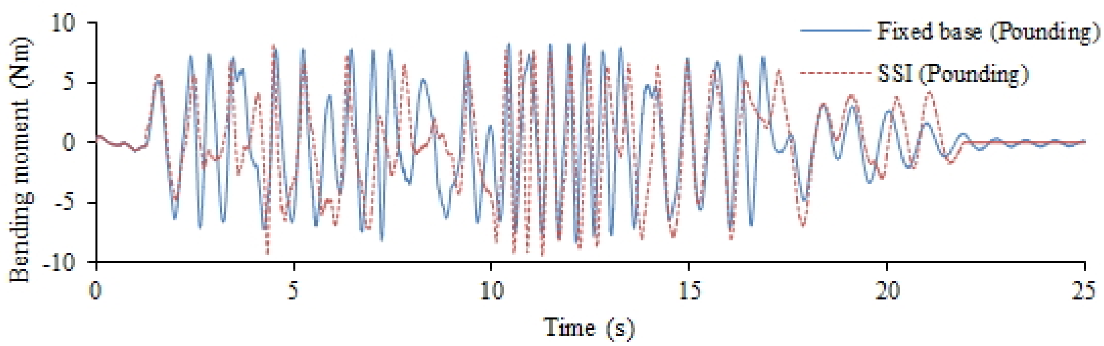

Fig. 4 – Bending moment of straight bridge for fixed base and SSI case when considering pounding

Interestingly, when a 30˚ skew angle was introduced, the bending moments for the fixed base and SSI cases did not show similar trend to that of the straight bridge. From Fig. 5, it can be clearly seen that SSI significantly increases the bending moment from 14.64 Nm to 22.72 Nm.

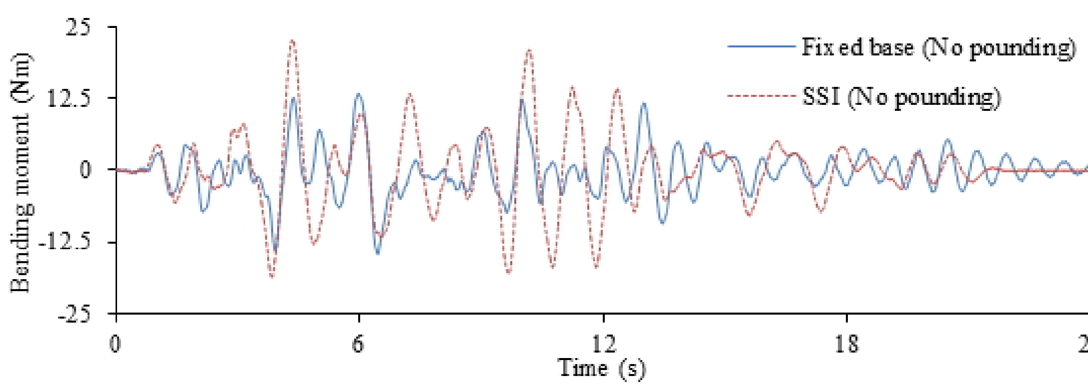

Fig. 5 – Bending moment of 30˚ skewed bridge for fixed base and SSI case without pounding

However, when pounding was introduced to the skewed bridge, similar to findings from the results of the straight bridge, SSI did not have much effect on the bending moment of the pier due to the restriction from adjacent abutments. The maximum bending moment for fixed base was found to be 8.69 Nm, whereas for SSI it was only slightly larger at about 9.26 Nm.

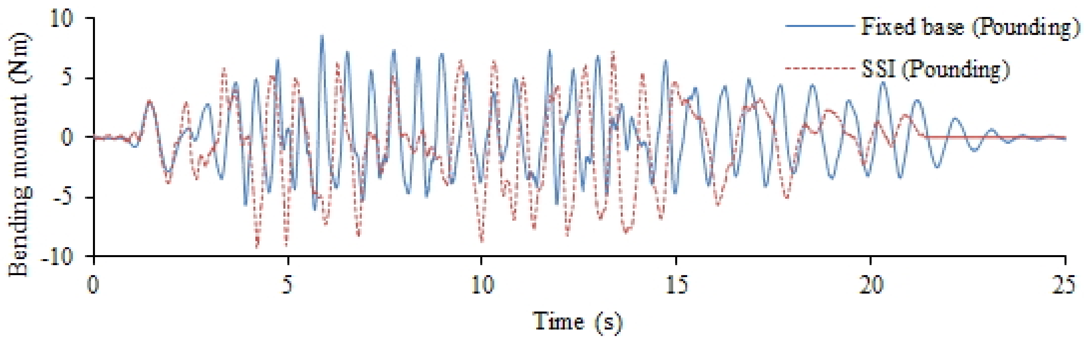

Fig. 6 – Bending moment of 30˚ skewed bridge for fixed base and SSI case considering pounding

A summary of the maximum bending moments of the straight and skewed bridges with and without considering pounding is shown in Table 3. For both bridges, pounding significantly reduced the bending moments in both the fixed base and SSI cases due to the restrictions of girder movement by the abutments. When pounding was not considered, the presence of the 30˚ skew angle affected the maximum bending moment differently depending on whether SSI was considered. For the fixed base case, the maximum bending moment of the bridge was less for the skewed bridge, but when SSI was introduced, a significant increase was seen.

Table 3 – Maximum bending moments of straight and skewed bridge with and without pounding

	Fixed base		SSI	
	No pounding	Pounding	No pounding	Pounding
Straight bridge	24.58 Nm	8.4 Nm	18.87 Nm	9.41 Nm
30˚ skewed bridge	14.64 Nm	8.69 Nm	22.72 Nm	9.26 Nm

3.3 In-plane rotations of skewed bridge girder

A possible reason for the increase in bending moments of the skewed bridge for the SSI case without considering pounding can be seen by investigating the in-plane rotations of the skewed bridge deck shown in Fig. 7. When SSI was considered, the maximum rotation induced was 0.09˚ for the SSI case, whereas when the bridge was fixed to the shake table, it was significantly less at only about 0.04˚.

This torsional response not only increases the loading demands on the bridge piers, it also significantly increases the girder unseating potential of the skewed bridge. This is because the increased rotations would likely result in larger relative displacements between the bridge segment and abutments, especially in the out-of-plane direction.

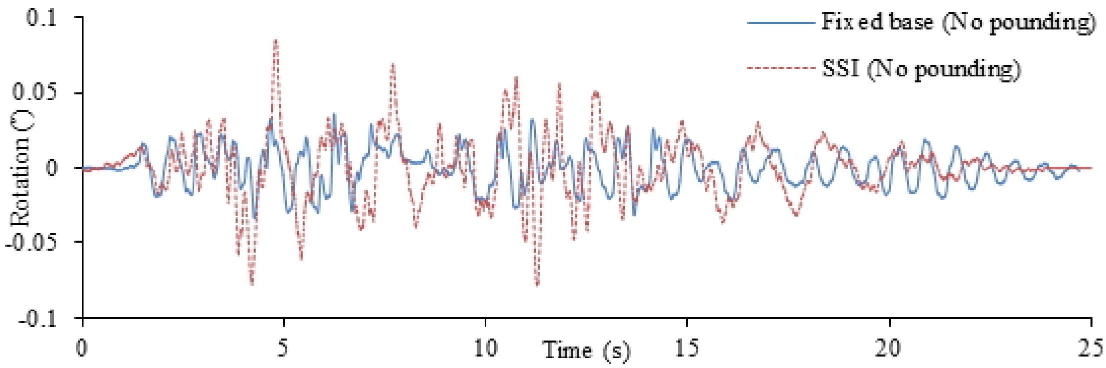

Fig. 7 – In-plane rotations of 30˚ skewed bridge for fixed base and SSI case without pounding

Fig. 8 shows the rotation of the skewed bridge deck when considering pounding. As was found with the bending moment and relative displacement, a similar trend was observed with the maximum rotation of the girder. The maximum rotations induced for the fixed base and SSI cases were very similar at about 0.1˚ and 0.09˚, respectively.

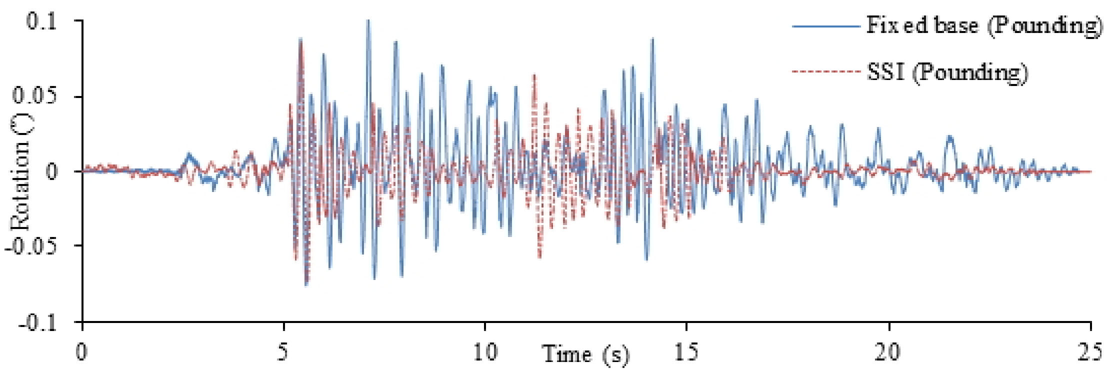

Fig. 8 – In-plane rotations of 30˚ skewed bridge for fixed base and SSI case with pounding

4. Conclusions

A 1:20 scale bridge-abutment model was constructed and subjected to shake table tests. Two bridges - straight and 30˚ skew were constructed. The bridge segment and abutments were subjected to uniform ground motions simulated based on the New Zealand design spectrum for shallow soil conditions. A rigid sand box was used to simulate SSI conditions and the results were compared with that of the fixed base case, where the bridge was fixed on the shake table. The results reveal:

- Without pounding:
    - When both the straight and skewed bridges were fixed on the shake table, the skewed bridge had smaller bending moments.
    - In the SSI case, the opposite was found, where the skewed bridge had larger bending moments.
    - SSI significantly increased the in-plane rotations of the skewed bridge girder.
    - SSI was beneficial in reducing the bending moments of the straight bridge compared to when the bridge was fixed to the shake table, but was detrimental for the skewed bridge.
- With pounding:
    - The maximum bending moments of both the straight and skewed bridge for fixed base and SSI cases were significantly reduced.
    - SSI had little effect on the maximum rotations induced in the bridge girder.

5. Acknowledgements

The authors would like to thank the Central South University, Changsha, China, for the opportunity to perform the tests and provide funding under the project 2013G002-A-1. A heartfelt gratitude is also given to colleagues Ellys Lim and Xiaoyang Qin for the help and support given throughout the project.

6. References

[1] Wood J, Jennings P (1971): Damage to freeway structures in the San Fernando earthquake. *Bulletin of the New Zealand Society for Earthquake Engineers*, **4** (3), 347–376.

[2] Mitchell D, Bruneau M, Saatcioglu M, Williams M, Anderson D, Sexsmith R (1995): Performance of bridges in the 1994 Northridge earthquake. *Canadian Journal of Civil Engineering*, **22** (2), 415-427.

[3] Chouw N (1996): Effect of the earthquake on 17th of January 1995 on Kobe, *D-A-CH meeting of the German, Austrian and Swiss Society for Earthquake Engineering and Structural Dynamics*, Technical University of Graz, Austria, 135-169.

[4] Kawashima K, Unjoh S, Hoshikuma JI, Kosa K (2011): Damage of bridges due to the 2010 Maule, Chile, Earthquake. *Journal of Earthquake Engineering*, **15** (7), 1036-1068. doi: 10.1080/13632469.2011.575531.

[5] Chouw N, Hao H (2009): Seismic design of bridge structures with allowance for large relative girder movements to avoid pounding. *Bulletin of the New Zealand Society for Earthquake Engineering*, **42** (2), 75-85.

[6] Maragakis E (1985): A model for the rigid body motions of skew bridges. *Technical Report Caltech EERL*, California Institute of Technology, Pasadena, California, USA. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0021938781&partnerID=40&md5=213fecabcd83a8e2c7e5c23349bb4ab2

[7] Wakefield RR, Nazmy AS, Billington DP (1991): Analysis of seismic failure in skew RC bridge. *Journal of Structural Engineering*, **117** (3), 972-986.

[8] Deepu SP, Prajapat K, Ray-Chaudhuri S. (2014): Seismic vulnerability of skew bridges under bi-directional ground motions. *Engineering Structures*, **71** (0), 150-160. http://dx.doi.org/10.1016/j.engstruct.2014.04.013

[9] Mylonakis G, Gazetas G. (2000): Seismic soil-structure interaction: beneficial or detrimental?. *Journal of Earthquake Engineering*, **4** (3), 277-301. doi: 10.1080/13632460009350372.

[10] Chouw N. (2008): Unequal soil-structure interaction effect on seismic response of adjacent structure. *Proceedings of the 18th New Zealand Geotechnical Society Symposium on Soil-structure Interaction*, 214-219.

[11] Chouw, N. & Hao, H. (2008). Significance of SSI and non-uniform near-fault ground motions in bridge response II: Effect on response with modular expansion joint. *Engineering Structures*, **30** (1), 154-162.

[12] Pitilakis D, Dietz M, Wood DM, Clouteau D, Modaressi A. (2008): Numerical simulation of dynamic soil–structure interaction in shaking table testing. *Soil Dynamics and Earthquake Engineering*, **28** (6), 453-467.

[13] Ghotbi AR. (2014): Performance-based seismic assessment of skewed bridges with and without considering soil-foundation interaction effects for various site classes. *Earthquake Engineering and Engineering Vibration*, **13** (3), 357-373. doi: 10.1007/s11803-014-0248-7.

[14] Dove RC, Bennett JG (1986): Scale modelling of reinforced concrete Category I structures subjected to seismic loading. *NUREG/CR-4474*, Los Alamos National Lab, New Mexico, USA. Retrieved from http://www.osti.gov/scitech/servlets/purl/6084387.