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Experimental analysis of the pounding between skewed bridge and abutments

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ABSTRACT: The seismic vulnerability of skewed bridges have been realised since the past three decades. They have been found to be prone to seismically induced poundings, which was attributed to the increase in girder unseating potential of these bridges. Past research has been done to estimate the seismic response of skewed bridges. However, most of the studies have been either numerical or analytical. In this work, the effects of pounding and presence of skew angle on the development of bending moment near the base of the bridge pier have been investigated experimentally. A 1:20 scale bridge-abutment model was constructed and subjected to uniform ground motions. The influence of skew angle was studied by comparing the results obtained with a straight bridge and 30˚ skewed bridge model under the same ground excitations. The results show that for a straight bridge, pounding causes a significant reduction in the bending moment developed, by more than 4 times from 17.25 Nm to 4.20 Nm. The presence of skew angle either increases or decreases the bending moment, depending on whether or not pounding was considered. When pounding was neglected, the bending moments developed tend to decrease, by as much as 2.18 times from 17.25 Nm to 7.91 Nm. However, when pounding was included, the presence of skew angle was found to increase the bending moments developed, up to 1.32 times, from 4.20 Nm to 5.55 Nm.

1 INTRODUCTION

A skewed bridge has its longitudinal axis at an angle to the abutments, normally supported by piers constructed at the same angle. The need for constructing these bridges was realised since the early 1800s (Gregory, R., 2011). Some of the main reasons for the construction of these bridges include the presence of obstacles, the need for spanning across complex intersections, and space and terrain restrictions.

The seismic vulnerability of skewed bridges has been observed as early as the 1970s – the February 1971 San Fernando earthquake (Wood and Jennings, 1971). They were also seen in subsequent earthquakes, such as in the 1994 Northridge earthquake (Mitchell *et al.*, 1995) and the 2010 Chile earthquake (Kawashima *et al.*, 2011).

Wood and Jennings (1971) reported extensive damage to lateral load resisting elements of bridges with moderate span and relatively large skew angles in the San Fernando earthquake. They also found that the damage was aggravated by the rotations of the bridge induced by the skew angle. Jennings (1971) and Watanabe and Kawashima (2004) found that the rotations were due to the interaction between the bridge and the approach fill.

Although there have been some investigations on the seismic vulnerability of skewed bridges, such as by Maragakis and Jennings (1987), Kwon and Jeong (2013), and Chegini and Palermo (2014), highlighting the detrimental effects of skew angle, not many have included the effects of pounding. One of these was the work done by Tirasit and Kawashima (2008), where they revealed that seismically induced pounding not only causes an increase in the torsional response of the bridge, but also increases the flexural ductility demand of the piers.

Huo and Zhang (2013) also studied the effects of skewness and pounding on the response of bridges. They found that when pounding was not considered, the skewed bridge performed better than the straight one, but pounding caused more damage, and was worsened by the increase in skew angle.

These studies however, have been conducted either numerically or analytically. Not many experimental works have been done to investigate the effects of pounding on the seismic response of skewed bridges. Chegini and Palermo (2014) did shake table tests to investigate the seismic response of a skewed bridge. They found that skew angle did not increase the size of the opening between the segment and abutments, but caused asymmetric rotation of the deck that could increase the girder unseating potential. However, pounding was not considered in their study.

This paper presents findings obtained from a series of shake table tests performed on a bridge-abutment model to investigate the effects of pounding and skew angle on the bridge behaviour. A 1:20 scale straight and skewed bridge-abutment model was constructed and subjected to uniform excitations. The effects of pounding and skew angle on the bending moment development near the base of the bridge pier are discussed.

2 METHODOLOGY

2.1 Prototype and model

The prototype bridge used in this study was the Newmarket Viaduct Replacement Bridge located in Auckland, New Zealand. The bridge spans 100 m, with a height of 15.5 m, and a pier-to-pier distance of 50 m. The dynamic properties of the prototype and model are summarised in Table 1.

Table 1: Dynamic properties of bridge prototype and model

	Bridge span (m)	Pier height (m)	Pier width (m)	Pier thickness (m)	Seismic mass (kg)	I_{deck} (mm^4)	I_{pier} (mm^4)	Longitudinal frequency (Hz)
Prototype	100	15.5	3.44	1.48	1,895,413	9.34	0.39	0.98
Model	5	0.775	0.1	0.006	487.44	1.13×10^7	1.8×10^3	0.98

The prototype was scaled according to principles of similitude outlined by Dove and Bennett (1986). The scale factors used are shown in Table 2.

Table 2: Scale factors derived from principles of similitude

	Length, L	Time, t	Modulus of Elasticity, E	Mass, m	Acceleration, a	Stiffness, k
Similitude	N_L	N_t	N_E	N_m	$N_a=N_L \div N_t^2$	$N_k=N_m \times N_a \div N_L$
Model	20	1	0.15	3888.487	20	3888.487

2.2 Setup

A bridge-abutment model was constructed to study the effects of pounding between bridge and abutments on the seismic response of the bridge segment. The model was fixed on a 4 m × 4 m shake table and was subjected to excitations in the longitudinal direction. Only uniform ground motions were considered. To investigate the effects of skew angle on the bridge, the ends of the girder were designed to be detachable so that they can be swapped with a section with the corresponding angle. In this study, a 30˚ skewed bridge was used. Strain gauges were attached near the base of the bridge piers to measure the bending moments developed. The setup of the straight and 30˚ skewed bridge on the shake table are shown in Figures 1 and 2, respectively.

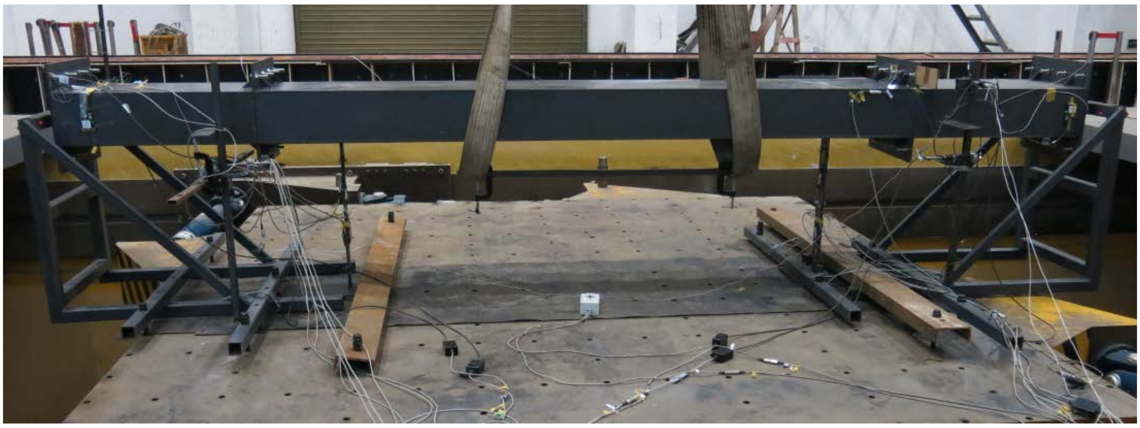

Figure 1: Setup of straight bridge on shake table

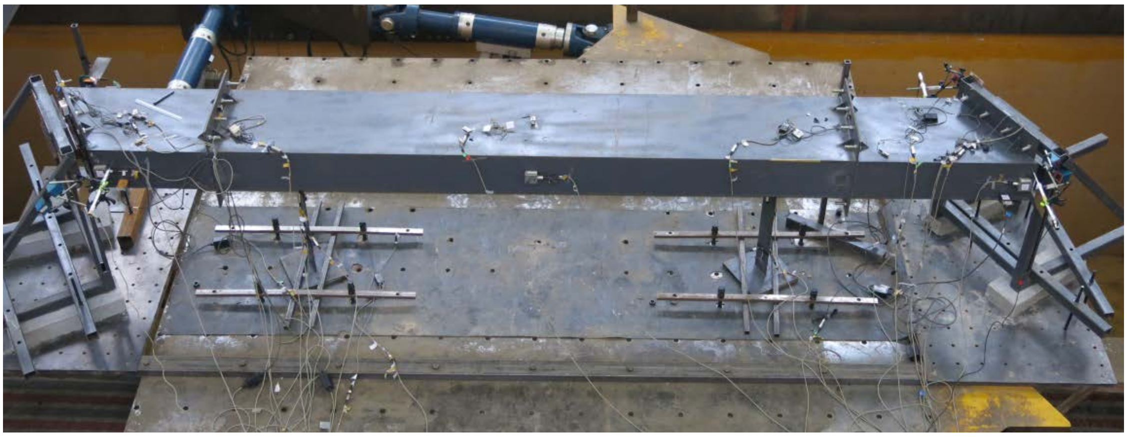

Figure 2: Setup of 30˚ skewed bridge on shake table

In the case when pounding was considered, the seismic gap between the segment and abutments was 2 mm, whereas when pounding was not considered, the abutments were spaced sufficiently further apart so that they do not come in contact.

2.3 Ground motions

The ground motion used in this study was a stochastically simulated ground motion based on the New Zealand Standard for Earthquake Loading, NZS 1170.5 for shallow soil conditions (Standards New Zealand, 2004).

Figure 3 shows the time history of the ground motion that was applied to the model.

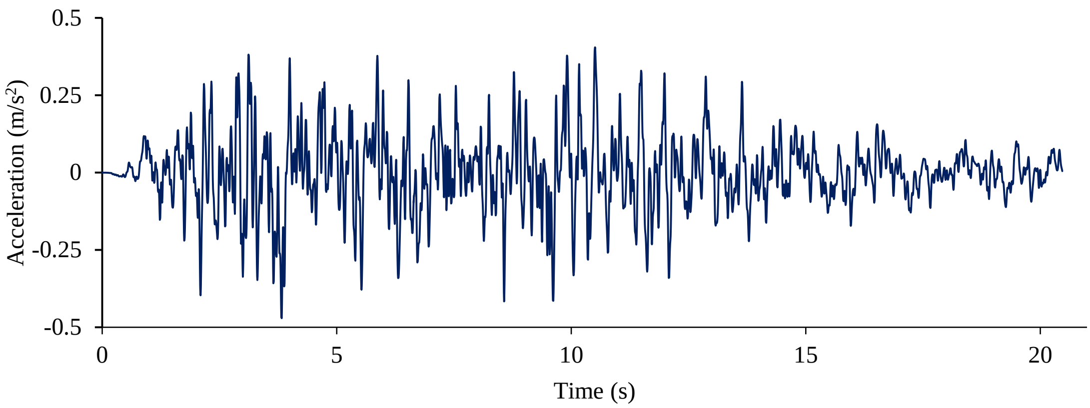

Figure 3: Time history of one of the ground motions used

The response spectrum of the ground motion and design spectrum from NZS 1170.5 are plotted in Figure 4.

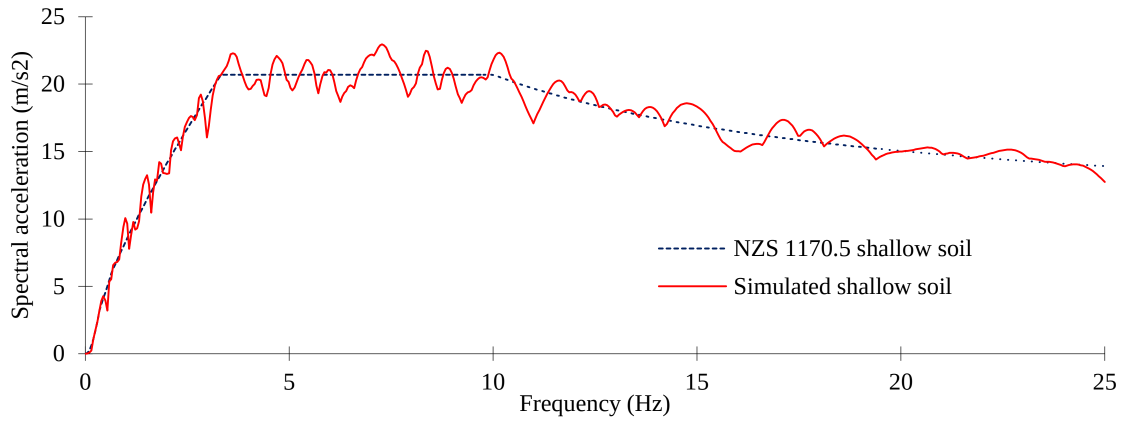

Figure 4: Design and response spectra of ground motion used

3 RESULTS AND DISCUSSION

3.1 Influence of pounding between bridge segment and abutments

Figure 5 shows the development of bending moment near the base of the bridge pier for one of the tests conducted on the straight bridge. Pounding between the segment and bridge abutments causes a significant reduction of the bending moments developed, from 17.25 Nm to 4.20 Nm. The reduction was caused by the restrictions provided by the adjacent abutments when pounding was allowed. However, the collisions produce high frequency responses that are not present in the case without pounding. Not only could the collisions cause severe localised damage at the expansion joints, but the high frequency responses induced could potentially lead to damage to secondary structures attached to the structure. This is because secondary structures are normally more rigid, i.e. have higher fundamental frequencies, than the bridge segment.

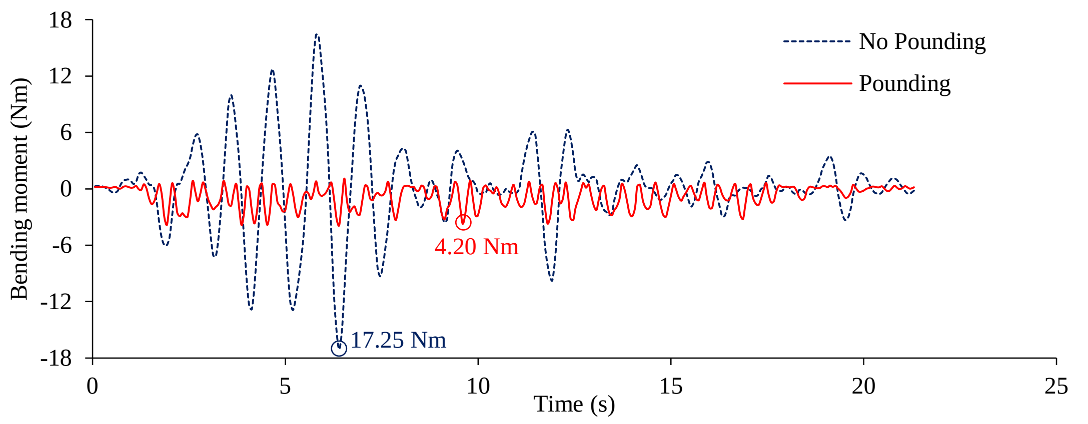

Figure 5: Bending moment development at the bridge pier of a straight bridge with and without pounding

3.2 Influence of skew angle on bridge response

A comparison of the bending moment developed at the bridge pier support was performed to investigate the effects of a skew angle on the bridge. Pounding was not included. From Figure 6, it can be seen that the presence of skew angle reduces the bending moments, from about 17.25 Nm to 7.91 Nm. However, this does not necessarily mean that the presence of a skew angle causes a reduction of the bending moment. The effects of presence of skew angle on the seismic response of the bridge depend on the contribution of other factors, in this case, the pounding.

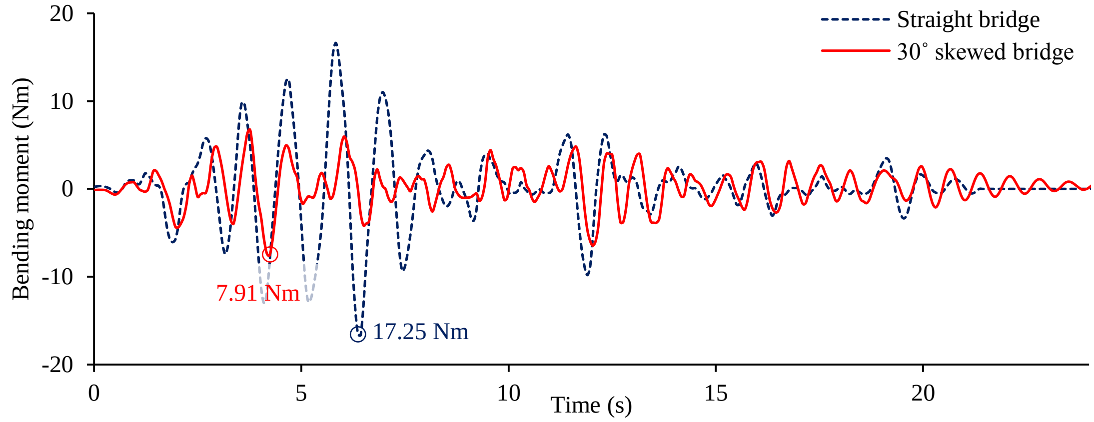

Figure 6: Bending moment development of the bridge pier for the straight and 30˚ skewed bridges without pounding

When pounding was considered, the skew angle was seen to have a different effect on the response. Figure 7 shows the bending moment development for the straight and skewed bridges with pounding effect. In contrast to the findings obtained from the case without pounding, when pounding was included, the skew angle causes a slight increase of the bending moment developed near the base of the bridge pier, from 4.20 Nm to 5.55 Nm. A possible reason for the smaller bending moment developed in the bridge pier of the straight bridge is because the large amount of collisions that occur impedes the bridge movement, thus reducing the bending moments measured.

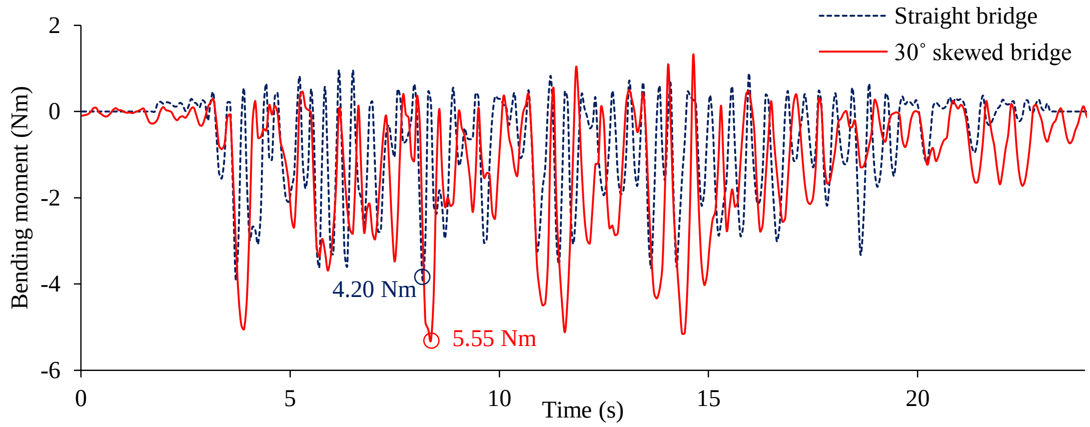

Figure 7: Bending moment development of the bridge pier for straight and 30˚ skewed bridge with pounding

4 CONCLUSIONS

This paper discussed the effects of pounding and skew angle on the seismic response of bridges. A series of shake table tests were conducted and the following conclusions can be drawn:

- Pounding between the bridge segment and abutments causes significant reduction of the bending moment developed near the base of the bridge pier.
- When pounding was neglected, the skew angle causes a reduction in the bending moments developed, but when pounding was included, the bending moments were increased.
- The collisions that happen when skew angle was introduced dissipate less energy than those of the straight bridge.

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