Earthquakes and Structures, *Vol. 14, No. 5 (2018) 467-476*
DOI: https://doi.org/10.12989/eas.2018.14.5.467

Seismic response of skewed bridges including pounding effects

Chern Kun*, Ziqi Yang and Nawawi Chouw

Department of Civil and Environmental Engineering, Faculty of Engineering, The University of Auckland, 20 Symonds Street, Auckland 1010, New Zealand

(Received October 13, 2017, Revised March 19, 2018, Accepted March 23, 2018)

Abstract. The seismic vulnerability of skewed bridges had been observed in many past earthquakes. Researchers have found that the in-plane rotation of the girders was one of the main reasons for the vulnerability of these types of bridges. To date, not many experimental works have been done on this topic, especially those including pounding between adjacent structures. In this study, shake table tests were performed on a bridge-abutment system consisting of a straight, 30°, and 45° bridge with and without considering pounding. Skewed bridges with the same fundamental frequency and those having the same girder mass as the straight bridge were studied. Under the loadings considered, skewed bridges with the same frequency as the straight tend to have smaller responses than those with the same mass. The average maximum bending moment developed in the piers of the 30° bridge with the same mass as that of the straight when pounding was not considered was 1.6 times larger than when the frequencies were the same. It was also found that the NZTA recommendations for the seat lengths of skewed bridges could severely underestimate the relative displacements of these types of bridges in the transverse direction, especially when pounding occurs. In the worst case, the average transverse displacement of the 45° bridge was about 2.6 times the longitudinal displacement of the straight, which was greatly over the limit suggested by the NZTA of 1.25 times.

Keywords: skewed bridge; pounding; shake table testing; girder unseating; bridge-abutment system

1. Introduction

Skewed bridges are bridges with longitudinal axes that are at an angle to the adjacent abutments. They have been known to be more prone to earthquake-induced damage compared to straight bridges. The presence of obstacles along the path of the bridge, bridges having to span over complex intersections, or space and terrain restrictions, are some of the reasons for having to construct these types of bridges (Huang *et al*. 2004).

Some of the damage to skewed bridges were observed in previous earthquakes, e.g., the 1971 San Fernando earthquake (Wood and Jennings 1971), the 1994 Northridge earthquake (Mitchell *et al*. 1995), the 1995 Kobe earthquake (Chouw, 1996), and the 2010 Chile earthquake (Kawashima *et al*. 2011, Yashinsky 2011). Wood and Jennings (1971) reported that damage to skewed bridges was aggravated by the in-plane rotations of the girders due to the presence of the skew angle. Jennings (1971), Watanabe and Kawashima (2004) found that the in-plane rotations were induced by the interaction between the bridge and the approach fill.

Maragakis (1985) studied the motions of skewed bridges and outlined six main types of movements of the bridge girders, i.e., rigid-body translational movements in the three principle axes, lateral and vertical flexural movements, and rigid-body torsional movements about the vertical axis. Most studies have focused on the rigid-body translational and torsional movements of skewed bridges. It was also found that the rotations of the girders were a result of the skew angle and collision between the girder and abutments.

Some numerical studies on the seismic response of skewed bridges have been done by Wakefield *et al*. (1991), Meng *et al*. (2001), Kwon and Jeong (2013). Meng *et al*. and Kwon and Jeong conducted parametric studies using numerical models on some of the factors that affect the response of skewed bridges: aspect ratio of the girder, skew angle, natural frequency of the bridge, and the ratio of rotational to translational frequency. Kwon and Jeong also concluded that the skew angle of the bridge had larger effects on the displacement demand in the longitudinal direction and less in the transverse direction. Large-scale cyclic tests were also performed by Shao *et al*. (2014) to study the ductile behaviour of bridge piers.

Some studies have also been performed on the seismic response of skewed bridges using seismic fragility functions. Soleimani (2017), Soleimani *et al*. (2017) found through sensitivity analysis that some of the common parameters that affect the behaviour of skewed bridges are such as ground motion intensity, longitudinal reinforcement ratio, column diameter, number of columns per bent, span length, and concrete compressive strength. Some other fragility and sensitivity analyses of skewed bridges were also performed by Kaviani *et al*. (2012), Zakeri *et al*. (2014, 2015), Yang *et al*. (2015).

Sullivan (2010) studied the influence of skew angle on the seismic response of bridges using seismic fragility functions. The author found that the responses of bridges with skew angles smaller than 30° were largely unaffected

∗Corresponding author, Ph.D. Candidate
E-mail: ckun005@aucklanduni.ac.nz

http://www.techno-press.com/journals/eas&subpage=7
ISSN: 2092-7614 (Print), 2092-7622 (Online)

by the skew angle, but larger skew angles increased the vulnerability of these types of bridges.

Although most studies such as by Wakefield *et al*. (1991), Deepu *et al*. (2014), Wood and Jennings (1971) reported that the damage experienced by skewed bridges were worsened by the in-plane rotations induced due to the bridges being skewed, some other studies reported otherwise. Huo and Zhang (2013) found that skewed bridges performed better than straight bridges when pounding did not occur. Catacoli *et al*. (2014) concluded that torsional responses in skewed bridges may not be induced when pounding was not considered.

Dimitrakopoulos (2011, 2013) proposed numerical approaches to estimate the response of skewed bridges, focusing on the out-of-plane displacements and in-plane rotations of the girders. The effects of seismically-induced pounding were considered. They revealed that skewed bridges are more likely to impact at the obtuse corners of the girder and consequently rotate in the direction that would cause an increase in the skew angle.

Most researches to date on skewed bridges have been conducted either numerically or analytically. Not many experimental works have been reported. To the authors' best knowledge, the only experimental studies on skewed bridges were conducted by Kun *et al*. (2017). They conducted shake table tests on a single-span bridge-abutment model consisting of straight and skewed bridges considering the effects of pounding. They found that seismically-induced pounding could significantly amplify the out-of-plane movements of the bridge girders, especially at the obtuse corner. The conventional assumption that the larger the skew angle, the larger the in-plane rotations of the girders may not necessarily be valid.

Current studies have found that seismically-induced pounding is particularly detrimental to skewed bridges as they induce larger in-plane rotations of the girder. Pounding occurs when the closing displacement between the bridge segment and adjacent abutments is larger than the size of the thermal expansion gap provided. It is usually difficult to avoid because of the typically small size of the gap provided for user comfort.

Pounding between adjacent structures have been more extensively studied compared to pounding of bridges. Those considering skew angle of bridges are even harder to come by. Some studies done on the pounding between buildings include Khatiwada and Chouw (2013), Khatiwada *et al*. (2014).

Pounding has been attributed to major collapses of bridges (Chouw and Hao 2008, Anagnostopoulos and Karamaneas 2008). Chouw *et al*. (2006), Won *et al*. (2008), Weiser and Maragakis (2013) were among those who reported the detrimental effects of pounding through numerical analyses. Some experimental work had been carried out by Li *et al*. (2011, 2012) on a three-span straight bridge model and a single-span straight bridge-abutment model. They also found that neglecting pounding when designing bridges could potentially cause significant underestimation of the responses. Pounding of straight bridges has been studied more extensively compared to those with skew angles.

In this study, the behaviour of a bridge-abutment model consisting of a straight, 30°, and 45° skewed bridge was analysed through conducting shake table tests. The dimensions of the straight and skewed bridges were identical. A parametric study focusing on two key properties, i.e., mass and frequency was conducted. In the first set of experiments, the skewed bridges were designed to have the same mass as the straight bridge. With the same pier size, this means that the fundamental frequencies of the bridges will be different. In the other set of experiments, the skewed bridges had the same fundamental frequencies as that of the straight bridge. This was achieved by adjusting the mass of each bridge accordingly to obtain the required frequency.

2. Methodology

2.1 Model and setup

A 1:100 scale bridge model was constructed based on the Newmarket Viaduct Replacement Bridge located in Auckland, New Zealand. The bridge is 100 m long, with a pier-to-pier distance of 50 m. The compressive strength of the concrete was assumed to be 50 MPa. Table 1 shows a summary of the parameters of the prototype bridge.

The prototype was scaled down using principles of similitude adopted from Makris (2014), Chen *et al*. (2017), and Qin *et al*. (2013). The fundamental analysis was based on Buckingham's π theorem (Buckingham 1914). The scale factors adopted were shown in Table 2.

Based on the scale factors, the dimensions of the straight bridge model were calculated, as shown in Table 3. Polyvinylchloride (PVC) was used to construct the bridge girder and piers. The model was kept elastic to allow for repeatability of subsequent tests.

A straight, 30°, and 45° skewed bridges were constructed. The dimensions of the bridge girders were selected to allow for assumption of rigid-body motion. In total, five bridges were constructed: a straight bridge, two 30° bridges, and two 45° bridges. The size of the bridge

Table 1 Parameters of Newmarket viaduct replacement bridge

Bridge span	100 m	I_{deck}	9.34 m^4
Pier height	15.5 m	I_{pier}	0.39 m^4
Distance between piers	50 m	$K_{bending}$	71.85 MN/m
Pier width	3.44 m	$E_{concrete}$	30 GPa
Pier thickness	1.48 m	Longitudinal frequency	0.98 Hz
Effective mass at height of girder	1895 t		

Table 2 Scale factors

Physical Quantity	Similitude	Scale factor
Length (N_L)	N_L	100
Time (N_t)	N_t	2
Modulus of Elasticity (N_E)	N_E	12
Mass (N_m)	N_m	224,442
Acceleration (N_a)	$N_a=N_L \div N_t^2$	25

Table 3 Parameters of bridge model

Bridge span	1000 mm	Mass	8.445 kg
Pier height	155 mm	I_{deck}	33,333 mm^4
Distance between piers	500 mm	I_{pier}	67.5 mm^4
Pier width	30 mm	E_{PVC}	2,500 MPa
Pier thickness	3 mm	Longitudinal frequency	1.96 Hz

Table 4 Cases/bridges considered

Case		Mass (kg)	Frequency (Hz)
Straight		8.445	1.96
30°	(*F*)	6.07	1.96
	(*M*)	8.445	1.45
45°	(*F*)	7.565	1.96
	(*M*)	8.445	1.75

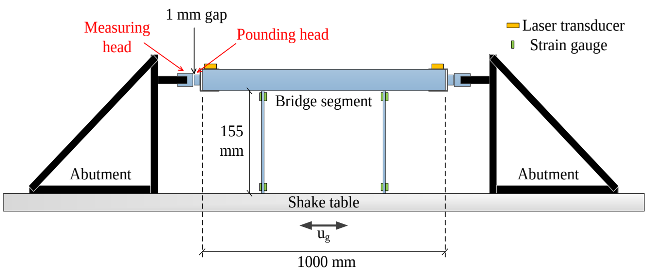


Fig. 1 Setup of straight bridge-abutment model when considering pounding

piers were kept the same for all bridges. For each skew angle, one of the bridges had the same longitudinal frequency as the straight bridge. The mass of the girders were adjusted accordingly to achieve this. The results for skewed bridges with the same frequencies as the straight will hereafter be denoted with an '*F*', e.g., for the 30° skewed bridge when pounding was considered, 30° (*F*) (Pounding). The other bridges for each skew angle were designed to have the same physical properties, i.e., dimensions of bridge and girder mass. This means that the longitudinal frequencies of the bridges will differ. The results for the skewed bridges with the same mass as the straight will hereafter be denoted with an '*M*', e.g., for the 30° skewed bridge when pounding was considered, 30° (*M*) (Pounding). A summary of the cases considered were shown in Table 4. The values in *italic* were kept the same.

The bridge segment and abutments were fixed on a uniaxial shake table with a payload of 10 kN. For the skewed bridges, the abutments were adjusted to be parallel to the face of the bridges. The bridge and abutments experience spatially uniform excitations. In the cases where pounding was considered, the abutments were fixed at 1 mm apart from the bridge segment, whereas when pounding was not considered, they were spaced sufficiently apart so that the bridge segment did not come in contact with the abutments. The setup of the bridge-abutment model considering pounding is shown in Fig. 1.

In order to measure the pounding forces at the bridge-abutment interface, two pounding and measuring heads were constructed using PVC. The pounding heads were

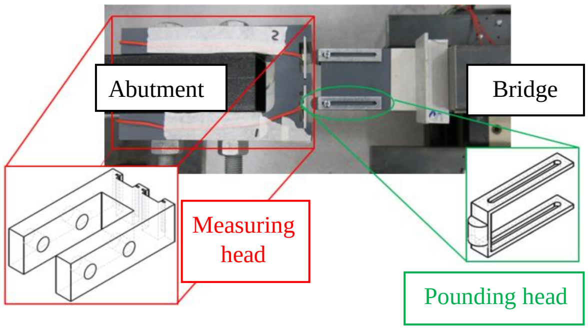


Fig. 2 Pounding and measuring heads

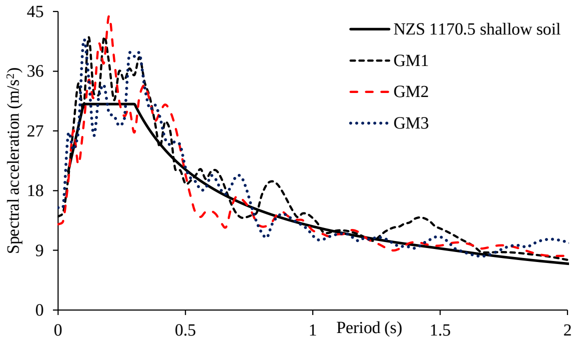


Fig. 3 Response spectra of 3 simulated excitations and the NZS 1170.5 design spectra

attached to the ends of the bridge, whereas the measuring heads were attached to the abutments. Two pounding and measuring heads were used on each side of the bridge to measure the pounding force at the acute and obtuse corners of the skewed bridges. Each measuring head was a sensor that measures force using a strain gauge attached to the back of a piece of steel. A photo of the pounding and measuring heads was shown in Fig. 2.

The bending moments developed near the top and base of the piers were measured using strain gauges attached to the piers. The displacements of the bridge girders relative to the abutments were measured using laser transducers. For the straight bridge, there were no movements in the transverse direction. The transverse displacements were only measured for the skewed bridges.

2.2 Ground motions

Ten earthquake excitations were stochastically simulated based on the design spectra for shallow soil (Class C) ground conditions as specified in NZS 1170.5 (Standards New Zealand 2004). Details of the simulated ground motions were elaborated by Kun *et al.* (2017) and the numerical approach for simulating the ground motions has been explicated in Chouw and Hao (2005).

The response spectra of three of the simulated ground motions and the corresponding NZS design spectra were plotted in Fig. 3.

2.3 Bridge design specifications

Many current bridge design specifications have not

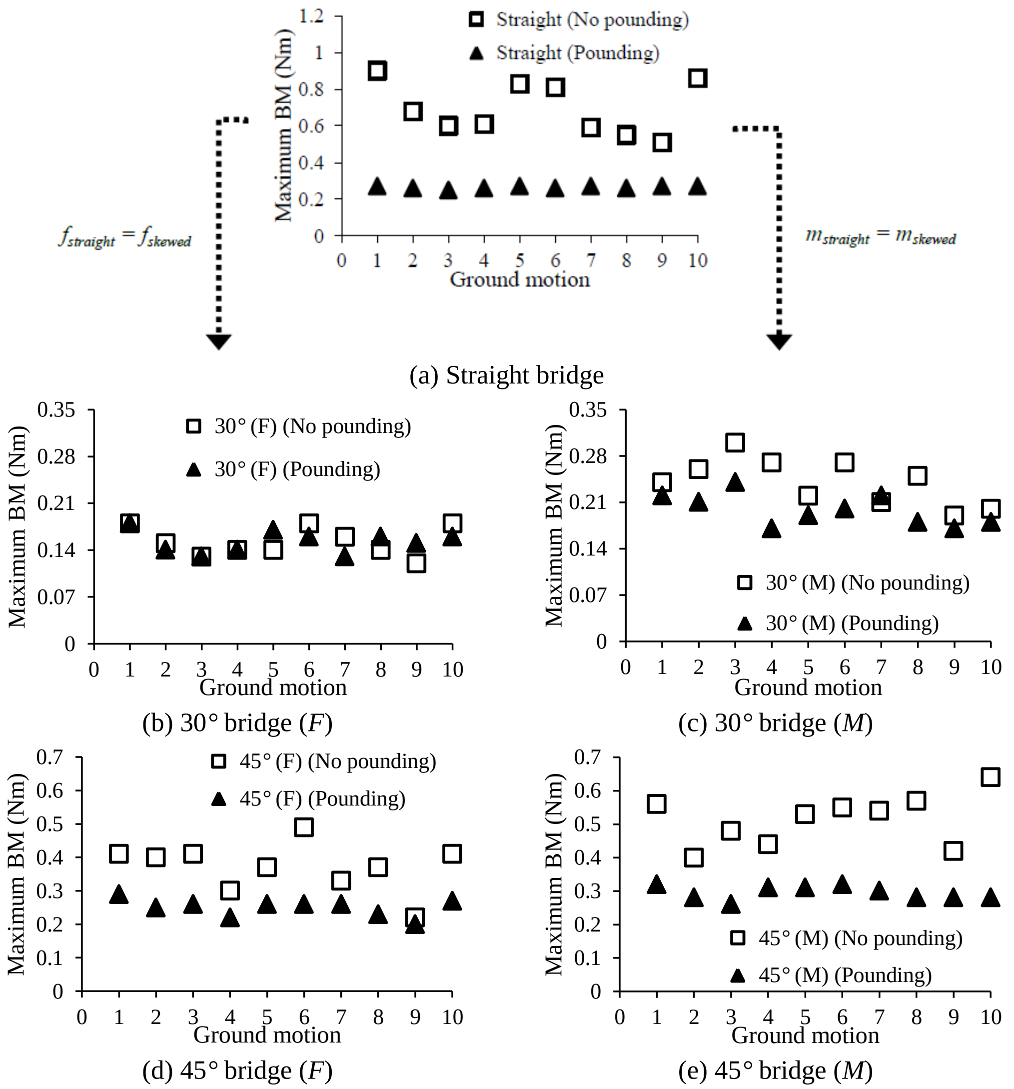


Fig. 4 Maximum bending moment near the top of the piers for the straight, 30°, and 45° bridges

considered the effects of pounding. This oversimplification could be one of the reasons for the occurrence of unseating of girders. In this study, the recommendations specified in the NZTA bridge manual will be used as an example to evaluate the adequacy of design standards when designing the seat lengths of skewed bridges.

2.3.1 NZTA bridge manual

The required seat length, *SL*, for a straight bridge recommended by the NZTA bridge manual (New Zealand Transport Agency 2016) is given in Clause 5.5.2 (d) as

$$SL = 2E + 100mm \geq 400mm \tag{1}$$

where *E* is the relative movement between span and support.

For short-span skewed bridges, the NZTA bridge manual recommends that the required seat length in both the longitudinal and transverse directions be increased by up to 25% of that of the straight bridge. This requirement implies that the expected relative displacements of the skewed bridge are only up to 25% larger than that of the straight bridge.

3. Results and discussions

The results in this paper discusses the bending moments developed near the top of the bridge piers, the relative displacement between the bridge segment and abutments in the longitudinal and transverse directions, and the in-plane rotations generated by the bridge girders of the skewed bridges.

3.1 Bending moment developed in bridge piers

Fig. 4 shows the maximum bending moment of the straight, 30°, and 45° bridges with and without considering the effects of pounding. It can be seen that other than the 30° (*F*) case, the bending moments of all bridges were always larger when pounding was not considered. A ‘capping’ behaviour was observed when pounding occurred; the abutments restricted the movements of the girders. In the 30° (*F*) case, the bending moments with and without pounding were similar. Comparing the (*M*) and (*F*) cases, the bending moments of the skewed bridges tend to be smaller in the latter case.

Table 5 Average maximum bending moments near the top of the piers for each bridge

Case		BM, NP* (Nm)	BM, P* (Nm)	BM, NP/ BM, P
Straight		0.69	0.26	1/ 0.4
30°	*F*	0.15	0.15	1/ 1.0
	M	0.24	0.20	1/ 0.8
45°	*F*	0.37	0.25	1/ 0.7
	M	0.51	0.29	1/ 0.6

* NP: No pounding; P: Pounding

Table 6 Average maximum longitudinal displacements of the girders of each bridge

		R_d, NP* (mm)	R_d, P* (mm)	R_d, NP/ R_d, P
Straight		4.03	1.08	1/ 0.27
30°	*F*	0.78	0.83	1/ 1.06
	M	0.71	0.75	1/ 1.06
45°	*F*	1.77	1.09	1/ 0.62
	M	2.45	1.44	1/ 0.59

* NP: No pounding; P: Pounding

The average maximum bending moments near the top of the piers were shown in Table 5. As expected, the largest bending moment was observed for the straight bridge without considering pounding. This is partly because the orientation of the piers of the straight bridge meant that it would receive the largest excitation in the bending direction, e.g., if the excitation has an amplitude of "1", the piers will experience "1" excitation. However, with the skewed bridges (skewed piers), the piers would only be subjected to "1"×cos(θ) in the direction of bending of the piers, where θ is the skew angle. This is illustrated in Fig. 5. Interestingly, with the larger skew angle of 45°, the bending moments were larger than that of the 30°. This is likely due to the larger movements of the girder of the 45° bridge in the longitudinal direction, as discussed in Section 3.2. For both skewed bridges, the case where they had the same mass as the straight bridge (*M*) had the larger response whether or not pounding was considered.

3.2 Relative displacement of bridge girders

The maximum displacements of the girders of the straight, 30°, and 45° bridges relative to the abutments in the longitudinal direction were plotted in Fig. 6. The displacements show almost an identical trend as the bending moments (Fig. 4). This proves that the bending moments developed in the bridge piers are very closely related to the longitudinal displacements of the girders. The transverse displacements may not have the same correlation with the bending moments.

The average maximum displacements and ratio of that of the NP to P case were calculated and shown in Table 6. The similar trend between the bending moments and longitudinal displacements was also seen with the ratio of the responses in the NP to P cases. From Table 5, the maximum bending moments of the piers of the straight, 30° (*F*), 30° (*M*), 45° (*F*), and 45° (*M*) bridges in the pounding cases were on average 0.38, 1, 0.82, 0.67, and 0.57 times that of the no pounding case, respectively. With the relative longitudinal displacements (Table 5), they were 0.27, 1.06, 1.06, 0.62, and 0.59 times, respectively.

The transverse displacements of the skewed bridges were plotted in Fig. 7. The displacements of the bridges in all cases were larger when pounding was not considered. This was possibly due to the restrictions provided by the

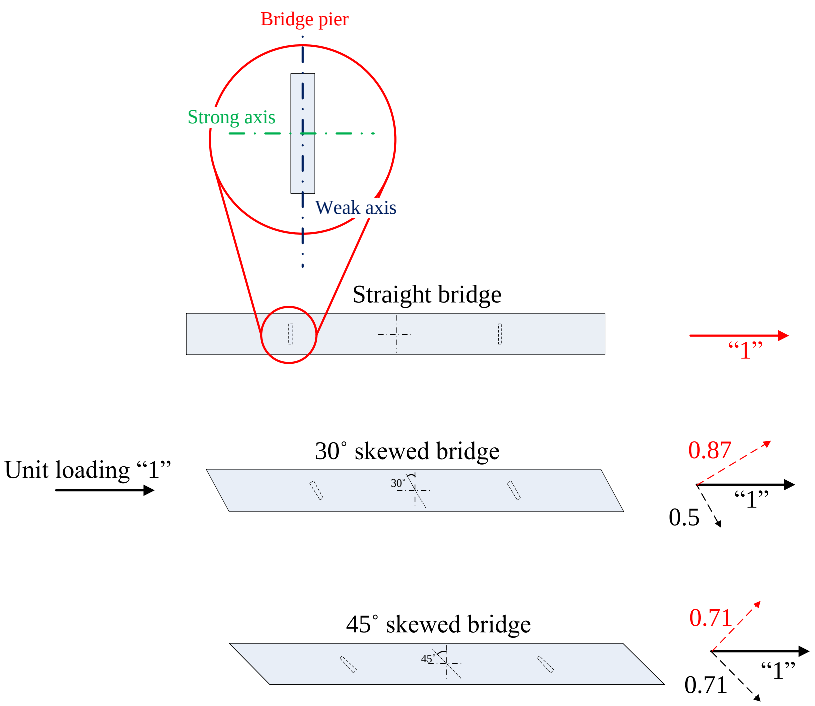


Fig. 5 Amplitude of loading experienced by bridge piers in the direction of bending (from Kun *et al*. 2017)

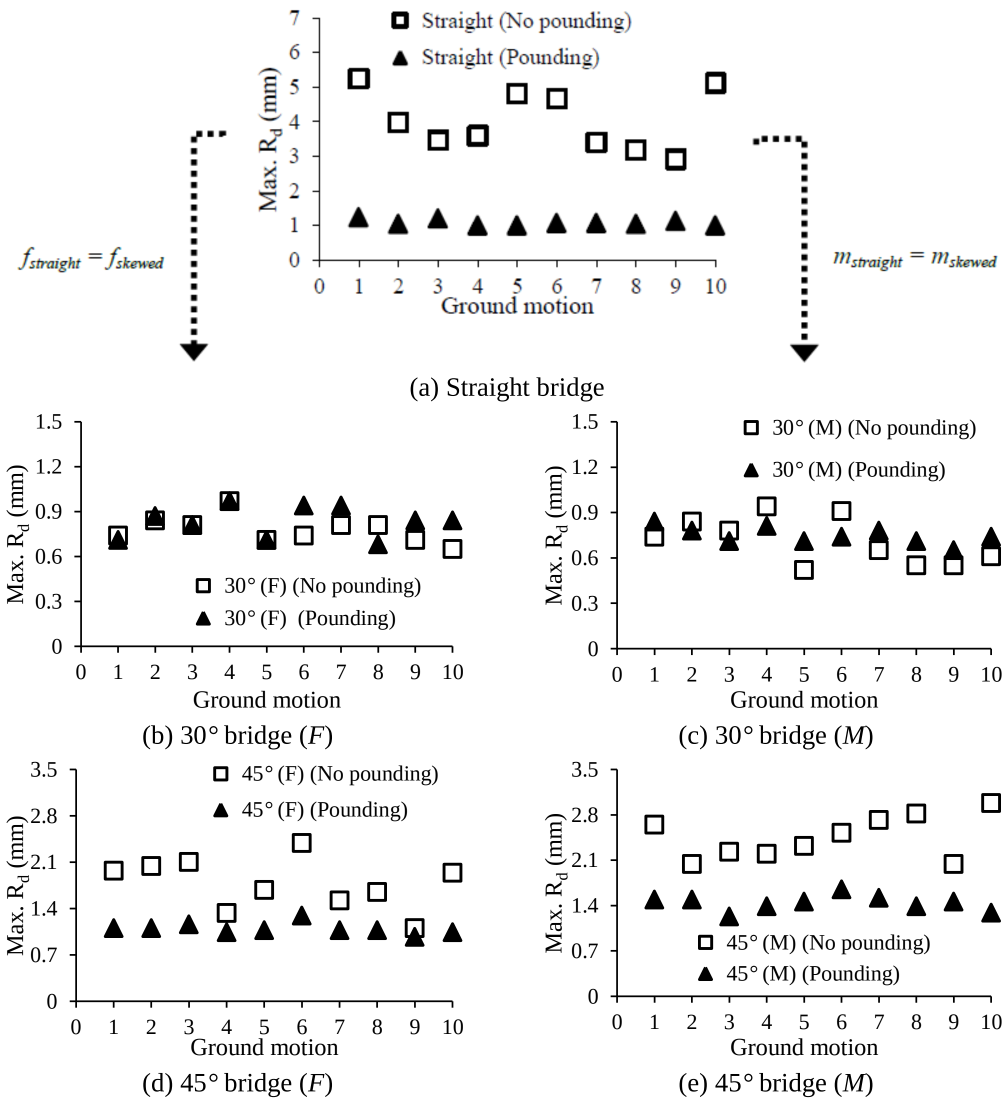


Fig. 6 Maximum relative displacement (Rd) of the girders of the straight, 30°, and 45° bridges in the longitudinal direction

Table 7 Average maximum transverse displacements of the girders of each bridge

		R_d, NP* (mm)	R_d, P* (mm)	R_d, NP/ R_d, P
30°	*F*	2.20	1.80	1/ 0.82
	M	3.20	2.37	1/ 0.74
45°	*F*	3.12	2.37	1/ 0.76
	M	3.94	2.79	1/ 0.71

* NP: No pounding; P: Pounding

abutments when pounding occurred. The transverse displacements in the (*M*) case were larger than in the (*F*) for both the 30° and 45° skewed bridges. This amplification was most significant in the 30° bridge without considering pounding.

The average maximum transverse displacements of the skewed bridges with and without considering pounding are shown in Table 7. Pounding reduced the maximum transverse displacement by up to 29% likely due to the restrictions provided by the abutments. The results also show that the displacements in the (*M*) case were significantly larger than those in the (*F*) case. The larger amplification was seen with the 30° bridge, where the transverse displacements without considering pounding were increased from 2.2 mm in the (*F*) case to 3.2 mm in the (*M*) case (amplification of approximately 1.45 times) and with pounding from 1.8 mm in the (*F*) case to 2.4 mm in the (*M*) case (amplification of approximately 1.32 times).

To evaluate the girder unseating potential of the skewed bridges based on the NZTA recommendations, the average maximum relative displacements of each bridge in the longitudinal and transverse (applicable only to skewed bridges) were normalised against the longitudinal displacement of the straight bridge in the corresponding with or without pounding cases. For example, to assess the longitudinal displacement of the 30° (*M*) bridge in the no pounding case, the average maximum displacement was normalised against the longitudinal displacement of the straight bridge in the no pounding case, i.e.

$$R_{d,\,Normalised} = \frac{30°(M), Longitudinal(NP)}{Straight, Longitudinal(NP)} \quad (2)$$

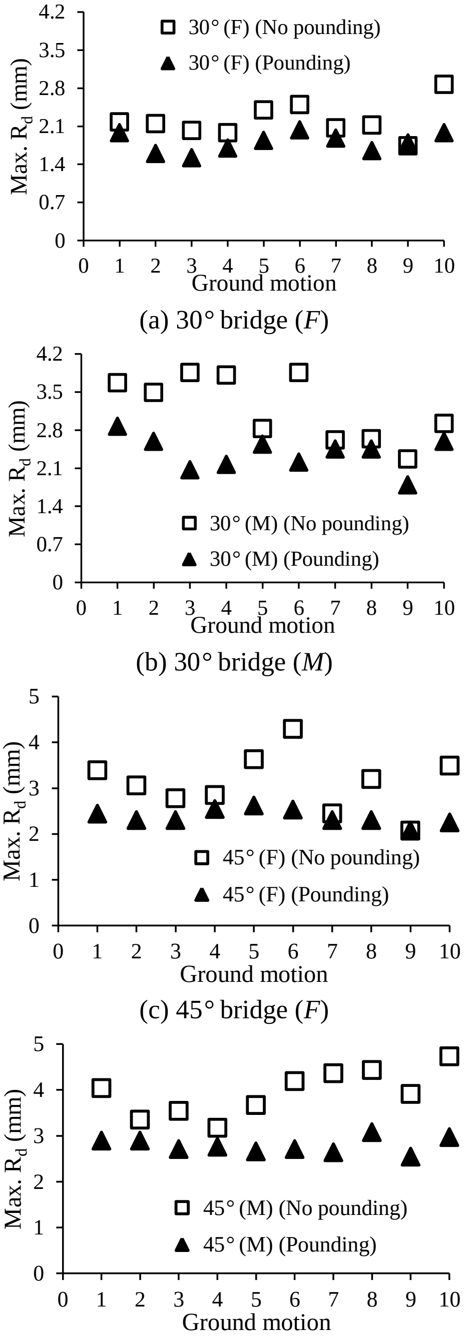


Fig. 7 Maximum relative displacement (Rd) of the girders of the 30° and 45° bridges in the transverse direction

And for the transverse displacement of the 30° (*M*) bridge in the pounding case,

$$R_{d,\,Normalised} = \frac{30°(M), Transverse(P)}{Straight, Longitudinal(P)} \tag{3}$$

The normalised displacements were given in Table 8. As the NZTA recommendations specified that the relative displacements of skewed bridges in both the longitudinal and transverse displacements were amplified by 25% of that of the straight bridge. As the straight bridge has no transverse displacements, the displacements of the skewed

Table 8 Normalised average maximum displacements of the girders of each bridge

		Longitudinal†		Transverse‡	
		NP*	P*	NP*	P*
Straight		$\frac{4.03}{4.03}=1$	$\frac{1.08}{1.08}=1$	N/A	N/A
30°	*F*	$\frac{0.78}{4.03}=0.2$	$\frac{0.83}{1.08}=0.8$	$\frac{2.20}{4.03}=0.55$	$\frac{1.80}{1.08}=\mathbf{1.7}$
	M	0.2	0.7	0.79	**2.2**
45°	*F*	0.4	1.0	0.77	**2.2**
	M	0.6	**1.3**	0.98	**2.6**

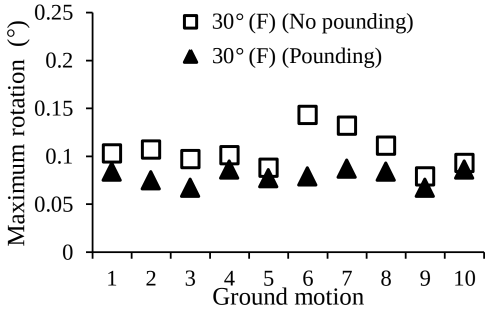
† From Table 6
‡ From Table 7
* NP: No pounding; P: Pounding

bridges were designed based on the longitudinal displacement of the straight bridge. This recommendation implies that the relative displacements of the girders of skewed bridges were expected to only be at most 25% larger than that of the straight. From Table 8, it can be seen that when pounding was not considered, the seat length recommended by the NZTA bridge manual was adequate. As pounding is difficult to avoid during strong seismic events due to the typically small thermal expansion gap, the relative displacements of the girders are likely significantly underestimated when pounding in fact does occur, as can be clearly seen from the results in Table 8. The values in **bold** were larger than 1.25, meaning that the NZTA requirements underestimated the displacements in those cases. All of the displacements of the skewed bridges in the transverse direction were severely underestimated. In the worst case i.e., 45° (*M*), Transverse (P), the average displacement was 2.6 times larger than that of the straight bridge in the longitudinal direction, much larger than the 1.25 times specified in the NZTA bridge manual. In the longitudinal direction, although in most cases, the NZTA requirements was sufficient to accommodate for the relative movements of the girders, when pounding was considered, there was still potential for the girder of skewed bridges to unseat, e.g., in this case the 45° (*M*), Longitudinal (P) case was underestimated.

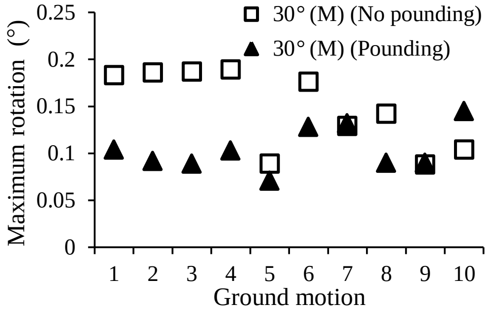
3.3 In-plane rotations of girders

Fig. 8 shows the maximum in-plane rotations of the girders of the skewed bridges. For the 30° bridge, the rotations were larger when pounding was not considered, whereas for the 45° bridge, the opposite was observed. This means that pounding potentially has a stronger effect on the in-plane rotations of the girders as the skew angle increases. The rotations were larger when the skewed bridges had the same mass as the straight bridge, compared to when they had the same fundamental frequencies.

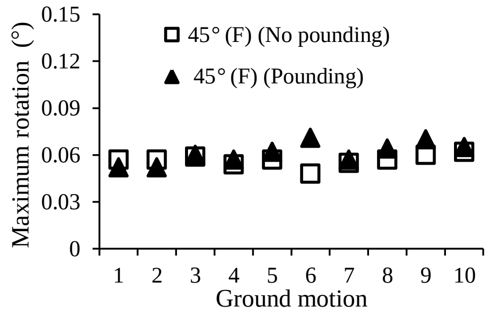
Although the 30° bridge had smaller skew angle compared to the 45° bridge, the latter had smaller in-plane rotations in both cases with and without considering pounding. For example, in the 30° (*F*) case without considering pounding, the girder had an average maximum



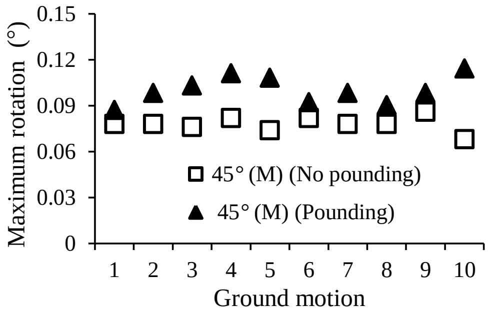
(a) 30° bridge (*F*)



(b) 30° bridge (*M*)



(c) 45° bridge (*F*)



(d) 45° bridge (*M*)

Fig. 8 Maximum in-plane rotations of the girders of the 30° and 45° bridges

rotation of 0.105°, but for the same case, when the skew angle was 45°, the average maximum rotation of the girder was only 0.057°, about 0.46 times smaller than that of the 30° bridge. A past study conducted by Catacoli *et al.* (2014) reported that the torsional responses do not necessarily arise just from a bridge being skewed, and that only happened when pounding occurred. The results found in this study (Table 9) showed that for the cases considered, the in-plane rotations of the girders can not only arise when pounding did not occur, they can in fact, be even larger than those induced when pounding was present. This highlights the need for skew angles of bridges to be considered in more detail when designing skewed bridges.

4. Conclusions

This paper presents a parametric study focusing on two parameters: mass and frequency conducted through experimental work. Assuming the dimensions of the piers do not change i.e., stiffness of the bridge remains constant, the mass of the bridges need to be changed to obtain the same longitudinal frequency between the straight and skewed bridges, and vice versa. This work discussed the experimental results of shake table tests conducted on bridge-abutment models consisting of straight, 30°, and 45° bridges. Two bridges were considered for each skew angle - skewed bridges that had the same translational frequency as the straight bridge (*F*), and those that had the same mass as the straight (*M*). The effects of frequency and mass of skewed bridges were discussed. It was revealed that:

- The bending moments developed in the bridge piers were directly proportional to the relative displacement of the bridge girder in the longitudinal direction than the transverse displacement and in-plane rotations of the girder.
- The bending moments and longitudinal displacements of the 30° (*F*) bridge were similar with or without considering pounding. In all the other cases, the responses tend to be larger when pounding was not considered. This is because of the restrictions to the girder movements provided by the abutments when pounding was considered.
- The transverse displacements of the girder of the skewed bridges, in both the (*M*) and (*F*) cases, the displacements were larger when pounding was not considered compared to when it was present.
- The in-plane rotations of the girders of the 30° bridge were smaller when pounding was considered compared to when pounding occurred, in both the (*M*) and (*F*) cases, but for the 45° bridge, pounding caused larger rotations instead.
- Skewed bridges with the same mass as the straight bridge counterpart tend to have larger responses compared to where they had the same frequencies, possibly due to the larger in-plane rotations induced.
- The seat length of skewed bridges recommended by the NZTA bridge manual could be greatly underestimated, especially in the transverse direction when pounding occurs. In the longitudinal direction, only the displacement of the 45° (M) bridge was underestimated.

Acknowledgments

The authors would like to thank the Ministry of Business, Innovation, and Employment for the support through the Natural Hazards Research Platform under the Award 3708936 for the first author.

References

Anagnostopoulos, S.A. and Karamaneas, C.E. (2008), "Use of collision shear walls to minimize seismic separation and to protect adjacent buildings from collapse due to earthquake-induced pounding", *Earthq. Eng. Struct. Dyn.*, **37**(12), 1371-1388.

Buckingham, E. (1914), "On physically similar systems: Illustrations of the use of dimensional equations", *Phys. Rev.*, **4**(4), 345-376.

Catacoli, S., Ventura, C.E., Finn, W.D.L. and Taiebat, M. (2014), "In-plane rotational demands of skewed bridges due to earthquake induced pounding", *The Tenth U.S. National Conference on Earthquake Engineering*, Anchorage, Alaska, US.

Chen, Y., Larkin, T. and Chouw, N. (2017), "Experimental assessment of contact forces on a rigid base following footing uplift", *Earthq. Eng. Struct. Dyn.*, **46**, 1835-1854.

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

Chouw, N. and Hao, H. (2005), "Study of SSI and non-uniform ground motion effect on pounding between bridge girders", *Soil Dyn. Earthq. Eng.*, **25**, 717-728.

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

Chouw, N., Hao, H. and Su, H. (2006), "Multi-sided pounding response of bridge structures with non-linear bearings to spatially varying ground excitation", *Adv. Struct. Eng.*, **9**(1), 55-66.

Deepu, S.P., Prajapat, K. and Ray-Chaudhuri, S. (2014), "Seismic vulnerability of skew bridges under bi-directional ground motions", *Eng. Struct.*, **71**, 150-160.

Dimitrakopoulos, E.G. (2011). "Seismic response analysis of skew bridges with pounding deck-abutment joints", *Eng. Struct.*, **33**(3), 813-826.

Dimitrakopoulos, E.G. (2013), "Nonsmooth analysis of the impact between successive skew bridge-segments", *Nonlin. Dyn.*, **74**(4), 911-928.

Huang, H., Shenton, H. and Chajes, M. (2004), "Load distribution for a highly skewed bridge: Testing and analysis", *J. Bridge Eng.*, **9**(6), 558-562.

Huo, Y. and Zhang, J. (2013), "Effects of pounding and skewness on seismic responses of typical multispan highway bridges using the fragility function method", *J. Bridge Eng.*, **18**(6), 499-515.

Jennings, P.C. (1971), "Engineering features of the San Fernando earthquake of February 9, 1971", *Casadena, California: National Science Foundation and Earthquake Research Affiliates of the California Institute of Technology*.

Kaviani, P., Zareian, F. and Taciroglu, E. (2012), "Seismic behaviour of reinforced concrete bridges with skew-angled seat type abutment", *Eng. Struct.*, **45**, 137-150.

Kawashima, K., Unjoh, S., Hoshikuma, J.I. and Kosa, K. (2011), "Damage of bridges due to the 2010 Maule, Chile, earthquake", *J. Earthq. Eng.*, **15**(7), 1036-1068.

Khatiwada, S. and Chouw, N. (2013), "A shake table investigation on interaction between buildings in a row", *Coupl. Syst. Mech.*, **2**(2), 175-190.

Khatiwada, S., Larkin, T. and Chouw, N. (2014), "Influence of mass and contact surface on pounding response of RC structures", *Earthq. Struct.*, **7**(3), 385-400.

Kun, C., Jiang, L. and Chouw, N. (2017), "Influence of pounding and skew angle on seismic response of bridges", *Eng. Struct.*, **148**, 890-906.

Kwon, O.S. and Jeong, S.H. (2013), "Seismic displacement demands on skewed bridge decks supported on elastomeric bearings", *J. Earthq. Eng.*, **17**(7), 998-1022.

Li, B., Bi, K., Chouw, N., Butterworth, J.W. and Hao, H. (2012), "Experimental investigation of spatially varying effect of ground motions on bridge pounding", *Earthq. Eng. Struct. Dyn.*, **41**(14), 1959-1976.

Li, B., Bi, K., Chouw, N., Butterworth, J.W. and Hao, H. (2013), "Effect of abutment excitation on bridge pounding", *Eng. Struct.*, **54**, 57-68.

Makris, N. (2014), "The role of the rotational inertia on the seismic resistance of free-standing rocking columns and articulated frames", *Bull. Seismol. Soc. Am.*, **104**(5), 2226-2239.

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

Meng, J.Y., Lui, E.M. and Liu, Y. (2001), "Dynamic response of skew highway bridges", *J. Earthq. Eng.*, **5**(2), 205-223.

Mitchell, D., Bruneau, M., Saatcioglu, M., Williams, M., Anderson, D. and Sexsmith, R. (1995), "Performance of bridges in the 1994 Northridge earthquake", *Can. J. Civil Eng.*, **22**(2), 415-427.

New Zealand Transport Agency (2016), Bridge Manual (SP/M/022), Wellington, New Zealand.

Qin, X., Chen, Y. and Chouw, N. (2013), "Effect of uplift and soil nonlinearity on plastic hinge development and induced vibrations in structures", *Adv. Struct. Eng.*, **16**(1), 135-147.

Shao, G., Jiang, L. and Chouw, N. (2014), "Experimental investigations of the seismic performance of bridge piers with rounded rectangular cross-sections", *Earthq. Struct.*, **7**(4), 463-484.

Soleimani, F. (2017), "Fragility of California bridges-Development of modification factors", Doctoral Dissertation, Georgia Institute of Technology, Georgia, USA.

Soleimani, F., Vidakovic, B., DesRoches, R. and Padgett, J. (2017), "Identification of the significant uncertain parameters in the seismic response of irregular bridges", *Eng. Struct.*, **141**, 356-372.

Standards New Zealand Technical Committee (2004), Structural design actions Part 5: Earthquake actions - New Zealand, NZS 1170.5: 2004, Wellington, New Zealand.

Sullivan, I.T. (2010), "Analytical seismic fragility curves for skewed multi-span steel girder bridges", Doctoral Dissertation, Clemson University, South Carolina, USA.

Wakefield, R.R., Nazmy, A.S. and Billington, D.P. (1991), "Analysis of seismic failure in skew RC bridge", *J. Struct. Eng.*, **117**(3), 972-986.

Watanabe, G. and Kawashima, K. (2004), "Effectiveness of cable-restrainer for mitigating rotation of a skewed bridge subjected to strong ground shaking", *The 13th World Conference on Earthquake Engineering*, Vancouver, Canada.

Weiser, J. and Maragakis, M. (2013), "Seismic performance of highway bridges with seat-type abutments subjected to near-fault ground motions", *Proceedings of the 2013 Structures Congress*, 827-838.

Won, J., Mha, H., Cho, K. and Kim, S. (2008), "Effects of the restrainer upon bridge motions under seismic excitations", *Eng. Struct.*, **30**(12), 3532-3544.

Wood, J. and Jennings, P. (1971), "Damage to freeway structures in the San Fernando earthquake", *Bull. NZ Soc. Earthq. Eng.*, **4**(3), 347-76.

Yang, C.S., Werner, S.D. and DesRoches, R. (2015), "Seismic fragility analysis of skewed bridges in the Central and

Southeastern United States", *Eng. Struct.*, **83**, 116-128.
Yashinsky, M. (2011), "Lessons learned from the February 27, 2010 Maule, Chile earthquake", *Caltrans Office of Earthquake Engineering*, Retrieved from http://www.dot.ca.gov/hq/esc/earthquake_engineering/damage_report/Lessons_Learned.pdf.
Zakeri, B., Padgett, J. and Amiri, G. (2014), "Fragility analysis of skewed single-frame concrete box-girder bridges", *J. Perform. Constr. Facil.*, **28**(3), 571-582.
Zakeri, B., Padgett, J. and Amiri, G. (2015), "Fragility assessment for seismically retrofitted skewed reinforced concrete box girder bridges", *J. Perform. Constr. Facil.*, **29**(2), 04014043.

CC