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Research Article

Experimental Evaluation of the Seismic Response of Skewed Bridges with Emphasis on Poundings between Girder and Abutments

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Observations from past earthquake events indicate that skewed bridges are seismically vulnerable due to induced horizontal in-plane rotations of the girder. To date, however, very limited experimental research has been done on the pounding behaviour of skewed bridges. In this study, shake table tests were performed on a single-frame bridge model with adjacent abutments subjected to uniform ground excitations. Bridges with different skew angles, i.e., 0°, 30°, and 45°, were considered. The pounding behaviour was observed using a pair of pounding and measuring heads. The results reveal that poundings could indeed influence the responses of skewed bridges in the longitudinal and transverse directions differently and thus affect the development of the girder rotations. Ignoring pounding effects, the 30° skewed bridges could experience more girder rotations than the 45° skewed bridges. With pounding, the bridges with a large skew angle could suffer more opening girder displacements than straight bridges.

1. Introduction

The damage of skewed bridges has been observed in many major earthquakes, e.g., the 1971 San Fernando earthquake [1], the 1989 Loma Prieta earthquake [2], the 1994 Northridge earthquake [3], the 1995 Kobe earthquake [4], the 2010 Maule, Chile, earthquake [5], and more recently the 2011 Canterbury earthquake [6]. These observations revealed that skewed bridges are more earthquake-prone compared to straight bridges due to the induced transverse displacements and in-plane rotations of the girder.

Following the 1971 San Fernando earthquake, Wood and Jennings [1] stated that the skew angle effect could aggravate the damage of bridges. Maragakis [7] reported that the induced rotations could result in significant transverse displacements of the girder. The same conclusion was drawn by Wakefield et al. [8], highlighting the influence of rigid-body motion, like in-plane rotations, on the overall response.

Many studies, however, only focused on the effect of skew angle and thus neglected other influence factors, e.g., the impact between bridge structures, although past observations affirmed that the collisions of adjacent decks or deck with an abutment appear to aggravate the damage to bridges [9–11].

Since a bridge pounding cannot be avoided during strong earthquakes due to the out-of-phase movements of adjacent bridge structures [12], a large number of studies have been conducted, e.g., by Dicleli and Bruneau [13], DesRoches and Muthukumar [14], Li et al. [15, 16], Li and Chouw [17], and Guo et al. [18], and showed that the effect of pounding can significantly influence bridge responses by reducing the bending moments of the piers but increasing the accelerations of the girders.

There have been some studies on the pounding effect of skewed bridges between adjacent bridge segments. Dimitrakopoulos [19], for example, concluded that the rotations of the girder increase due to the effect of pounding but decrease with an increase in the natural frequency of bridges. Huo and Zhang [20] used a fragility function to study the coupled effect of pounding and skew angle on the seismic behaviour of multispan highway bridges. They revealed that pounding would aggravate the seismic vulnerability of skewed bridges, whereas it only has a limited influence on straight bridges.

Compared to girder-to-girder collisions, the girder-abutment pounding is more likely to occur due to the significant difference between the fundamental frequencies of the participating structures. Thus, it is critical to consider the influence of the girder-abutment pounding.

Kaviani et al. [21] performed a nonlinear time-history analysis of a bridge-abutment system and demonstrated that skewed bridges would have greater seismic responses like the girder rotations and the column drifts than straight bridges. The numerical study conducted by Upadhyay et al. [22] showed that, with supporting soil, the pounding forces at the girder-abutment interface mainly depend on the characteristics of the excitations. The earthquake response of skewed bridges was also sensitive to the abutment skew angle. Omrani et al. [23] numerically investigated a seat-type box bridge with the abutment backfill. The authors revealed that bridges with large skew angles, i.e., 30° and larger, would be more sensitive to a variation of the abutment backfill than straight bridges. The higher the backfill passive resistance, the more likely the bridges would collapse. On the contrary, through a numerical study, Chen et al. [24] concluded that although the girder-abutment pounding might cause significant girder displacements and increase the failure possibility of the abutment shear keys, it could reduce the rotations of the bridge girder. Wang et al. [25] performed numerical research on the seismic response of skewed bridges with buckling-restrained braces. The results indicated that the use of BRB would significantly dissipate the seismic energy of skewed bridges and thus reduce the failure possibility.

Although many numerical or analytical works on the pounding effect of skewed bridges have been conducted, the results sometimes even contradict each other due to the lack of verification using the results obtained from physical experiments. To date, not many experimental tests have been reported. To the authors' best knowledge, only a few experimental studies on skewed bridges have been performed, and very few of them considered the pounding mechanism and the girder rotations simultaneously.

By considering the skewed abutment and its backfill, Rollins and Jessee [26] through laboratory tests pointed out that the increasing skew angle would reduce the maximum passive force for skewed abutments. A similar conclusion was also drawn by Marsh [27]. The author also concluded that the passive force versus backwall deflection relationship of skewed bridges would be overestimated in the current design methods. However, their research mainly focused on the abutment response and thus neglected the seismic response of skewed bridges. Kun et al. [28] carried out shake table tests on a 1 : 20 scale bridge-abutment system. The authors reported that the skew angle effect could drastically increase transverse displacements and rotations of the bridge girder, especially at the obtuse corner. Further research conducted by Kun et al. [29] showed that the development of the bending moments is closely related to the relative longitudinal displacements of bridges girder whether or not the skew angle was considered.

This study aims to enhance the understanding of the pounding behaviour on skewed bridges. A series of shake table tests have been performed on a bridge-abutment system with various skew angles. This paper particularly focuses on the pounding forces developed at the girder-abutment interfaces and on the rotations of the bridge girder. A point-to-point contact, as similarly performed by others, e.g., Li et al. [16], Kun et al. [23], and Guo et al. [30], was considered mainly to limit the influence factors. This approach can provide insights into the development of pounding forces at obtuse and acute corners.

2. Methodology

2.1. Prototype Structure and Model. Bridge models with 0°, 30°, and 45° skew angles were constructed based on a segment of the Newmarket Viaduct Replacement Bridge located in Auckland, New Zealand. The prototype bridge has only one segment of 100 m and a height of 15.5 m. The segment has two piers with a pier-to-pier distance of 50 m and a pier cross-section of 3.44 m × 1.48 m. The prototype structure is a reinforced-concrete box-girder bridge. The sketch of the prototype segment is presented in Figure 1(a).

The modified Buckingham's π theorem was adopted as a scaling approach, which was first developed by Buckingham [31] and modified by Li et al. [16]. Due to the limitation of the facility, a small geometry scale of 1 : 100 was adopted in the study. To ensure the strength of the simulated ground excitations, a time scale of 2 was used which in turn resulted in an acceleration ratio of 25. The scale factor of acceleration is derived based on that of length (L) and time (T), as shown in Table 1. Polyvinylchloride (PVC) was chosen to construct the bridge model to reduce the mass due to its low modulus of elasticity of 2.5 GPa. The cross-section of the piers of 30 mm × 3 mm was designed to fulfil the requirement of the fundamental frequency. The girder cross-section of 50 mm × 20 mm was selected. The longitudinal and rotational stiffness of the straight bridge was 1280 N/m and 6750 N/m, respectively. Based on a series of snap-back tests, the average fundamental frequencies are 1.96, 1.45, and 1.75 Hz for the straight and 30° and 45° skewed bridges, respectively.

To better understand the pounding response between the girder and the adjacent abutments, additional influence factors of the bridge like the restrainer and bearing were not considered and the masses were assumed concentrated in the bridge girder. Tables 1 and 2 show a summary of the scale factors and the parameters of the prototype and the straight bridge model, respectively.

2.2. Experimental Setup. The bridge-abutment system was fixed on a 1.5 m × 1 m uniaxial shake table with a capacity of 10 kN and subjected to uniform excitations in the

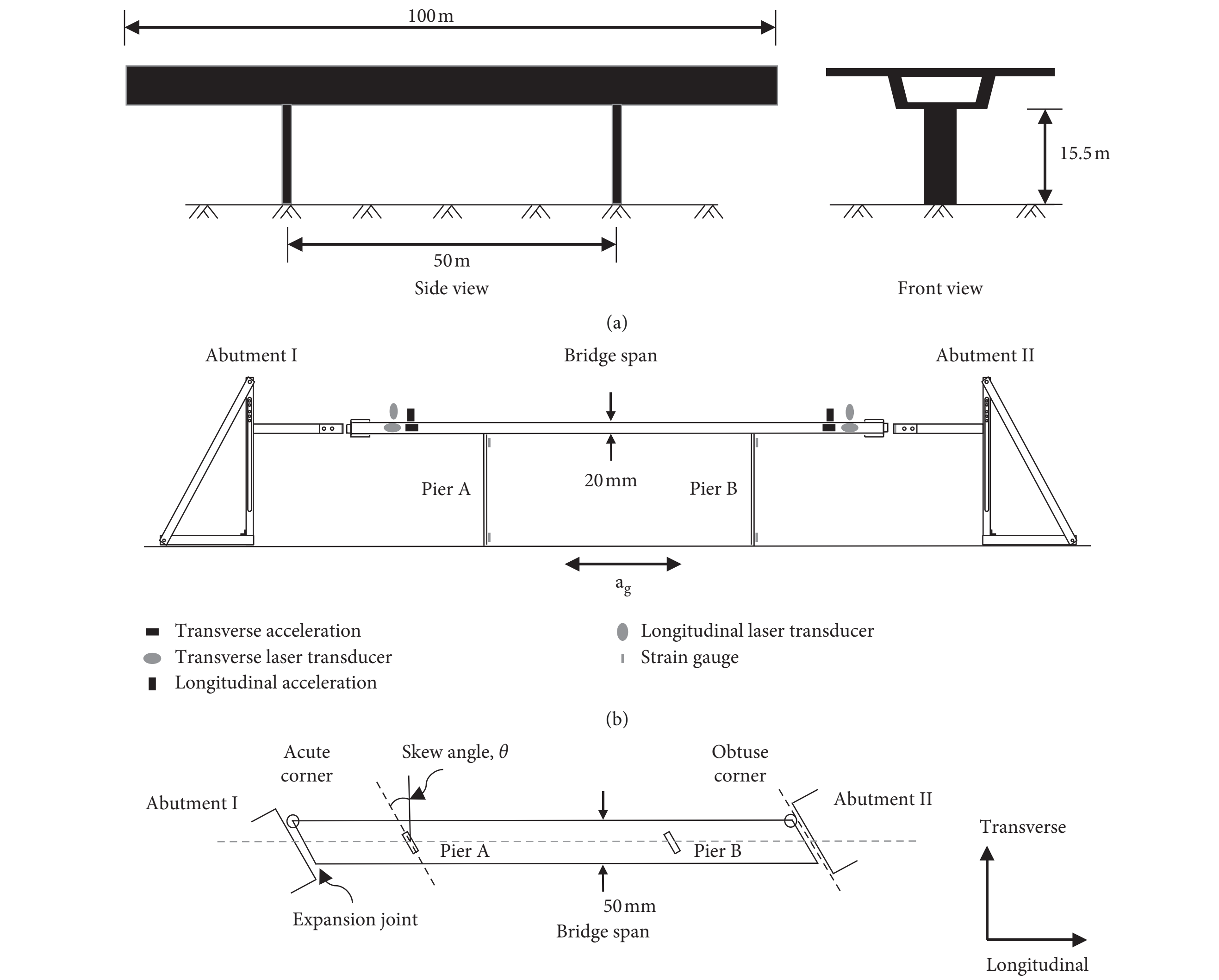


Figure 1: Sketch of the prototype bridge segment (a) and of a bridge-abutment system with sensors: side view (b) and top view (c).

Table 1: Scale factors.

Physical quantity	Similitude	Scale factor
Length	N_L	100
Time	N_t	2
Modulus of elasticity	N_E	12
Mass	N_M	224, 442
Stiffness	$N_K = N_M \div N_t^2$	56, 110.5
Fundamental frequency	$N_F = \sqrt{(N_K \div N_M)}$	0.5
Acceleration	$N_a = N_L \div N_t^2$	25

Table 2: Parameters of the prototype and model.

Parameter	Prototype dimension	Model dimension
Bridge span	100 m	1000 mm
Pier height	15.5 m	155 mm
Pier-to-pier distance	50 m	500 mm
Pier width	3.44 m	30 mm
Pier thickness	1.48 m	3 mm
I_{pier}	0.39 m^4	67.5 mm^4
K_{bending}	7.189×10^7 N/m	1.28×10^3 N/m
Effective mass	1.895×10^6 kg	8.445 kg
f_{straight}	0.98 Hz	1.96 Hz
f_{30°	—	1.45 Hz
f_{45°	—	1.75 Hz

longitudinal direction of the girder. The uniaxial ground motions in the longitudinal direction of the bridges were chosen to make an interpretation of the experimental results easier. The idealised fixed base condition was chosen to eliminate the number of influence factors considered and thus to provide a better understanding of the pounding response on skewed bridges. Accelerometers with a capacity of ±2 g were fixed at each end of the span to measure the longitudinal and transverse accelerations of the girder. Strain gauges were attached at the top and bottom of the piers to measure the strain for calculating the moment due to bending about the weak axes of the piers. Four laser displacement transducers were used. Two of them were placed at each end of the bridge deck to measure the relative displacements between the girder and the adjacent abutments in the longitudinal direction, whereas another two were attached at both the obtuse and acute corners of the girder to obtain the transverse displacements of skewed bridges. The locations of sensors are shown in Figure 1.

The abutments were simulated using steel frames made up of rectangular hollow sections. They were designed to be much rigid than the bridge segment, i.e., with a significantly higher fundamental frequency, so it is reasonable to assume that only the rigid-body movements of the abutments had been activated during the experiment.

The pounding response at the girder-abutment joint was simulated using a pair of pounding and measuring heads, which were oriented at the same angle as the piers. The pounding head consisted of 10 mm diameter PVC cylindrical blocks glued to a thin steel frame. They were attached to each end of the girder and can be detached and changed to another girder at a different angle. The pounding forces were calculated using calibrated strain. The strain was measured by a strain gauge, glued to the back of an aluminium strip with a dimension of 30 mm × 20 mm and a thickness of 2 mm. The measuring head consisted of a pair of aluminium strips and a PVC block. They were fixed to the abutment at each side of the girder. The details of pounding and measuring heads are presented in Figure 2. Strain gauges were used to measure the strains of contact areas for calculating the pounding forces. To ensure the repeatability of subsequent tests, the pounding and measuring heads were designed only to behave elastically.

When pounding was considered, the size of the gap between abutments and the span were 1 mm, whereas when pounding was not considered, the span and abutments were fixed sufficiently apart so that they were unable to get in contact with each other. A photo of the assembled bridge and abutments is shown in Figure 3 highlighting the girder-abutment contact interface.

2.3. Ground Motions. The ground excitations considered were stochastically simulated based on the design spectrum specified in NZS 1170.5 for the shallow soil condition (Class C) [32]. To ensure the generality of the results, for the straight bridge and each skewed bridge, seven ground motions were considered in each of the no pounding and pounding cases, resulting in a total of 42 tests, as shown in Table 3. The scaled displacement- and acceleration-time histories of the two of the seven simulated ground motions are shown as an example in Figure 4. They are hereafter denoted as GMs 1 and 2, respectively. A comparison of the target design spectrum and the response spectra of GMs 1 and 2 is presented in Figure 5. A good match can be observed.

The spectral values of the straight and 30° and 45° skewed bridges are indicated by solid lines in Figure 5. The straight bridge with a fundamental frequency of 1.96 Hz has the largest spectral value, whereas the smallest spectral value can be observed in the case with a 30° skewed bridge.

3. Results and Discussion

3.1. Relative Displacements. The relative displacement between the girder and adjacent abutments is one of the most important seismic responses of bridges since the closing displacements could lead to the pounding between adjacent bridge structures during strong earthquakes. The subsequent pounding-induced opening movements might result in the unseating of the girders. This is the case when opening displacements exceed the provided seat length.

Figure 6 shows the response time history of the longitudinal displacement of straight and 30° and 45° skewed bridges with and without pounding when the models were subjected to GM 1. It can be seen that, without pounding, the maximum longitudinal displacements (dashed lines) are 5.24 mm, 1.04 mm, and 2.65 mm for the straight and 30° and 45° skewed bridges, respectively. The straight bridge has the largest relative displacement among the bridges considered. The larger maximum displacement of the 45° skewed bridge compared to that of the 30° skewed bridge is likely due to a greater spectral value (refer to Figure 5).

When pounding was considered, a reduction of the maximum longitudinal displacements can be observed in all the cases, which shows the restriction of girder movements by the abutments. The 45° skewed bridge showed the largest longitudinal displacement of 1.49 mm.

The maximum relative longitudinal displacements of the bridges with and without pounding are summarised in Table 4. The straight bridge shows that poundings reduce the maximum displacements from 4.16 mm to 1.11 mm. For the 30° and 45° skewed bridges, the maximum displacements are 0.85 mm and 1.46 mm, respectively. On average, pounding reduces the maximum displacements by 73.3%, 12.4%, and 38.7% for the straight and 30° and 45° skewed bridges, respectively. It means that the abutments with a skew angle will provide less restriction. The 45° skewed bridge shows the largest longitudinal displacement among the three bridges considered. The maximum displacement of the 45° skewed bridge is even larger than that of the straight bridge. It is due to the pounding-induced in-plane rotations of the girder.

The response time history of the transverse displacement at both obtuse and acute corners of the deck is shown in Figure 7. An increase in the maximum transverse displacements is observed as the skew angle increases whether or not pounding was considered. The transverse displacements at the obtuse corner are always larger than those at the acute corner. Without pounding, the maximum transverse displacements are, respectively, 1.69 mm and 2.87 mm at the acute corner and 2.43 mm and 3.23 mm at the obtuse corner for the 30° and 45° skewed bridges. When pounding was considered, the transverse displacements are 1.57 mm and 2.25 mm at the acute and the obtuse corners for the 30° skewed bridge, respectively, whereas in the case of the 45° skewed bridge, the corresponding displacements are 2.56 mm and 2.89 mm, respectively.

Since the obtuse corner is more likely to have larger transverse displacements than the acute corner, the maximum transverse displacements at this corner are summarised in Table 5. A comparison between Tables 4 and 5 shows

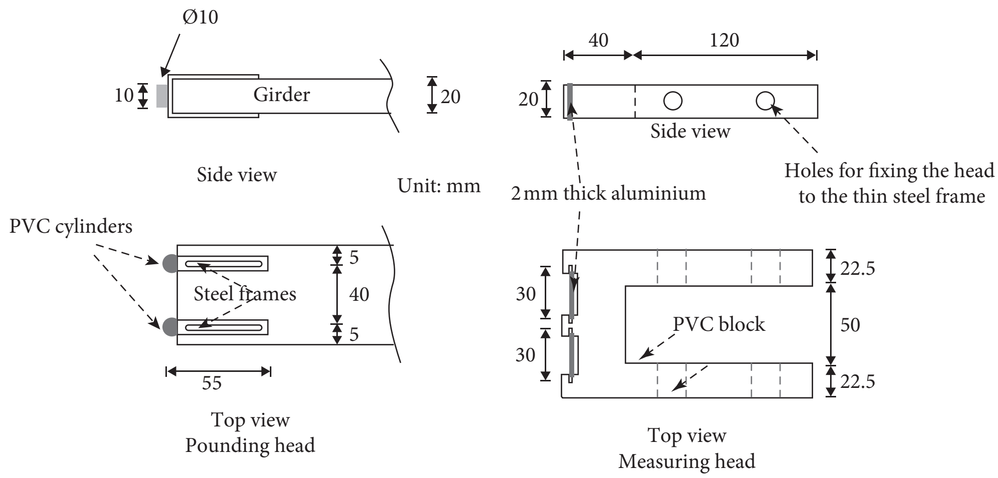


Figure 2: Details of the pounding and measuring heads.

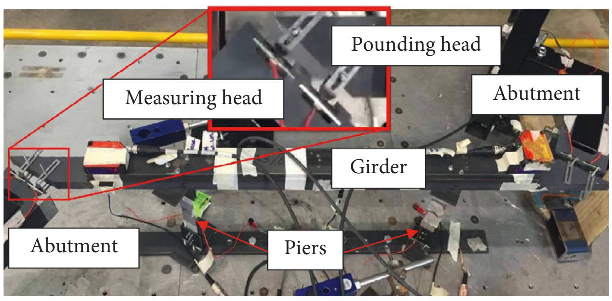


Figure 3: Experimental setup of the scaled bridge-abutment system.

that the maximum displacements in the transverse direction are always larger than the longitudinal displacements. On average, poundings reduce the maximum displacements in the transverse direction by 29% and 37% for 30° and 45° skewed bridges, respectively. The results show that pounding has more influence on the transverse displacements of the girder of the 45° skewed bridges than 30° skewed bridges.

3.2. Bending Moment Development. Figures 8(a)–8(c) show the response time history of bending moment developed at the base of pier B for the straight and 30° and 45° skewed bridges, respectively, with and without pounding. A very similar trend between the bending moments and the displacements in the longitudinal direction is observed for the straight bridge, whereas for the 30° and 45° skewed bridges, the same correlation cannot be observed. In contrast, in the case of skewed bridges, the bending moments of the piers do not reflect the longitudinal displacements of the girder.

Without pounding, the maximum bending moments are 0.89 N.m, 0.24 N.m, and 0.56 N.m for the straight and 30° and 45° skewed bridges, respectively. It suggests that skewed bridges would experience less bending moments of piers than the straight bridge. The 45° skewed bridge shows greater bending moments compared to the 30° skewed bridge. The increase in the bending moments with increasing skew angle is likely due to the larger displacements in both the longitudinal and transverse directions of the 45° skewed bridge (refer to Tables 4 and 5). When pounding was considered, the maximum bending moments are reduced to 0.27 N.m, 0.21 N.m, and 0.32 N.m for the straight and 30° and 45° skewed bridges, respectively. Pounding results in the greatest reduction in the straight bridge of 0.62 N.m.

Table 3: Test matrix.

Case	Skew angle (°)		
	0	30	45
Fixed base without pounding	7	7	7
Fixed base with pounding	7	7	7

A summary of maximum bending moments is shown in Table 6. When pounding was not considered, the average bending moments are 0.72 N.m, 0.26 N.m, and 0.50 N.m for the straight and 30° and 45° skewed bridges, respectively, whereas when pounding occurred, they are 0.26 N.m, 0.20 N.m, and 0.30 N.m, respectively. By considering pounding, a decreasing trend can be observed across all tests. In addition, with pounding, the 45° skewed bridge has the largest maximum bending moments among the bridges considered.

3.3. Rotations of the Girder. Further investigation is carried out on the girder rotations of skewed bridges. The difference of the transverse displacements at the obtuse and acute corners was measured for calculating the in-plane rotations of the girder of the 30° and 45° skewed bridges (see Figure 9). With pounding, the maximum girder rotation of the 30° skewed bridge reduces from 0.144° to 0.104°, whereas it increases from 0.078° to 0.113° in the case of the 45° skewed bridge. The different trend between the 30° and 45° skewed bridges shows that other than restricting the longitudinal and transverse movements, the abutment with a skew angle also affects the rotations of the girder.

The maximum girder rotations are summarised in Table 7. On average, pounding reduces the girder rotation of the 30° skewed bridge by about 40%. In contrast, it results in

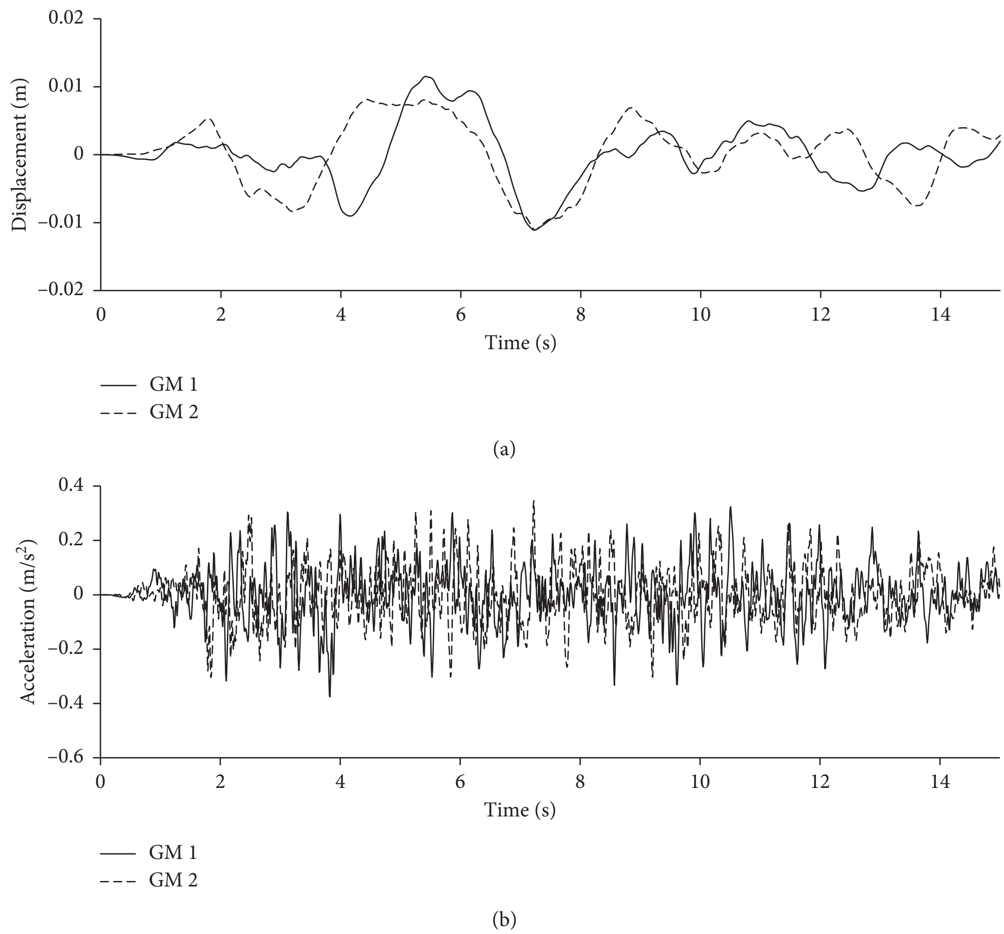


Figure 4: Time histories of the simulated (a) displacement and (b) acceleration of GM 1 and GM 2.

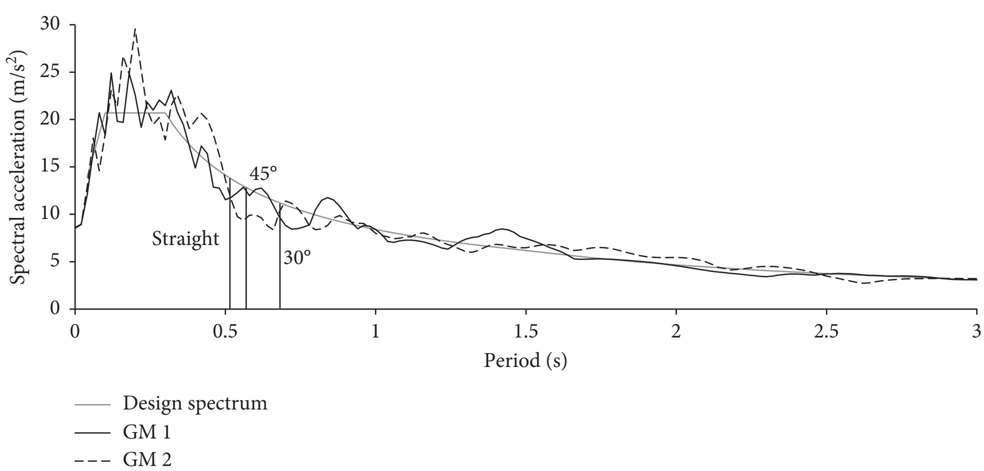


Figure 5: Target spectrum for a shallow soil condition according to NZS 1170.5 and two response spectra of the simulated ground motions.

an increase in the girder rotations of the 45° skewed bridge by about 30%. The results show that, for the 30° skewed bridge, poundings restrict the movement of the girder and thus result in smaller rotations. However, the 45° skewed bridge experiences more severe eccentric poundings than the 30° skewed bridge. Thus, even if poundings still limit the translational girder movement in the longitudinal and transverse directions, they contribute to larger rotations. The conclusion concurs with the results obtained from the numerical study done by Bi et al. [33].

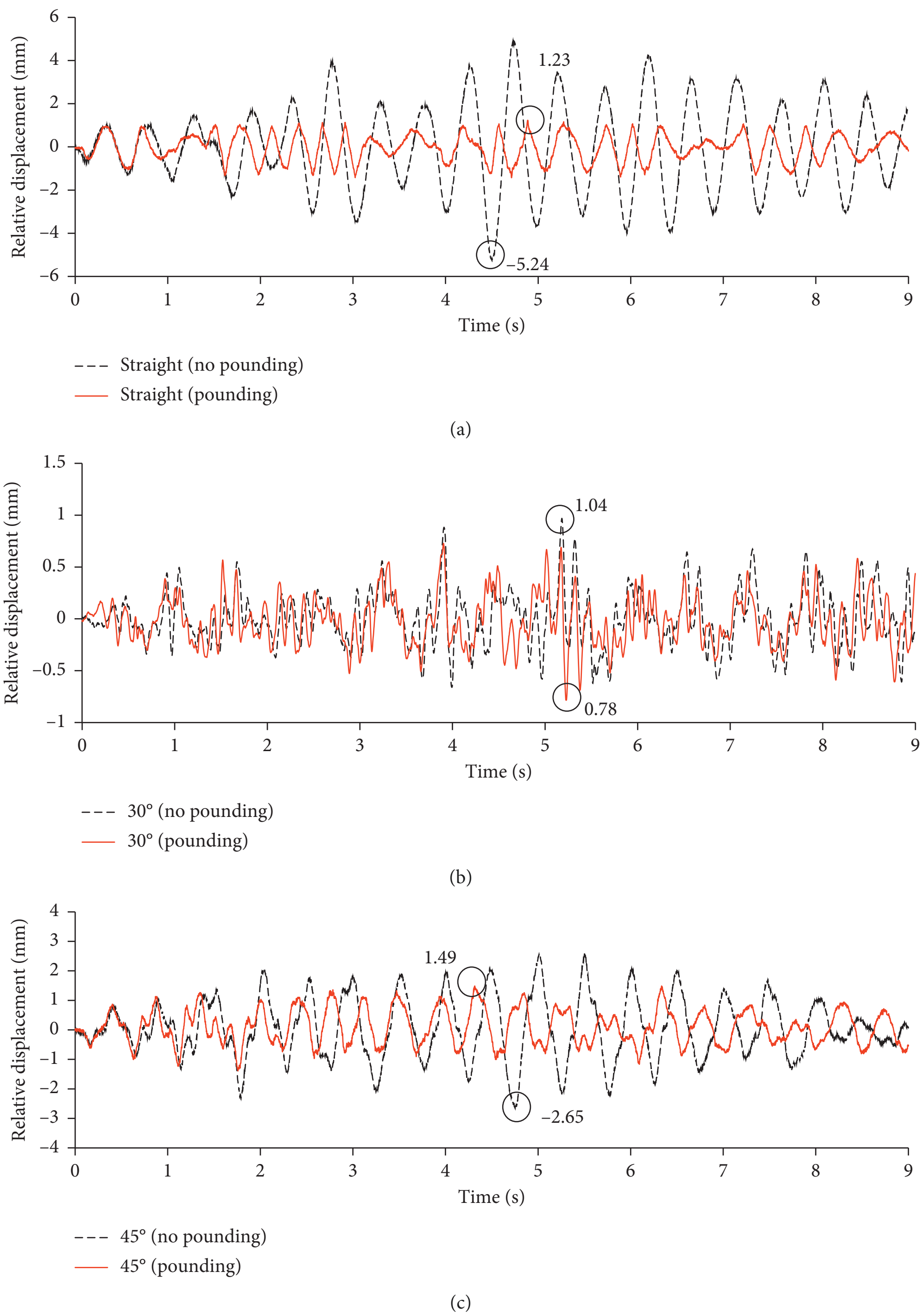
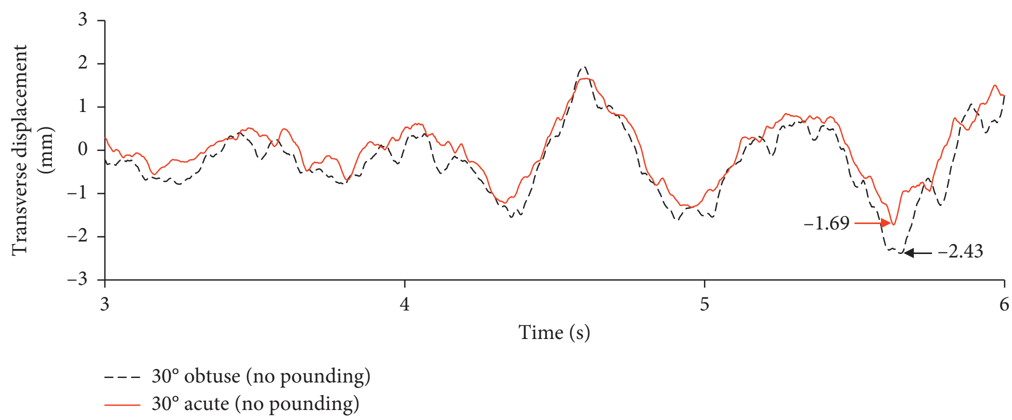


Figure 6: Effects of skew angle and pounding on longitudinal displacement of the (a) straight, (b) 30° skewed, and (c) 45° skewed bridges due to GM 1.

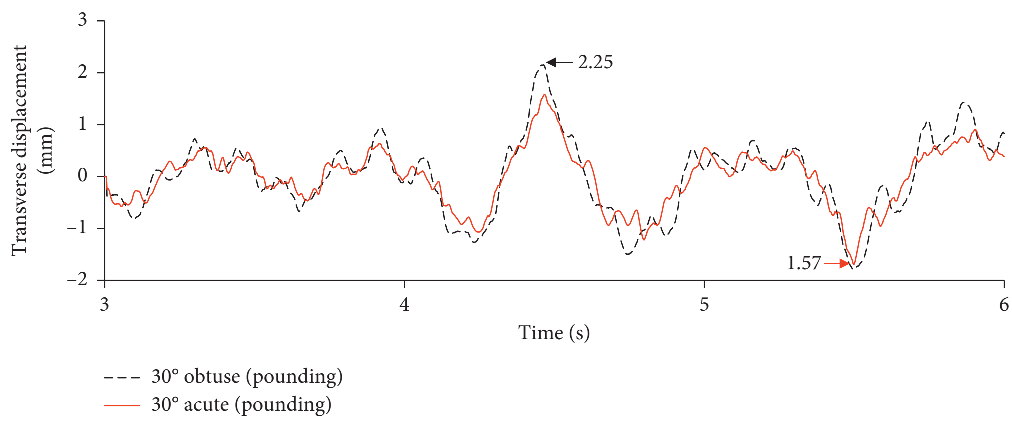
3.4. Pounding Force Development. The pounding forces developed at the girder-abutment interface were measured. The results are illustrated in Figure 10. It can be seen that, for the straight bridge, there are fewer poundings, but of larger magnitudes, whereas for skewed bridges, there are more frequent poundings, but of smaller magnitudes. The straight bridge has the largest pounding force of 38.14 N, whereas the maximum pounding forces are 8.59 N and 18.24 N in the cases of 30° and 45° skewed bridges, respectively. These pounding forces obtained are likely overestimated because of the assumption of rigid abutments. In reality, poundings will also generate waves that propagate via the interface between the abutment and backfill soil. These spreading waves will transmit part of the impact energy away from the bridge-abutment system and thus result in different girder-abutment interaction and pounding forces.

Table 4: Effects of skew angle and pounding on the maximum opening relative displacement of the girder.

Case	Pounding	Longitudinal displacement (mm)							
		GM							Average
		1	2	3	4	5	6	7	
Straight	Without	5.24	3.98	3.46	3.59	4.82	4.66	3.4	4.16
	With	1.23	1.04	1.20	1.11	1.06	1.07	1.07	1.11
30°	Without	1.04	0.87	0.84	1.07	1.00	1.04	0.94	0.97
	With	0.78	0.88	0.71	0.84	0.97	0.97	0.72	0.85
45°	Without	2.65	2.04	2.23	2.2	2.32	2.52	2.72	2.38
	With	1.49	1.49	1.23	1.39	1.46	1.65	1.52	1.46



(a)



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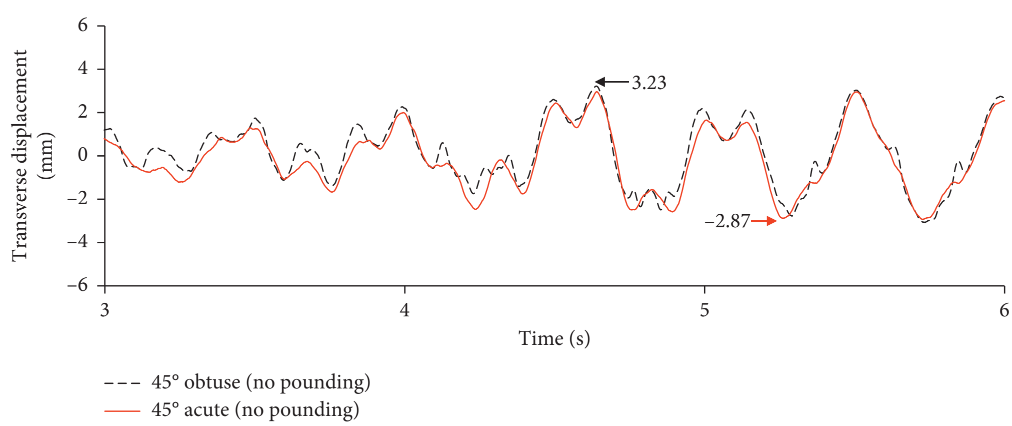
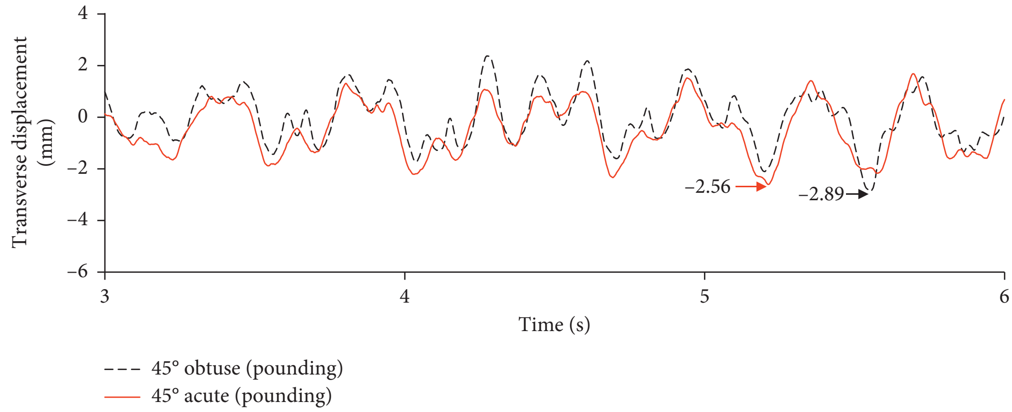


(c)

Figure 7: Continued.

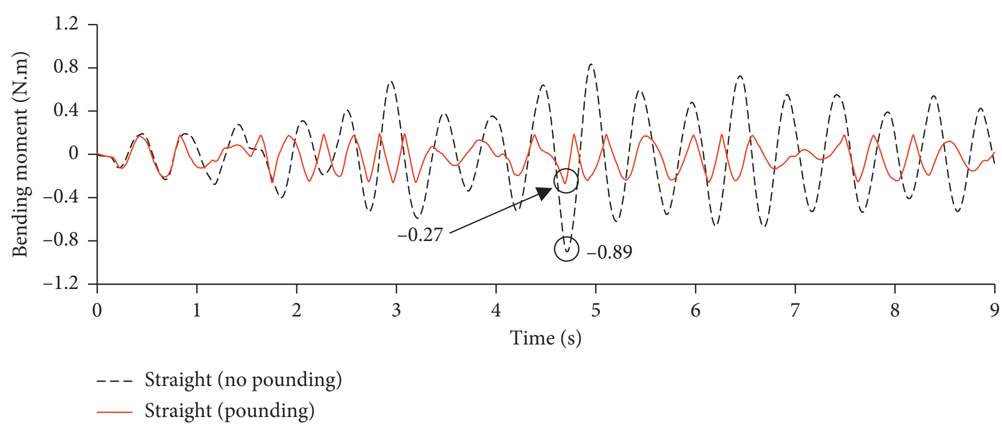


(d)

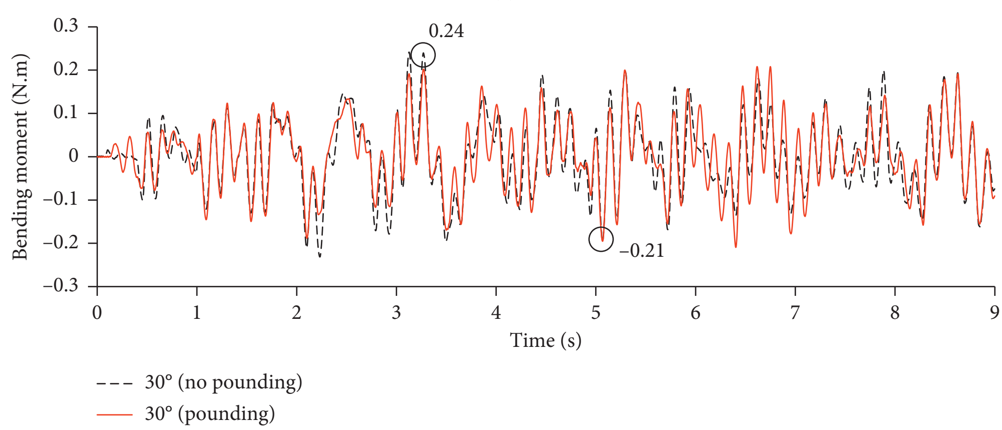
Figure 7: Effects of skew angle and pounding on the transverse displacements of (a, b) 30° and (c, d) 45° skewed bridges without and with pounding, respectively, due to GM 1.

Table 5: Effects of skew angle and pounding on the maximum transverse displacement at the obtuse corner.

Case (°)	Pounding	Displacement (mm) GM 1	2	3	4	5	6	7	Average
30	Without	2.43	2.30	2.57	2.57	2.23	2.99	2.62	2.55
	With	2.25	2.34	1.98	1.84	1.65	1.84	2.03	1.98
45	Without	3.23	3.35	3.54	3.17	3.58	4.18	4.36	3.75
	With	2.89	2.89	2.71	2.76	2.66	2.71	2.57	2.74



(a)



(b)

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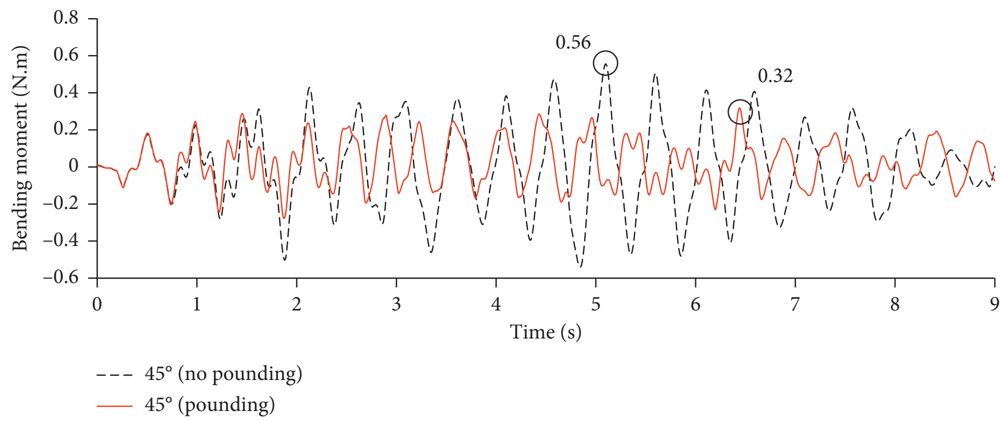
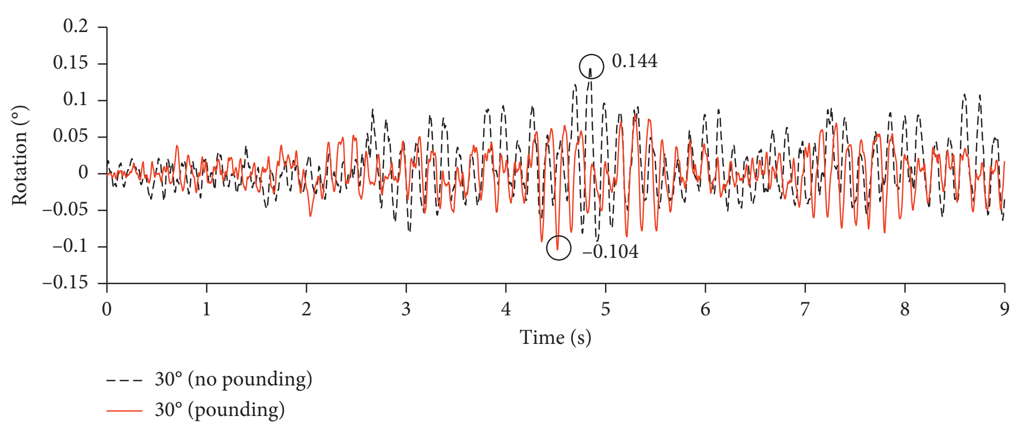


(c)

Figure 8: Effects of skew angle and pounding on bending moments developed near the base of (a) straight, (b) 30° skewed, and (c) 45° skewed bridges due to GM 1.

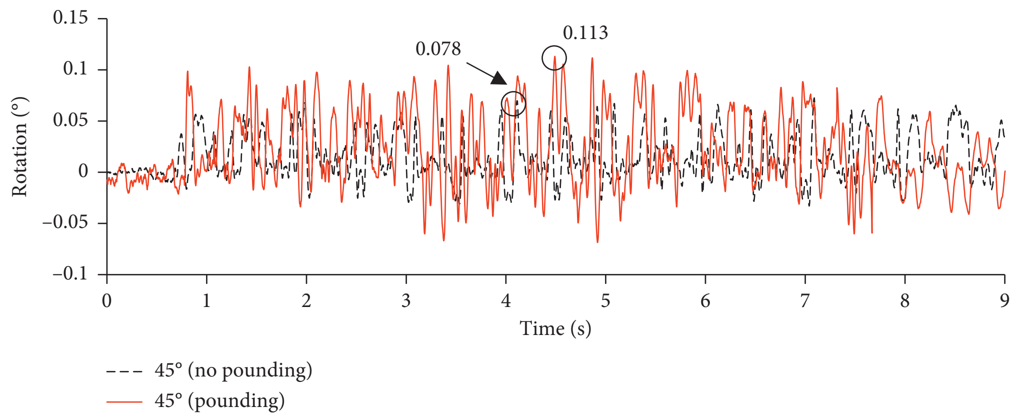
Table 6: Effects of skew angle and pounding on maximum bending moments measured at the base of the pier.

Case	Pounding	Bending moment (N.m) GM 1	2	3	4	5	6	7	Average
Straight	Without	0.89	0.68	0.6	0.61	0.83	0.81	0.59	0.72
	With	0.27	0.26	0.25	0.26	0.27	0.26	0.27	0.26
30°	Without	0.24	0.26	0.3	0.27	0.22	0.27	0.25	0.26
	With	0.21	0.21	0.24	0.17	0.19	0.20	0.18	0.20
45°	Without	0.56	0.4	0.48	0.44	0.53	0.55	0.54	0.50
	With	0.32	0.28	0.26	0.31	0.31	0.32	0.30	0.30



(a)

Figure 9: Continued.



(b)

Figure 9: Influence of pounding on the GM 1-induced rotations of the (a) 30° and (b) 45° skewed bridges.

Table 7: Effects of skew angle and pounding on the maximum rotation of the girder.

Case (°)	Pounding	Girder rotations (°) GM 1	2	3	4	5	6	7	Average	P/NP
30	Without	0.144	0.186	0.187	0.189	0.089	0.176	0.129	0.152	0.599
	With	0.104	0.092	0.089	0.103	0.071	0.128	0.132	0.091	
45	Without	0.078	0.078	0.076	0.082	0.074	0.082	0.078	0.079	1.304
	With	0.113	0.098	0.103	0.111	0.108	0.092	0.098	0.103	

P: pounding; NP: no pounding.

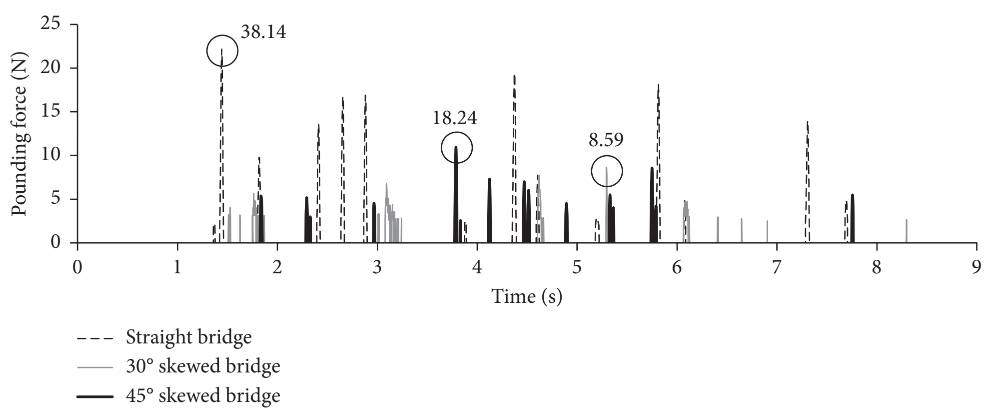


Figure 10: Effect of skew angle on the development of pounding forces of straight and 30° and 45° skewed bridges due to GM 1.

The maximum pounding forces are summarised in Table 8. The average values are 28.48 N, 9.93 N, and 17.18 N for the straight and 30° and 45° skewed bridges, respectively. The results show that having a small skew angle would be beneficial in reducing the development of pounding force.

To figure out the mechanism of pounding between the girder and adjacent abutments, the velocities and accelerations of the girder at pounding instants for the straight bridge due to GM 1 are plotted in Figures 11(a) and 11(b), respectively. Figures 11(c) and 11(d) are the zoomed-in curves of Figures 11(a) and 11(b), respectively, at the time window between 2.6 s and 2.75 s to exhibit the influence of pounding on the subsequent girder responses. The observation shows that the girder accelerations reach the negative peak at the time instant when the pounding force reaches the positive maximum (see the vertical solid line in Figures 11(c) and 11(d)). Before getting connected with the abutment, the amplitude of the girder velocity is 0.5 m/s, and it is reduced to 0.36 m/s after the impact (indicated by the vertical dashed lines in Figures 11(c) and 11(d)).

The observation shows that apart from restricting the girder movements, pounding could also push the girder in the opposite direction. With pounding, the kinetic energy is transferred into the elastic strain energy as the interface deformed. Hence, the magnitude of the velocity reduces, whereas that of the acceleration increases. Just after

Table 8: Influence of skew angle on the pounding force at the girder-abutment interface.

Case	Maximum pounding force (N)							
	GM							
	1	2	3	4	5	6	7	Average
Straight	38.14	24.05	21.56	35.66	28.19	31.51	26.54	28.48
30°	8.59	10.56	9.20	9.56	8.70	9.01	13.94	9.93
45°	18.24	19.90	10.78	19.07	16.58	15.76	19.90	17.18

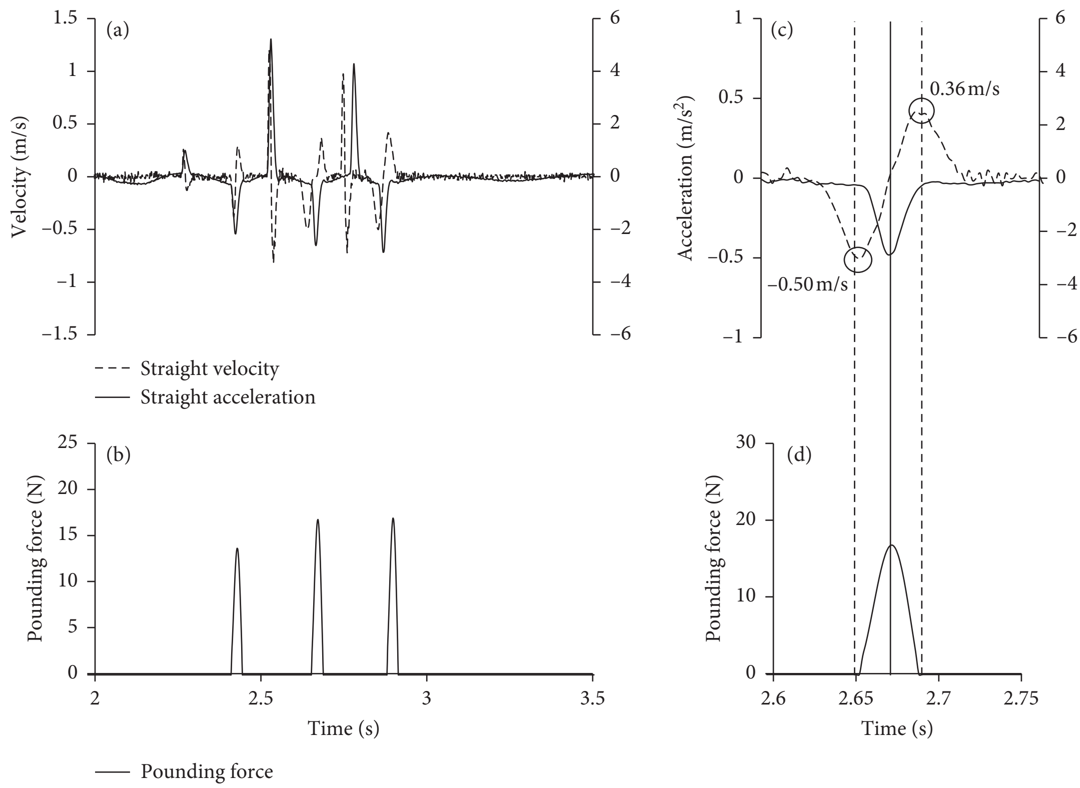


Figure 11: Influence of pounding on the girder velocities and accelerations of the straight bridge at the time windows (a, b) between 2 s and 3.5 s and (c, d) between 2.6 s and 2.75 s due to GM 1.

pounding force reaches its maximum, the elastic strain energy will retransfer into the kinetic energy as the girder moves away from the abutments; thus, a reduction in the acceleration and increase in the velocity can be observed. The energy loss during the process leads to a reduction in the subsequent amplitude of the girder velocities.

As mentioned before, pounding has a complex influence on the subsequent responses of the bridge with a large skew angle. To reveal this aspect, the girder accelerations in the longitudinal and transverse directions of the 45° skewed bridge within different time windows are plotted in Figure 12, while the pounding forces are shown below the corresponding accelerations.

At the time window between 4 s and 4.25 s, the girder acceleration in the longitudinal direction of 1.972 m/s^2 is significantly greater than the transverse acceleration of 0.139 m/s^2 when pounding occurs (illustrated by the vertical dashed line in Figures 12(a) and 12(b)). It implies that pounding at the time instant would mainly affect the development of the longitudinal response.

Between 5.6 s and 5.85 s, the accelerations in transverse and longitudinal directions have almost the same magnitude when pounding occurs (see the vertical dashed line in Figures 12(c) and 12(d)). The pounding reduces the maximum longitudinal acceleration from 0.392 m/s^2 to 0.165 m/s^2, while it significantly increases the maximum transverse acceleration from 0.039 m/s^2 to 1.148 m/s^2.

Figures 12(e) and 12(f) show that the magnitude of the longitudinal acceleration of 0.094 m/s^2 is smaller than that of the transverse acceleration of 1.116 m/s^2 at the pounding instant. The pounding force is significantly small when it is accompanied by a transverse response that is larger than the longitudinal response. The result from Figures 12(a), 12(c), and 12(e) suggests that the magnitude of the pounding force is more significantly affected by the longitudinal movements of the girder than the transverse girder movements.

The observation from Figure 12 also shows that pounding has a different influence on the subsequent longitudinal and transverse responses of the girder and thus

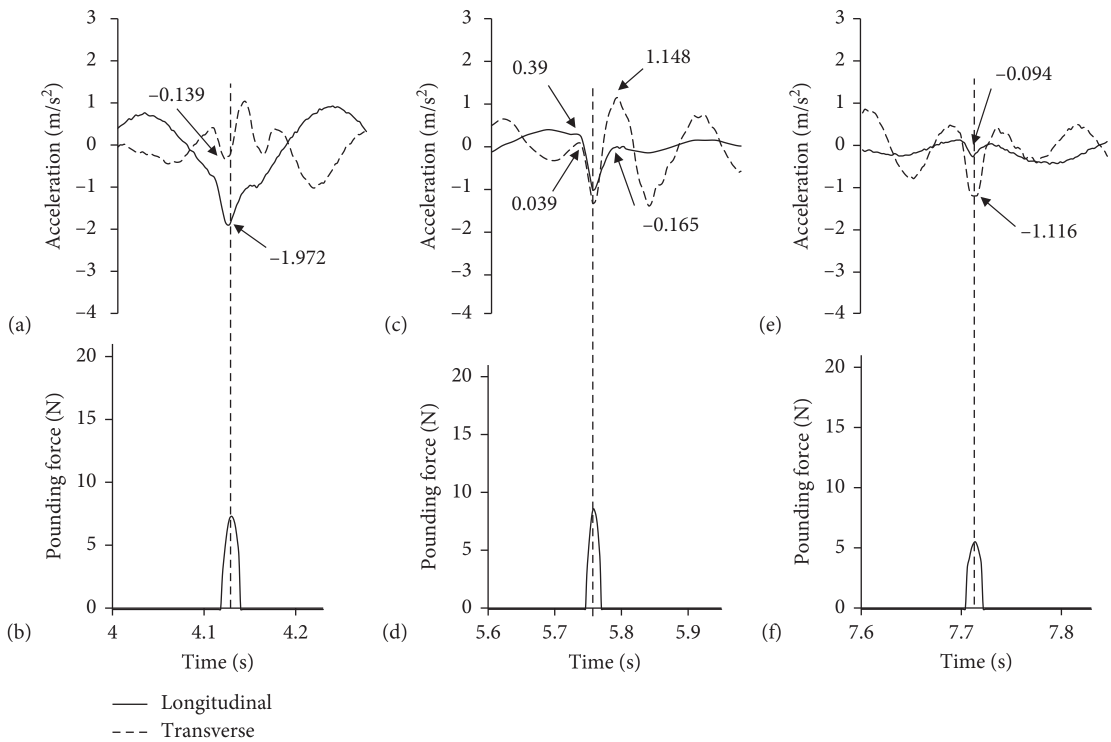


Figure 12: Influence of pounding on the longitudinal and transverse girder accelerations for the 45° skewed bridge at the time windows (a, b) between 4 s and 4.25 s, (c, d) between 5.6 s and 5.85 s, and (e, f) between 7.6 s and 7.85 s.

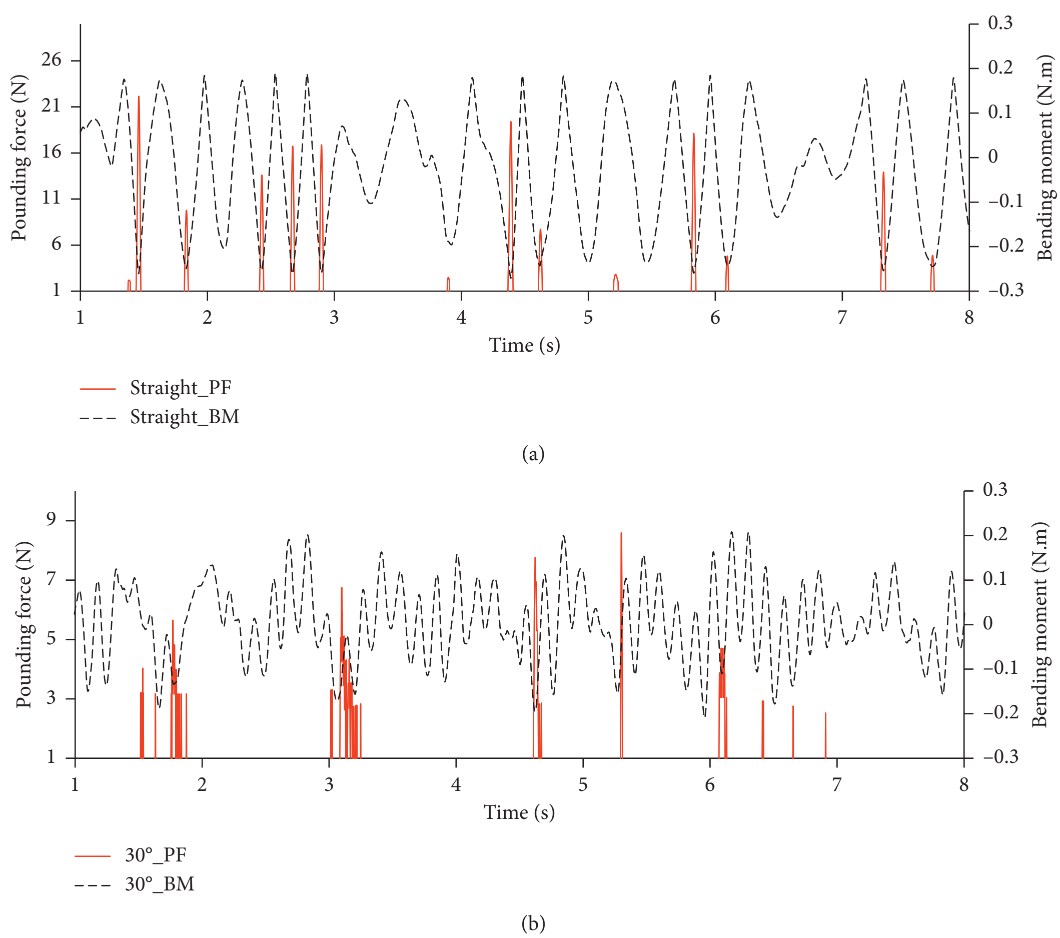
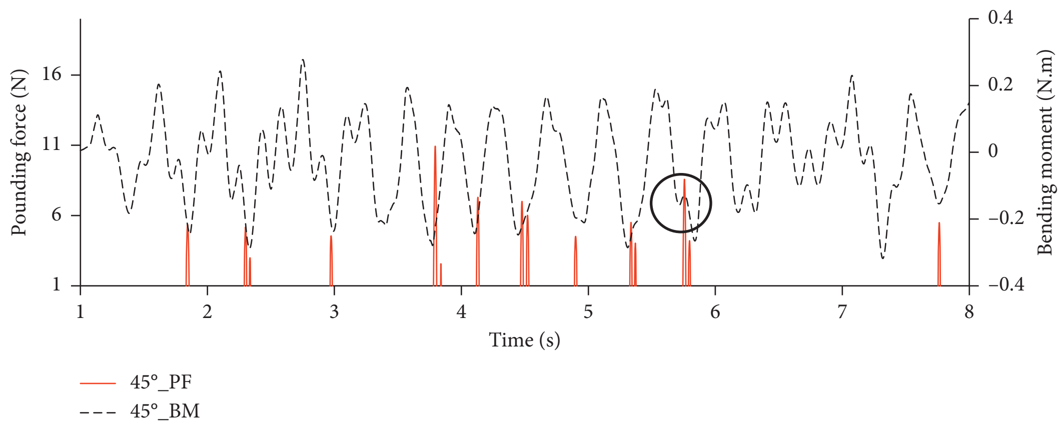


Figure 13: Continued.



(c)

Figure 13: Influence of pounding on the bending moment development of (a) straight, (b) 30° skewed, and (c) 45° skewed bridges (BM: bending moment and PF: pounding force).

results with the time in an increase in the girder rotations of bridges with a large skew angle.

To investigate the influence of pounding on the response of the pier, a comparison between the pounding forces and the bending moments of all the bridges is presented in Figure 13. The pounding forces of each bridge are indicated by the solid red lines, whereas the bending moments are indicated by the dashed black lines. The result shows that the effect of pounding on the bending moments of the piers differs significantly for the straight and skewed bridges.

As it can be seen from Figure 13(a), for the straight bridge, poundings occur at almost every occasion when the bending moments reach the peaks. The result confirms the impediment of girder movements by the abutments and thus restricts the development of the bending moments. Only one pounding force can be observed when the impact happened. For the skewed bridges, however, a number of pounding forces can be observed while in contact, as presented in Figures 13(b) and 13(c). The frequent impacts could be associated with the in-plane rotations of the girder. In this case, when pounding occurred, the bending moments still further developed, as circled at 5.3 s in Figure 13(c). The result shows that the pier bends further in the same direction; that is, the pounding might not effectively limit the movements of the pier.

4. Conclusions

To investigate the effect of skew angle on the earthquake response of bridges by considering poundings between the girder and the adjacent abutments, 42 shake table tests were performed on a bridge-abutment system subjected to uniform ground motions acting in the longitudinal direction to the bridge. The results obtained in this study are only applicable to the same or very similar cases, i.e., with similar dynamic properties of the structures and subjected to similar ground motions. The following conclusions are drawn:

(1) In the case considered, without and with pounding, a 45° skew angle increases the maximum transverse displacements by 1.47 and 1.38 times larger than a 30° skew angle, respectively.

(2) Pounding reduces the bending moments of piers of skewed bridges due to the restriction of the bridge movements in both the longitudinal and transverse directions.

(3) Relative to the response without pounding effect, pounding reduces the overall responses for the bridge with a 30° skew angle. In contrast, pounding increases the in-plane girder rotations up to 1.3 times for the bridge with a 45° skew angle.

(4) When pounding was considered, the 45° skewed bridge will have larger opening girder displacements than the straight bridge; that is, the bridges with a relatively large skew angle have more unseating likelihood than the straight bridges.

(5) On average, bridges with a 45° skew angle have a larger maximum pounding force and bending moment than bridges with a skew angle of 30°.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request. Requests for these data should be made to (Ziqi Yang, zyan511@aucklanduni.ac.nz).

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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