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Effect of soil flexibility on bridges subjected to spatially varying excitations

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Abstract. Pounding is a major cause of bridge damage during earthquakes. In an extreme situation, it can even contribute to the unseating of bridge girders. Long-span bridges will inevitably experience spatially varying ground motions. Soil-structure interaction (SSI) may play a significant role in the structural response of these structures. The objective of this research is to experimentally investigate the effect of spatially varying ground motions on the response of a three-segment bridge considering SSI and pounding. To incorporate SSI, the model was placed on sand contained in sandboxes. The sandboxes were fabricated using soft rubber in order to minimise the rigid wall effect. The spatially varying ground motion inputs were simulated based on the New Zealand design spectra for soft soil, shallow soil and strong rock conditions, using an empirical coherency loss function. The results show that with pounding, SSI can amplify the pier bending moments and the relative opening displacements.

Keywords: ground motion spatial variation; plastic hinge development; pounding; relative displacement; shake table experiment

1. Introduction

Bridge damage due to pounding is frequently observed in earthquakes. Examples include 1994 Northridge earthquake (Hall 1994), the 1995 Kobe earthquake (Park *et al*. 1995), the 1999 Chi-Chi earthquake (Uzarski and Arnold 2001), the 2008 Wenchuan earthquake (Lin *et al*. 2008), the 2010 Chile earthquake (Schanack *et al*. 2012) and the 2011 Christchurch earthquake (Chouw and Hao 2012). Pounding takes place as a consequence of the adjacent structures having an insufficient seismic gap to accommodate large relative closing displacements induced by the earthquakes. Normally the gaps of conventional bridge joints are only a few centimetres for serviceability purposes. Relative displacements between neighbouring structures can arise for the following reasons (Chouw and Hao 2008a): (1) the adjacent structures have unequal fundamental frequencies; (2) the ground motions along the bridge are spatially non-uniform (Kiureghian and Neuenhofer 1992) and (3) the adjacent bridge segments respond differently to soil-structure interaction (SSI) because of different soil and structural properties (Hao and Chouw 2008a). Spatial variation of

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ground motions arises from: (1) the propagation of seismic waves with finite velocity, causing delay of excitations at the various supports, known as the wave passage effect; (2) variation of local soil conditions and (3) the loss of coherency of the seismic wave due to refraction and reflection of the waves through heterogeneous soil media (Kiureghian and Neuenhofer 1992).

For simplicity, early investigations on the response of bridges to pounding often assumed fixed base foundations and uniform ground excitations. As the importance of ground motion spatial variation became more commonly recognised, researchers started to incorporate spatial variation effects into their studies of structural pounding. Jankowski *et al*. (1998) investigated the pounding response of an isolated elevated bridge due to spatially varying ground excitations considering only the wave passage effect. By conducting a parametric study on multi-span simply supported bridges, Zanardo *et al*. (2002) found that spatially varying ground motions can result in stronger pounding forces and relative displacements than uniform ground motions or ground motions considering only the wave passage effect. Chouw *et al.* (2006) performed a numerical analysis on the response of a four-span bridge considering spatially varying ground motions. The effect of multi-sided pounding was addressed. The study concluded that analyses of bridge seismic response without considering multi-sided pounding effects would result in an underestimation of the pounding force.

The SSI effect was given little consideration in conventional bridge design, as it was assumed to reduce structural responses owing to increased structural damping and elongation of the structure's fundamental period. However, the study by Mylonakis and Gazetas (2000) used the response spectra of the 1985 Mexico City earthquake record to show that the effects of SSI can be detrimental. The importance of SSI in analyses of seismic bridge response has been widely recognised. By studying the effect of SSI on the pier behaviour of a short bridge, Spyrakos (1990) concluded that SSI could increase pier displacements. Similar conclusions were drawn by Tongaonkar and Jangid (2003) in their investigation of the soil flexibility effects on an isolated bridge. Sextos *et al*. (2003) performed a parametric study on RC bridges considering spatial variation of ground motions and SSI, and concluded the combined effects can increase the absolute and relative displacements between girders. Bi *et al*. (2011) studied the separation distance of bridge structures required to avoid pounding, and considered the simultaneous influences of ground motion spatial variation and SSI. The results show that SSI can significantly affect the structural response, and should not be neglected. Other research also included pounding in the investigation of the combined effects of ground motion spatial variation and SSI. Mylonakis *et al*. (1999) conducted an analytical study on the performance of the southbound separation and overhead bridge, taking into account the influence of spatial variation of ground motion, SSI and non-linear contact at the expansion joints. The results show that the spatial variability of ground motion appears to have lesser impact on the structural response than SSI. This is probably due to the high coherence of the ground motions considered in the analyses. Chouw and Hao investigated the influence of spatially varying ground motions and SSI on the relative response of two bridge frames with pounding (Chouw and Hao 2008a) and without (Chouw and Hao 2008b) pounding. Both studies found that neglecting SSI effects can lead to the underestimation of the relative response of bridge frames

Pounding experiments are few and carried out mainly for buildings. Van Mier *et al*. (1991) conducted a number of pounding experiments on a prestressed concrete pile and a concrete striker of variable mass. Based on the results of those experiments, a simple elastoplastic contact model to predict the pressure in the contact zone was proposed. Chau *et al*. (2003) compared the pounding response of two-storey steel towers with that obtained from an analytical model based on the Hertz contact law. Jankowski (2010) performed pounding experiments on two buildings made of different materials, and concluded that the coefficient of restitution depends heavily on both the pre-impact velocity and the contact material properties. Very limited experimental research has been conducted on pounding between bridges. Vlassis *et al*. (2000) investigated the impact between adjacent bridge spans at in-span hinges and found that impacts between the adjacent frames produce acceleration levels significantly higher than what is typically assumed in design. Crewe and Norman (2006) carried out an experimental study on bridge pounding considering the wave passage effect of ground motions and concluded that assuming uniform ground motions will lead to unsafe bridge design. Li *et al*. (2012) conducted an investigation on the pounding behaviour of three identical segments considering spatially varying ground motions. The study showed that spatially varying ground motions can cause out-of-phase movements of adjacent segments even if they have the same fundamental frequencies, and pounding can increase the relative response of the bridge. Li *et al*. (2013) also studied pounding between a single segment bridge and its abutments, taking into account spatially varying ground motions. It was found that spatially varying ground motions can increase the bridge response compared to the uniform ground motions.

This study focuses on the seismic response between three identical segments considering the effects of spatially varying ground motions, SSI and pounding. Soil flexibility was addressed by constructing the sandboxes using soft rubber. The spatially varying ground motions considered soft soil, shallow soil, and strong rock conditions corresponding to the New Zealand design spectra (NZS 1170.5, 2004). The results were compared with those obtained from the fixed base tests. To the authors' best knowledge, no experimental investigation has ever incorporated the simultaneous effects of spatial variation of ground motions, SSI and pounding. Although the response of the sand filled rubber boxes did not exactly reflect the real soil behaviour, the results are still useful because the movability of the foundation soil was accounted for - something which has not been considered in the past.

2. Experimental model

2.1 Prototype bridge, model and testing

This research considers three identical bridge segments, each with a scale ratio of 1:125. The model was based on one segment of the Newmarket Viaduct replacement bridge in Auckland, New Zealand. The prototype structure has a girder length of 100 m and a column height of 15.5 m. The bridge model was constructed, and scaling was based on the similitude laws (Moncarz and Krawinkler 1981). More details about the prototype structure and the development of the scale model are provided by Li *et al*. (2012).

The models were fabricated using Polyvinylchloride (PVC) with a deck length of 800 mm and a pier height of 124 mm. The mass of each model including both the girder and the additional mass was 10.11 kg. The experiment considered separately both fixed base foundation and SSI. The fundamental frequencies and the damping ratios of the models with fixed base supports were around 1.98 Hz and 2%, respectively. Shallow foundations were assumed. Each footing was constructed by a square plywood board with dimensions of 90 × 90 × 10 mm. The footings were bedded on sand with the top surface of the footings flush with the sand surface. With footings on sand, the fundamental frequency and the damping ratio of the models were respectively found to be around 1.90 Hz and 4.6%.

Three unidirectional shake tables, each with platform dimensions of 350 × 350 mm were utilised to apply the excitations. The relative girder displacements were measured by the displacement transducers. Three-dimensional wireless accelerometers with a measuring capacity of ± 10 g were fixed to the centre of each deck. Strain gauges were glued to one side of each pier at the base to measure unit strains. The force at the pier top required to cause unit strain can be obtained using calibration factor that relates the measured strain and force and the bending moment can then be calculated from this force and the height of the bridge pier. The setup of the shake tables, bridge models, and rubber boxes, is shown in Fig. 1. Bridge segments 1, 2 and 3 in Fig. 1 are on sites 1, 2 and 3, respectively.

The ground motions were simulated using an empirical coherency loss function proposed by Bi and Hao (2012). The ground excitations were simulated based on the New Zealand design spectra (NZS 1170.5, 2004) for soft soil, shallow soil, and strong rock conditions. To incorporate the effect of coherency loss, spatially varying ground motions of soft soil conditions were further categorised as highly, intermediately or weakly correlated, whilst ground motions of shallow soil and strong rock conditions were simulated with only high correlation. To assure generality of the results, for each soil condition and coherency loss, 20 sets of ground motions were used, resulting in a total of 100 sets of stochastically independent spatially varying ground motions to be considered. These ground motions have an average peak ground acceleration of 1.0 g. The previous study (Li *et al.* 2012) provided more details on the ground motion simulation. Fig. 2 shows one set of simulated ground motions associated with soft soil condition with a high correlation. Fig. 3 shows the design spectra and the response spectra of the simulated ground motions. The spatial variation of the ground displacements can be clearly seen from Fig. 2(b). The solid, dotted and dashed lines are the ground motions at the supports of the right (segment 1), middle (segment 2) and left bridge segment (segment 3), respectively. The time delay of 0.2 s due to the considered wave apparent velocity of 500 m/s can be observed throughout the time history. The coherency loss can be seen especially in the time windows between 2 s and 7 s as well as between 15 s and 20 s. Fig. 3 shows that the ground motions of soft soil condition have a broader frequency content starting from around 1.5 Hz, while those of shallow soil and strong rock conditions have almost the same frequency content.

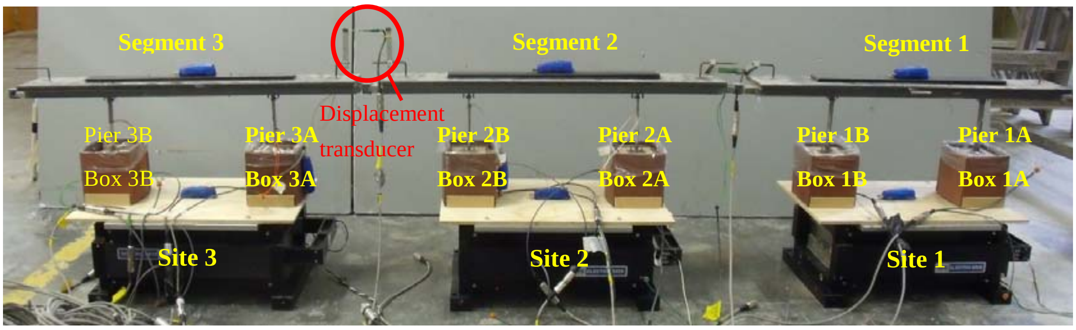

Fig. 1 Setup of the test system with rubber sandboxes

To ensure the same ground excitations were applied by the shake tables for both types of test - with and without SSI, an additional mass of 5 kg was loaded on each shake table for the fixed base case. This was done in order to maintain a consistent total mass on each shake table, with the additional 5 kg mass substituting for the mass of the sand used in the SSI case.

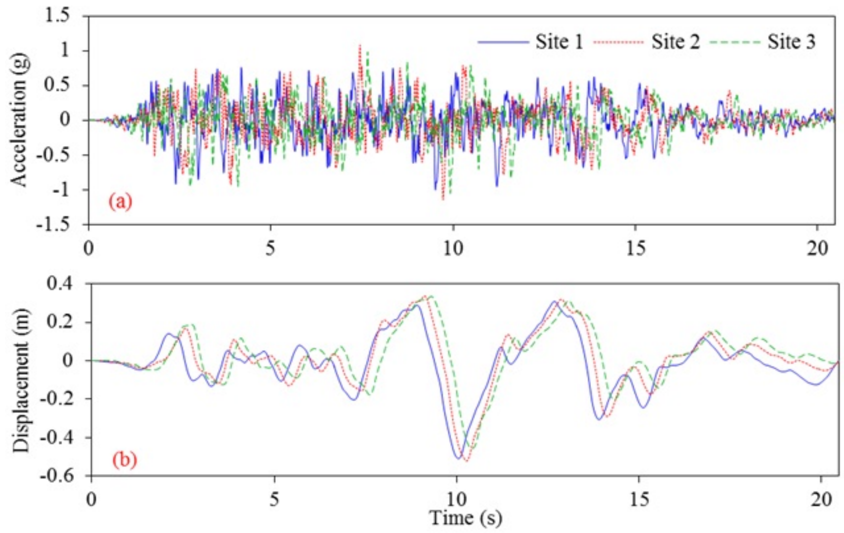

Fig. 2 Simulated ground motions: (a) Accelerations and (b) displacements for highly correlated excitations under soft soil conditions

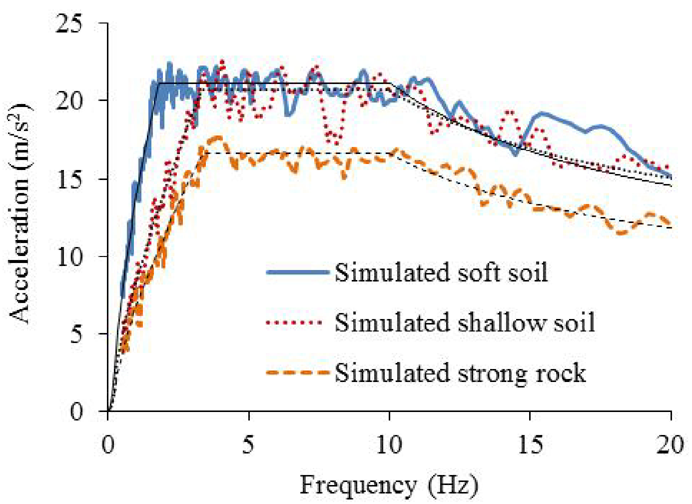

Fig. 3 The response spectra of the simulated ground motions (thick lines) and the target design spectra (thin lines)

2.2 Flexible rubber boxes

To incorporate soil flexibility, six identical rubber boxes were constructed with the dimensions shown in Fig. 4. Rubber was used to reduce the influence of the boundary condition (the rigid wall effect) arising from wave reflection on the boundary and variation of system vibration mode (Lu *et al*. 2002). Natural rubber with a hardness of 40-50 points (Durometer Shore hardness scale) was used. Side barriers made of plywood with dimensions of 100 × 100 × 10 mm were glued vertically on the wooden base (shown in Fig. 4(c)). The side barriers were used to prevent the sand expanding sideways, as this study only considered the soil flexibility in the excitation direction. Strip connectors were used to hold the rubber boxes together with bonding occurring along the wooden base. A gap of 5 mm was left between the bottom of the rubber box and the wooden base, in order to allow motion of the walls in a direction perpendicular to the direction of excitation, with minimal frictional effects. Plastic bags were used to prevent sand leakage.

For each shake table, a rectangular wooden base with dimensions of 540 × 330 × 8 mm was used to support the rubber boxes on the shake table. Sand was used to fill the boxes to a depth of 100 mm. A single box with sand was weighed, and found to be 2.45 kg. By applying white noise, the fundamental frequencies of the rubber boxes with and without sand were found to be 24.7 Hz and 15.1 Hz, respectively. To ensure the same initial soil conditions for each test, the rubber boxes were refilled after each excitation and compacted by applying a sinusoidal signal with a frequency of 50 Hz and duration of 30 seconds.

Fig. 5 compares the displacements of box 1A (measured at the centre of the outward wall) with those of the shake table due to the ground motion under strong rock conditions. As can be seen, the displacements of box 1A and the shake table show a significant discrepancy, which shows the influence of the flexibility of the sandboxes. In the case considered the movement of the rubber box follows the shake table with a time delay. The measurements show that the rubber box can also have lower or higher magnitudes depending on the ground motion characteristics.

Owing to the intrinsic difficulties associated with scaling soil particles, the bridge model on sand reflected the characteristics of a prototype structure founded on stiff soil. For this study, only the influence of the characteristics of excitations of different soil conditions on the model response were considered while the same sand was used.

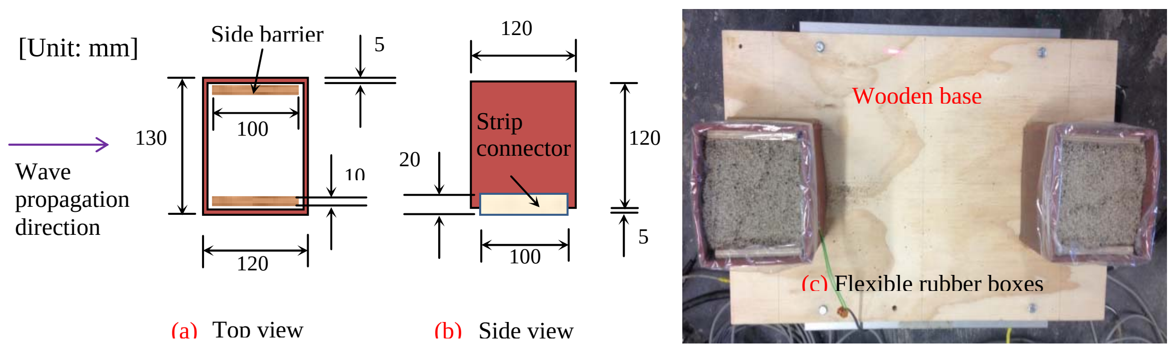

Fig. 4 Flexible rubber boxes: (a) Top view, (b) side view, and (c) top view of boxes filled with sand

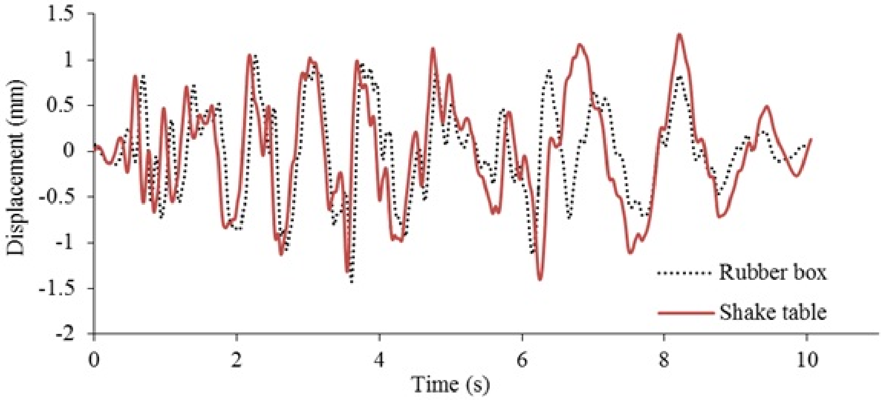

Fig. 5 Comparison of displacements of the rubber box (box 1A, see Fig. 1) and the shake table, subjected to the same highly correlated ground motion associated with the strong rock condition

3. Results and discussion

In order to compare the structural responses in a valid manner, the bending moment at the pier support, the relative girder displacement, and the pounding force, were normalised by the reference values, which were, respectively, the averages of the 20 maximum bending moments, the maximum displacements, and the base shear of segment 1 due to the 20 corresponding ground motions of different soil conditions without pounding. Table 1 summaries the corresponding reference values and the maximum and minimum responses for each case. The reference values reflected the characteristics of the seismic bridge responses due to the simulated ground motions. The ratios of the normalised results are only valid for the cases considered or for very similar cases.

Table 1 Ground motion cases and reference responses

Case	Soil condition	Coherence	Reference response (min, max)		
			Displacement (mm)	Bending moment (Nm)	Base shear (N)
1	Soft soil	Highly	4.85 (4.05, 5.92)	0.92 (0.77, 1.12)	7.42 (6.21, 9.06)
2	Soft soil	Intermediately	4.85 (4.05, 5.92)	0.92 (0.77, 1.12)	7.42 (6.21, 9.06)
3	Soft soil	Weakly	4.85 (4.05, 5.92)	0.92 (0.77, 1.12)	7.42 (6.21, 9.06)
4	Shallow soil	Highly	3.55 (2.89, 4.62)	0.65 (0.53, 0.85)	5.26 (4.28, 6.85)
5	Strong rock	Highly	2.74 (2.17, 3,21)	0.49 (0.39, 0.57)	3.96 (3.13, 4.63)

3.1 Effect of SSI on girder displacement without pounding

To reveal the interaction between the soil and the bridge segment sand in rubber boxes was used as the support of the surface footing. The difference in the response with and without considering the sand support reflects the effect of SSI. Fig. 6 shows the absolute displacements of segment 1 with and without SSI due to the excitations associated with different soil conditions. Pounding was excluded by providing sufficient gaps of sufficient width between the adjacent girders. In Fig. 6(a), the maximum girder displacement under fixed base conditions of 4.75 mm was almost the same as that of 4.83 mm with consideration of SSI effects. Fig. 6(b) shows that under the ground motion with shallow soil condition, SSI reduced the maximum girder displacement from 3.74 mm to 3.27 mm, i.e., a 13% reduction. From Fig. 6(c), the maximum absolute displacements are 2.73 mm and 2.26 mm, with and without SSI, respectively, i.e., SSI effects cause a 21% of increase in the maximum girder displacement.

Figs. 6(a) and 6(b) show that the patterns of the girder displacements with and without SSI were similar. In contrast, Fig. 6(c) shows greater discrepancies between the girder displacements with and without SSI. SSI had a larger influence on the bridge model under the ground motions associated with the strong rock condition. The observations reveal that SSI can have a detrimental effect in terms of causing a greater displacement of the bridge model when the ground motions of strong rock condition apply.

Fig. 7 shows the 20 normalised maximum displacements of segment 1 with respect to the 20 corresponding ground motions of various soil conditions with and without SSI. Pounding effects are excluded. The reference responses are shown in Table 1. The number in brackets is the average of the 20 maximum responses.

In Figs. 7(a) and 7(b), it is shown that SSI effects resulted in almost the same average maximum absolute displacement of segment 1 due to the ground motions of the soft and shallow soil conditions, i.e. only a 2% decrease and 4% increase, respectively. When the ground motions of the strong rock condition were considered, an increase of 16% in the average maximum absolute girder displacement was observed. SSI can increase the maximum girder displacement by up to 8% (ground motion set 17), 32% (ground motion set 8) and 36% (ground motion set 9) due to the ground motions of soft soil, shallow soil and strong rock conditions, respectively. In Fig. 7(c), only two ground motions (sets 6 and 18) among the twenty were found to reduce girder displacements when SSI effects were considered. It is almost certain that SSI can increase the girder displacement when the ground motions of the strong rock condition were applied.

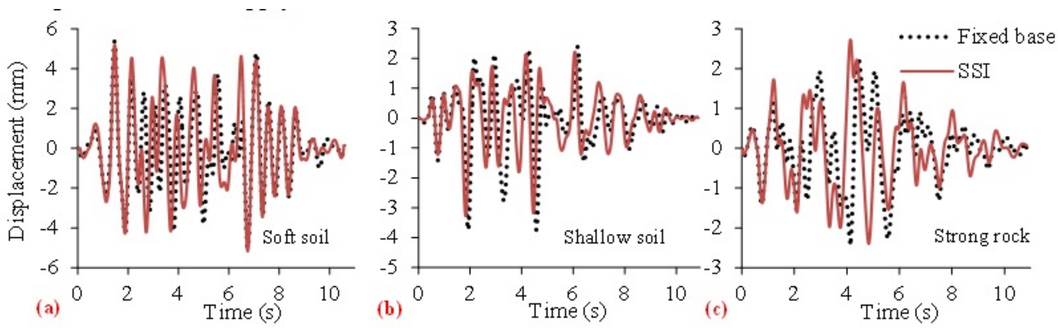

Fig. 6 Absolute displacements of segment 1, with and without SSI, for ground motions of (a) soft soil, (b) shallow soil, and (c) strong rock conditions

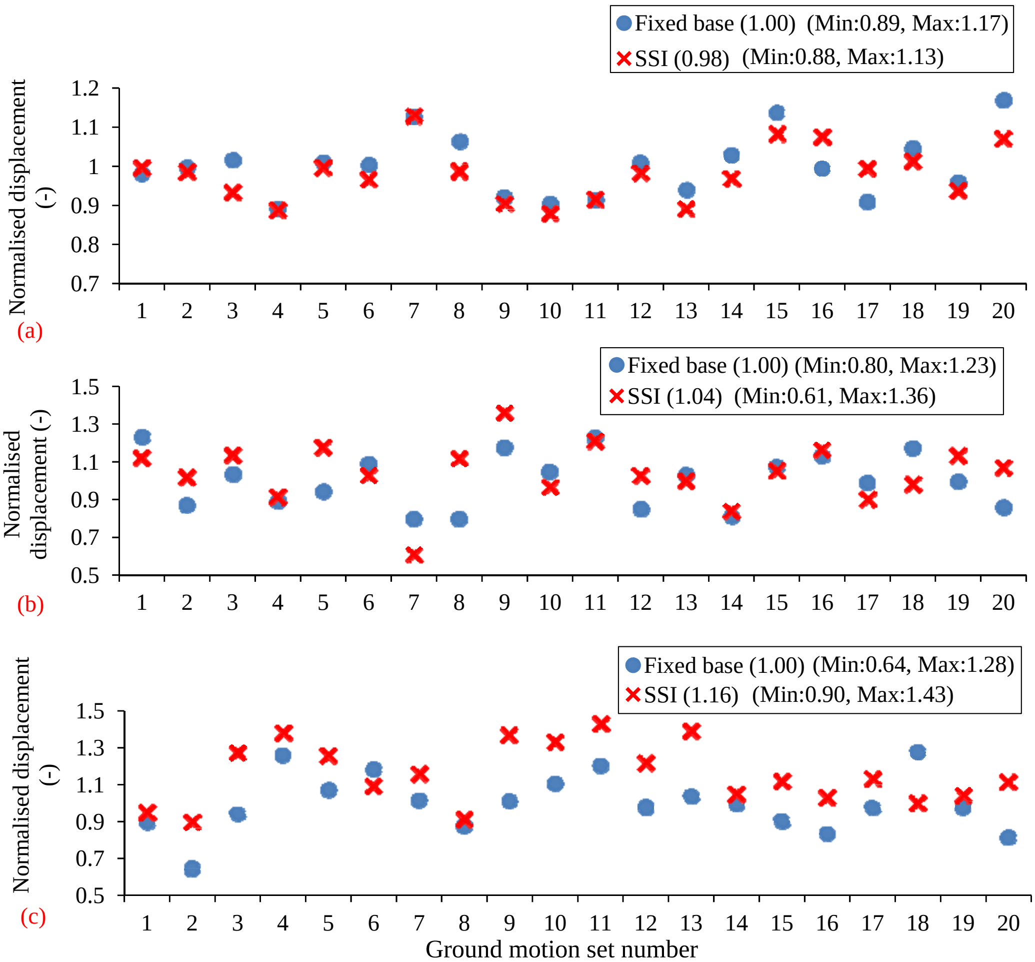

Fig. 7 Consequences of SSI for the normalised maximum absolute displacements of segment 1, without pounding, due to the ground motions of (a) soft soil, (b) shallow soil, and (c) strong rock conditions

3.2 Simultaneous effect of SSI and spatially varying excitation

To investigate the combined effects of SSI and spatially varying ground motions, the normalised maximum relative opening displacements between segments 1 and 2, with and without SSI, were compared (see Fig. 8). The relative opening displacements were measured by the displacement transducer shown in Fig. 1, and are equivalent to the difference between the displacements of segments 1 and 2. This is done only for the purpose of isolating the influence of pounding. Under actual and real conditions, this does not have any significant practical meaning. To avoid pounding, the segments were given a sufficient gap between them. High correlations between the ground motions at adjacent supports were considered.

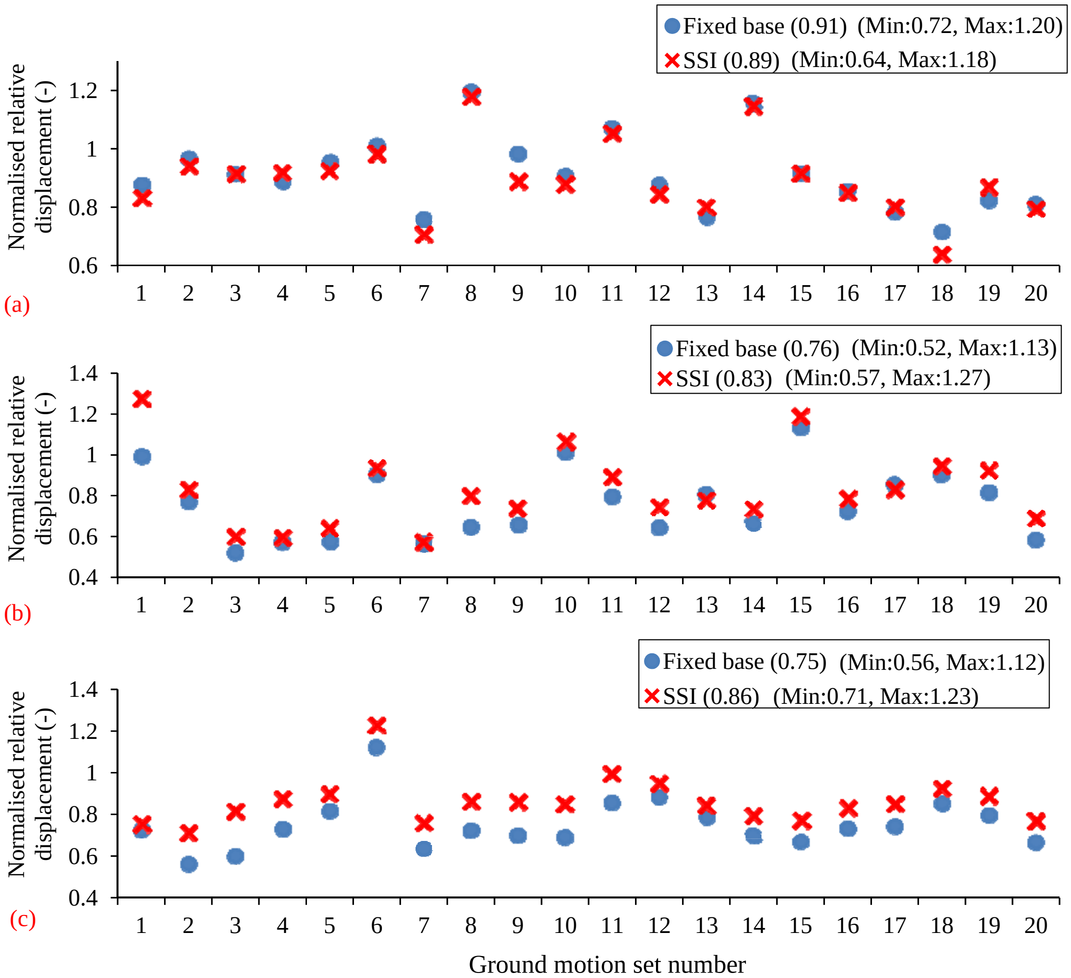

Fig. 8 Consequences of SSI for the normalised maximum relative opening displacements between segments 1 and 2, without pounding effects. Results for highly correlated ground motions of (a) soft soil, (b) shallow soil, and (c) strong rock conditions

Fig. 8 shows that relative displacement between identical segments cannot be avoided if spatially varying ground motions are anticipated. In Fig. 8(a), very little variation between the normalised maximum relative opening responses was observed. This is expected as the result of Fig. 7(a) has revealed that SSI, on average, had very little influence on the absolute displacement of the bridge girder under the ground motions of the soft soil condition. Therefore, with a high correlation of the ground motions, the absolute displacements of segment 2 with SSI can be expected to be similar with those of the fixed base condition. Still, noticeable differences between the normalised relative displacements with and without SSI were observed in ground motion sets 9, 18 and 19. The difference due to ground motion 9 was more than 10% of the reference displacement (0.98 cf. 0.89 for fixed base and SSI, respectively). In contrast, Figs. 8(b) and 8(c) show that SSI increased the relative opening displacements of the segments by, on average, 7%

and 11% of the reference displacements due to the highly correlated ground motions of the shallow soil and strong rock conditions, respectively. The most significant increase of the normalised maximum relative opening displacements that included SSI effects occurred due during ground motion set 1 of the shallow soil condition, and set 3 of the strong rock condition, with respective increases of 27% and 37%. As shown in Fig. 8(b), in almost all cases, the maximum relative displacements with SSI are greater than those with fixed base, with only two exceptions. These exceptions are seen in Fig. 8(b) (sets 13 and 17) and Fig. 8(c). For these two cases SSI increased the maximum relative opening displacements for all the ground motions considered.

The results show that without pounding, SSI led to a greater increase in the maximum relative opening displacement under the spatially varying ground motions of the strong rock condition, than those of the shallow soil condition. Under the ground motions of the soft soil condition, SSI had negligible effect on relative movement between the girders.

3.3 Simultaneous effect of SSI, spatially varying excitation, and pounding

In order to investigate the simultaneous effects of SSI and the spatial variation of excitations including pounding, the relative opening displacement and the pounding force time histories between segments 1 and 2 are compared (see Fig. 9). The segments were given a zero initial gap, and subjected to the highly correlated excitation of the shallow soil condition. Including the effects of SSI resulted in both the maximum relative opening displacement and the maximum bending moment at the pier base, being larger than the measured values for the fixed base assumption. In contrast, the maximum pounding force with the fixed base condition is larger than that with SSI effects included.

The damage potential of bridge girders depends not only on the magnitude of the contact force, but also on the number of strong impacts. As shown in Fig. 9(b), the fixed base case resulted in more strong impacts than the SSI case. SSI reduced the impact forces and lessened the number of strong pounding impacts. In the cases considered, SSI can reduce pounding damage to the structure. However, SSI resulted in larger relative opening displacements. Hence, SSI may increase the risk of unseating. The results presented in Fig. 9 show that with pounding, SSI can contribute to larger bridge displacement responses, even though SSI can increase the damping in a structure.

In Fig. 10(a), the normalised pounding forces in the fixed base case are larger than those of SSI case, for almost all cases with the exception of the set 8 ground motion. For set 8, the maximum responses with and without SSI, are essentially the same. More than 50% of the pounding force due to ground motion set 1, was reduced when SSI was considered. On average, the pounding force for the SSI case is 19% less than that of the fixed base case. In Fig. 10(b), SSI, for most cases considered, caused larger relative opening displacements, leading to a 33% increase in the averaged maximum relative opening displacements compared to the fixed base case. This is equivalent to a 10 cm difference in the prototype structure. Increases in the normalised bending moments due to SSI conditions were also observed in Fig. 10(c). The average normalised maximum bending moment of pier 1B with fixed base assumption is 0.74, while for the SSI case it is 0.95 (an increase of 28%).

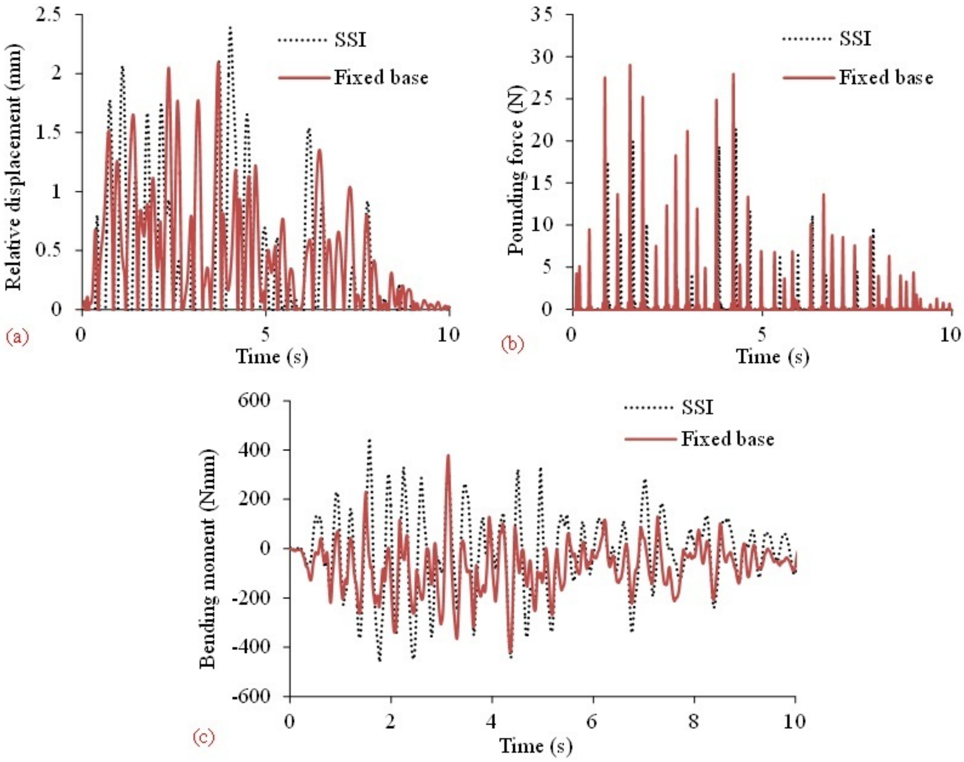

Fig. 9 Consequence of SSI for (a) relative opening displacement, (b) pounding forces of segments 1 and 2, and (c) bending moment of pier 1B, due to highly correlated excitation of shallow soil condition

Fig. 11 shows the differences between the maximum responses, with and without SSI effects, subjected to the highly correlated ground motions of soft soil, shallow soil and strong rock conditions. The results are presented in a normalised form with the reference responses indicated in Table 1. The positive and negative values indicate whether SSI has, respectively, increased or reduced the structural responses. The averages of the differences corresponding to the 20 ground motions of different soil conditions are shown in brackets.

The positive averages shown in Fig. 11(a) indicate that SSI can increase the pier bending moment of the middle segment regardless of soil conditions. The values shown in brackets show that the spatially varying ground motions of the strong rock condition resulted in the largest averaged difference, i.e., 0.13, which means that SSI can increase the bending moment of pier 2A by up to 13% of the corresponding reference bending moment (presented in Table 1). The differences due to the ground motions of the soft and shallow soil conditions have a spread above and below zero, while those due to the excitations of the strong rock condition are all above zero except for the case due to ground motion set 16. This observation confirms that SSI will induce amplification of the pier bending moments of the middle segment, under spatially varying ground motions of the strong rock condition.

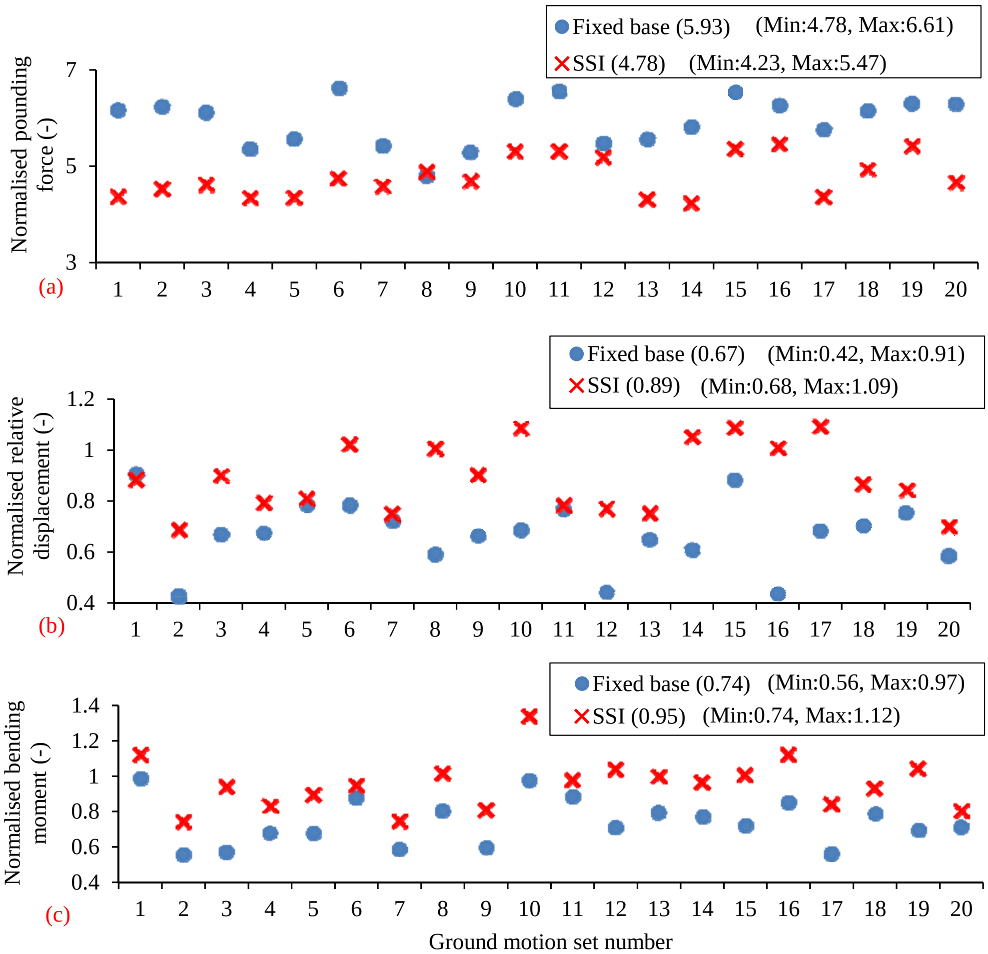

Fig. 10 Consequences of SSI under highly correlated excitations of the shallow soil condition. Maximum values of the normalised (a) pounding force, (b) relative opening displacement between segments 1 and 2, and (c) bending moment of pier 1B

SSI can reduce the maximum pounding forces, regardless of soil condition. It can be seen that all the averaged values shown in Fig. 11(b) are negative, except for a few associated with ground motions of the soft soil condition. By comparing these averaged values (in brackets), it can be seen that compared to the other coherency loss cases, SSI resulted in more reduction of the pounding force under the ground motions of the strong rock condition, i.e. 2.58 times of the reference base shear. The maximum reduction was found when the bridge was subjected to the set 12 ground motions of the shallow soil condition, i.e. 4.4 times of the reference base shear. The average results in Fig. 11(c) show that SSI tends to increase the relative opening displacement. Hence it is anticipated that there will be increased unseating potential under the ground motions of the soft soil condition.

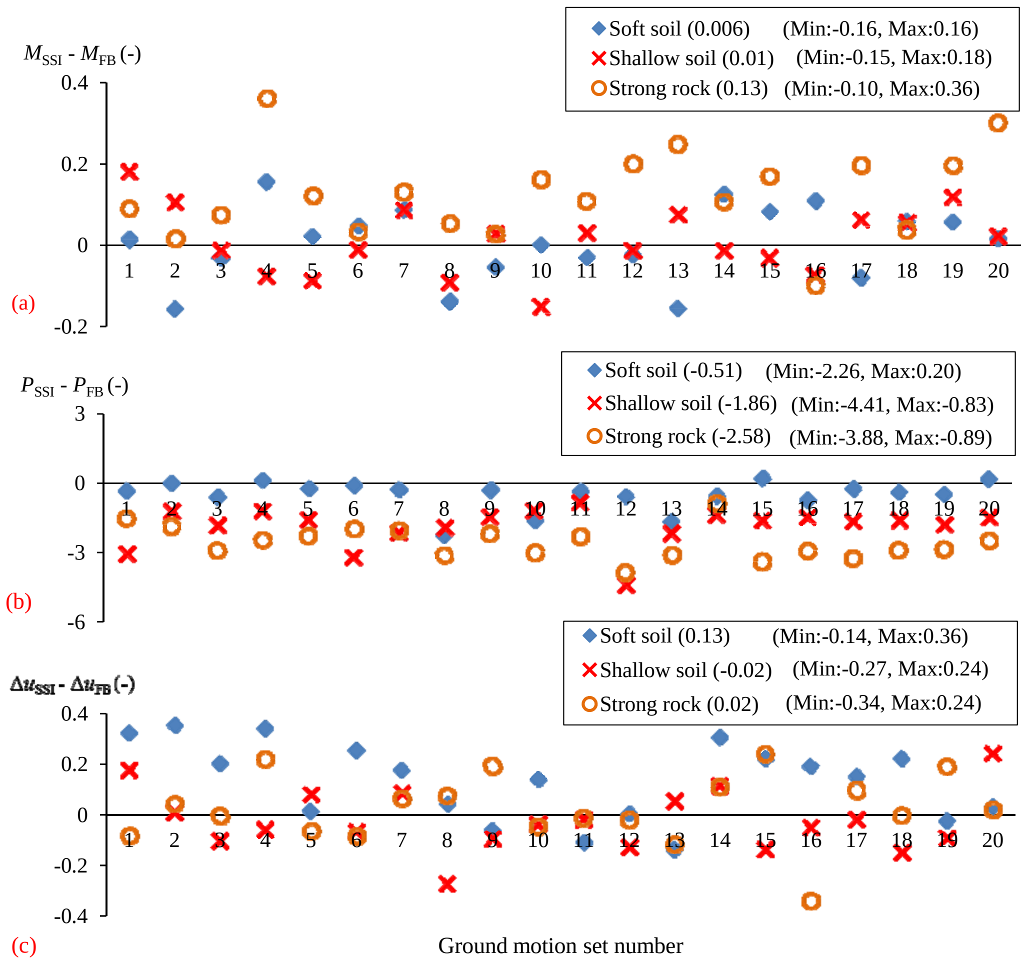

Fig. 11 Consequence of SSI and excitation soil conditions for the maximum values of the normalised (a) bending moment of pier 2A, (b) pounding force, and (c) relative opening displacement between segments 2 and 3

3.4 Effect of SSI and coherency loss of ground motions

To investigate the simultaneous influence of coherency loss and SSI on structural response, the differences between the maximum responses for the SSI case on the one hand, and the fixed based case on the other hand, are shown in a normalised form in Fig. 12 (average values given in brackets). Ground motions based on the soft soil spectrum with high, intermediate and weak correlation were considered.

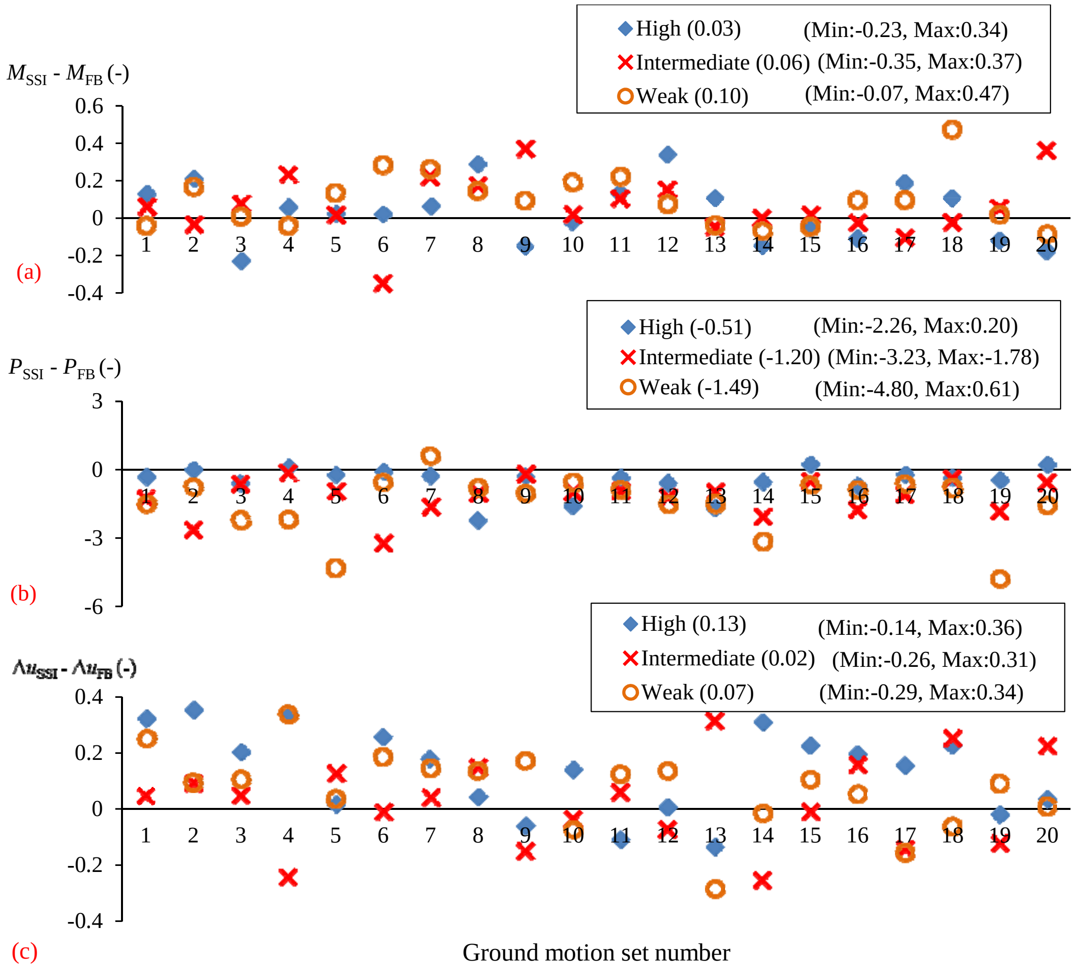

Fig. 12 Consequence of SSI and coherency loss for the maximum values of the normalised (a) bending moment of pier 3A, (b) pounding force, and (c) relative opening displacement between segments 2 and 3

Positive averages were observed for all the coherency loss cases in Fig. 12(a), indicating that SSI can increase the bending moment of pier 3A. By comparing the averages of the normalised differences, the spatially varying ground excitations with the weak correlation caused a 10% increase in the maximum bending moment due to the ground motion of the soft soil condition. From Fig. 12(b), it can be seen that under most ground motions, SSI reduced the maximum pounding force between segments 2 and 3, regardless of the correlation of ground motions. If a weak correlation is anticipated for the spatially varying excitations of adjacent supports, the pounding force can be reduced by almost 1.5 times, compared to the maximum base shear from the same ground motion, but without pounding. In an extreme case, the reduction can even be as much as an 80% reduction. Fig. 12(c) shows that SSI increased the relative opening displacement between segments 2 and 3, especially when the bridge was subjected to highly correlated ground excitations. Notably, at least 13% greater seating length is demanded to avoid unseating between segments 2 and 3, when the structure is subjected to highly correlated spatial excitations where pounding and SSI are considered simultaneously.

3.5 Simultaneous effect of pounding and SSI on unseating potential

In order to investigate the potential for girder unseating, the normalised maximum relative opening displacements of the adjacent girders with and without pounding, under spatially varying ground motions are presented in Fig. 13. For the results of Fig. 13, SSI effects are considered. The differences between these normalised average maximum responses, with and without pounding, are summarised in Table 2, with positive values indicating increased the relative opening displacement due to pounding.

Table 2 shows that pounding, for most cases, increased the relative opening displacements between the adjacent girders. There was one exception, and this was between segments 1 and 2 under the ground motions of the soft soil condition. Between segments 2 and 3, the increase of the relative opening displacement due to the excitations of the soft soil condition, in terms of percentage of the reference displacements (shown in Table 1) is most significant, while those due to the excitations of the strong rock condition is the least significant. However, such trends are not found between segments 1 and 2. In fact, the ground motions of the strong rock condition caused the larger increase in the maximum normalised relative opening displacement between segments 1 and 2. In most cases, pounding increased the unseating potential, when both SSI and spatially varying ground motions were considered. However, pounding affected the bridge response differently, between different adjacent girders. Segments 2 and 3 tended to suffer the effect more than segments 1 and 2.

From Fig. 13, it can also be observed that regardless of soil conditions, the relative opening displacements between segments 1 and 2 have a greater maximum than those between segments 2 and 3. In the case of the excitations of the strong rock condition, the unseating potential of segments 1 and 2 can be as much as twice that of segments 2 and 3, when pounding effects are neglected.

Therefore, according to the results shown in Figs. 12(c) and 13, when designing the seating length to include both pounding and SSI effects, for highly correlated ground motions, the maximum relative opening displacement between the first two segments should be adopted for all of the other bridge joints.

Table 2 Consequence of excitation characteristics, SSI, and pounding for normalised relative opening displacements

$u_{\text{pounding}} - u_{\text{nonpounding}}$	Ground motion soil condition		
	Soft soil	Shallow soil	Strong rock
Segments 1 and 2	-0.06	0.06	0.09
Segments 2 and 3	0.21	0.19	0.18

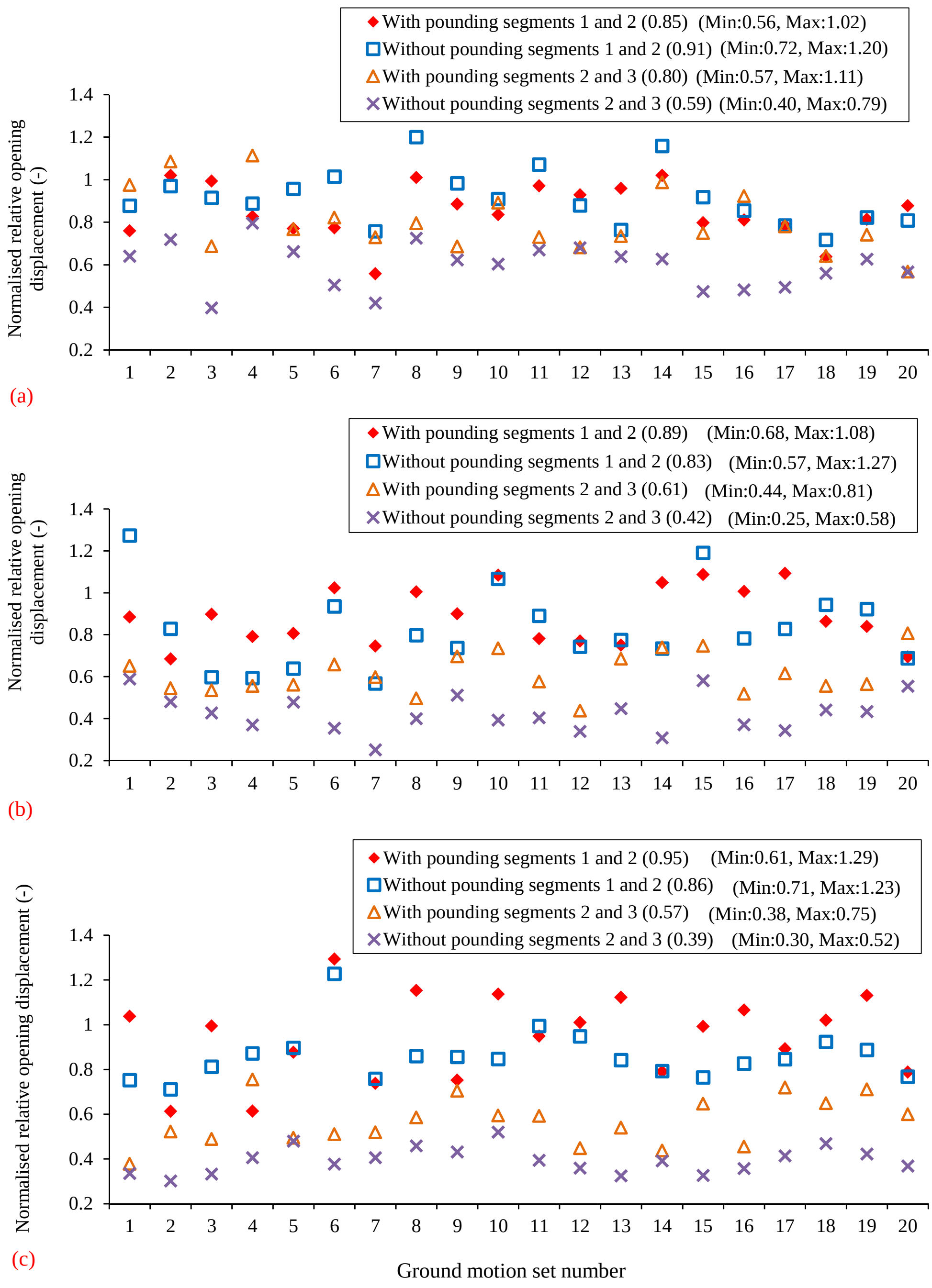

Fig. 13 Consequence of pounding and SSI for the normalised relative opening displacements between different segments, for(a) soft soil, (b) shallow soil and (c) strong rock conditions

4. Conclusions

This research addressed the response of three bridge models with almost identical properties, to account for the spatial variation of ground motions, and soil-structure interaction (SSI). Pounding effects were also considered. The spatially varying ground motions were stochastically simulated and based on the New Zealand design spectra for the soft soil, shallow soil, and strong rock conditions. Coherency loss effects of the spatially varying ground motions were studied by considering high correlation for all three soil conditions, as well as intermediate and weak correlations for the ground motions of the soft soil condition. The influence of the flexibility of the proposed rubber sandboxes was quantified by comparing the displacements of the rubber box and the shake table. To limit the influence factors in this study, only sand was used to support the surface footings of the bridge model. Since sand cannot be scaled, thus the soil is stiff soil.

In order to understand the effects of SSI, the bridge models with both fixed base and SSI conditions, were separately subjected to the same ground excitations. The relative opening girder displacements, pounding forces, and bending moments at the pier bases were measured and normalised by the corresponding reference responses obtained for each soil condition without pounding. In total, 200 experiments considering SSI and another 200 with fixed base supports were conducted. By comparing the normalised results obtained from these experiments, the following conclusions are drawn:

- If ground motions of strong rock condition are anticipated, and pounding effects exclud ed, SSI is likely to increase the maximum girder displacement by 16% on average, co mpared to fixed base case. In the extreme case, the increase can be as large as 21%.
- In most of the cases considered, the combined effect of SSI and pounding is shown to increase both the maximum pier bending moment and the maximum relative opening displacements, on average, by 33% and 28%, respectively.
- The SSI can result in approximately 20% smaller maximum pounding force than that of the bridge structures with an assumed fixed base.
- With weakly correlated ground motions, SSI can increase the maximum bending mome nt and reduce the maximum pounding force more significantly compared to other coher ency loss cases, while highly correlated ground motions tend to result in more increase in the maximum relative opening displacement.
- With SSI, pounding can lead to an increase of unseating potential.

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