Experimental study of the inelastic bridge behaviour under spatially varying excitations

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ABSTRACT:

Bridges experience spatially varying ground excitations during seismic events, causing relative displacement between adjacent bridge structures. Pounding and girder unseating have been found to be caused by the relative displacement of bridges. Previous research has been done to investigate the effects of spatially varying ground excitation on bridge responses. However, most studies are numerical. Investigations that incorporate the effects of pounding and inelastic response of bridges have rarely even been reported. This work studies the effects of spatially varying ground excitations including the effects of pounding and bridge inelastic response through a series of shake table tests. A small scale two-span bridge model was constructed and subjected to simulated spatially varying ground excitations. The bending moment generated in the bridge piers is investigated. The results show that pounding could increase or decrease the generated bending moment depending on the different sets of ground motions applied. Plastic hinging has been found to be beneficial to the development of bending moment in the piers in most cases.

1 INTRODUCTION

Pounding between adjacent bridges and girder unseating have been observed in past earthquakes such as the 1994 Northridge Earthquake (Hall, 1994), the 1995 Kobe Earthquake (Chouw, 1995) and the more recent 2011 Christchurch Earthquake (Chouw and Hao, 2012). Pounding is caused by insufficient gap size whereas girder unseating is due to the underestimation of the necessary seating length. Pounding is inevitable because gap sizes in expansion joints are only a few centimetres to allow for smooth traffic flow. One important reason of underestimation of seating length is mainly due to the assumption of uniform ground excitations used in current design practice. However, in reality, bridge supports experience spatially varying excitations due to the wave passage effect, the coherency loss effect, and the site response effect (Li et al., 2012 and 2013).

Many past investigations addressed the effects of spatially varying excitations on seismic response of structures such as by Bogdanoff et al. (1965), Zerva (1990), and Chouw and Hao (2009). These studies however, were conducted numerically, and so more experimental work is needed. Furthermore, experimental investigations of the inelastic behaviour of bridges due to spatially varying ground excitations incorporating the effects of pounding have not been reported.

During major earthquake events, other than pounding, plastic hinge development in bridge piers inevitably occurs. Thus, in order to have a more realistic understanding of the behaviour of bridges during major earthquakes, experimental study on inelastic bridge behaviour incorporating pounding effects when subjected to spatially varying ground excitations is needed.

In this study a series of shake table tests were conducted on a small scale two-segment bridge model. The effects of pounding and plastic hinges on the bending moment at bridge pier support were investigated. Artificial plastic hinges were constructed to simulate possible plastic behaviour of the bridge pier.

2 METHODOLOGY

2.1 Prototype and scaled bridge model

The prototype bridge used comprises of two identical segments, each made up of a deck 100 m in length and two piers 21.5 m in height. The parameters of the bridge prototype are listed in Table 1.

Table 1. Prototype parameters

Span	100 m	Seismic mass	1.65×10^6 kg
Height of pier	21.5 m	Modulus of Elasticity	30 GPa
Width of pier	3.44 m	Bending stiffness	5.64×10^7 N/m
Thickness of pier	1.48 m	Longitudinal frequency	1.0 Hz

The prototype structure was then scaled down 125 times according to principles of similitude outlined by Moncarz and Krawinkler (1981). The scaled bridge model was constructed using Polyvinyl-chloride (PVC). The bridge model parameters are given in Table 2.

Table 2. Scaled bridge model parameters

Span	800 mm	Pier height	172 mm
Deck thickness	3 mm	Pier width	21 mm
Girder depth	20 mm	Pier thickness	3 mm
Girder width	120 mm	Bending stiffness	1.2×10^3 N/m
Seismic mass	8.8 kg	Longitudinal frequency	2.0 Hz

The scale factors used are shown in Table 3.

Table 3. Scale factors for experimental model

Length (*L*)	Time (*t*)	Modulus of Elasticity (*E*)	Mass (*M*)	Acceleration (*a*)	Force (*F*)
1:125	1:2	1:12	1:187,500	1:31.25	1:1,500,000

2.2 Setup

Two 23 kg test load capacity unidirectional shake tables were placed in line with each other and the bridge model was fixed onto the shake tables. A draw wire displacement transducer was used to measure the relative displacement of the girders, whereas the girder displacement relative to the corresponding base (shake table platform) was measured using a linear variable differential transformer (LVDT). The experimental setup of the two-segment bridge model on the corresponding shake tables is shown in Figure 1.

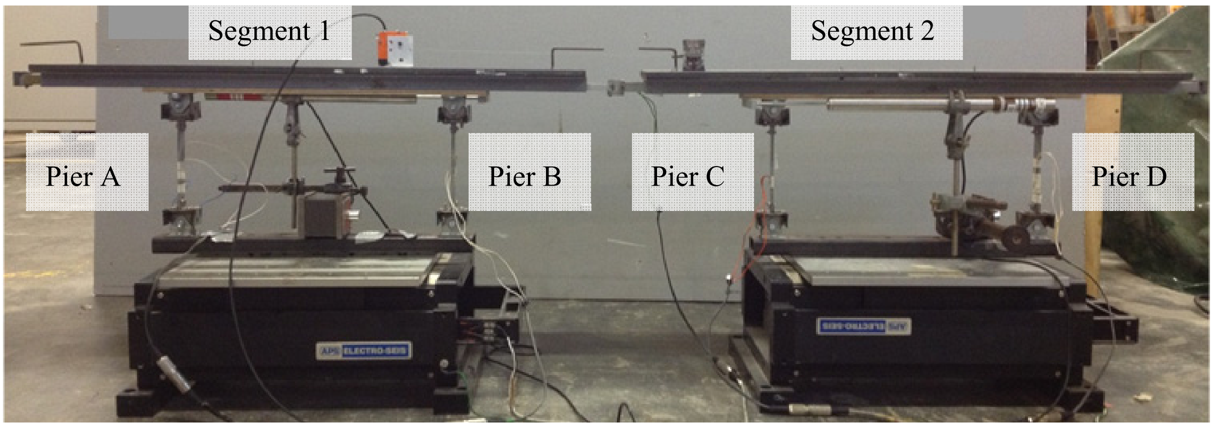

Figure 1. Experimental setup

In order to simulate the plastic damage experienced by the bridge during major earthquakes, artificial

plastic hinges were constructed and installed at the base of the piers as well as at the deck-pier joints. Strain gauges were placed on one side of each pier near the bases to measure the generated bending moments. Plastic hinge development was achieved by adjusting the torque on the hinges (hinge capacity) to 2.5 Nm. The constructed plastic hinge is shown in Figure 2. It has been observed that not all plastic hinges occur simultaneously as the loads will be redistributed once plastic hinging starts to occur.

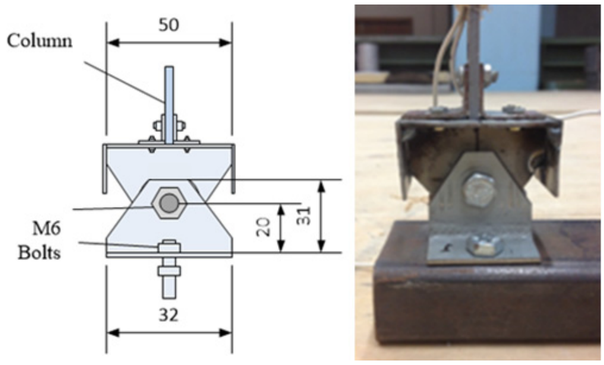

Figure 2. Artificial plastic hinge used to simulate plastic damage

2.3 Ground motions

The spatially varying ground motions used in this test were simulated based on the New Zealand design spectrum for soft soil condition, class D (NZS 1170.5, 2004). A total of 10 sets of ground motions were simulated. The target peak ground acceleration was 1 g. The empirical equations proposed by Bi and Hao (2012) formed the basis of development for the simulated spatially varying ground motions. The time history of the simulated spatially varying ground motion Set 1 for both segments is shown in Figure 3.

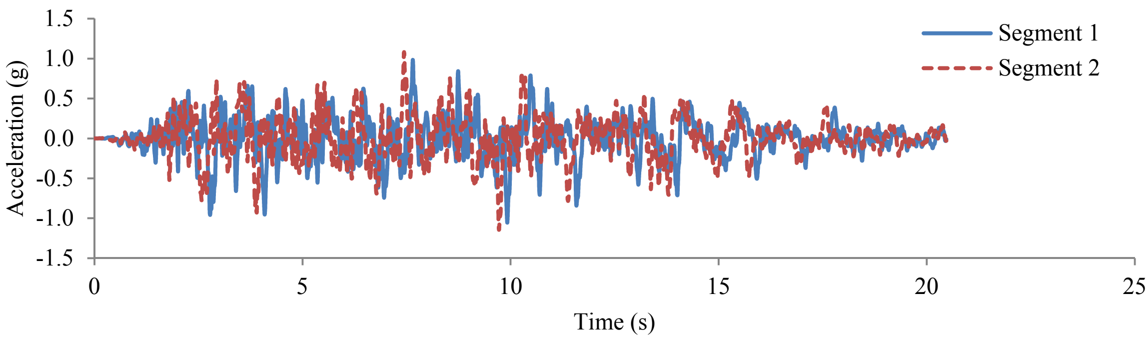

Figure 3. Time history of ground motion Set 1

3 RESULTS AND DISCUSSION

3.1 Effect of pounding

The bridge model was subjected to the simulated spatially varying ground excitations and the effect of pounding on the bridge response was investigated. The bending moment development of the bridge pier at the support of Pier B (see Figures 1 and 2) when neglecting pounding and when pounding was introduced is shown in Figure 4.

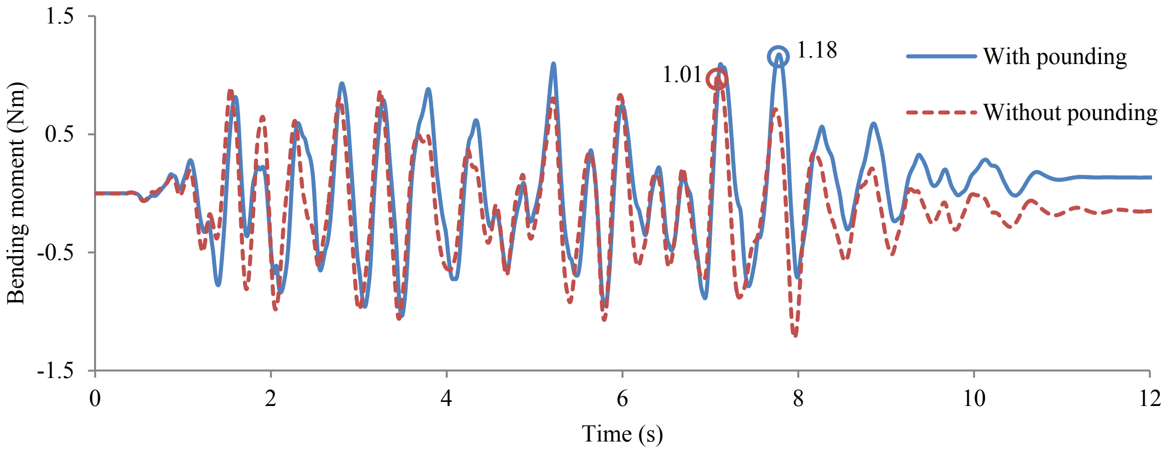

Figure 4. Bending moment of bridge pier subjected to ground motion Set 1 with and without pounding

It can be seen that when subjected to ground motion Set 1, without considering the effects of pounding, the maximum bending moment generated at the base of the bridge pier is 1.01 Nm, whereas when pounding is introduced, the maximum bending moment generated is 1.18 Nm. This means that including the effects of pounding could increase the bending moment generated in bridge piers.

On the other hand, when subjected to a different set of ground motion (Set 3), it can be seen that the maximum bending moment generated in the bridge pier when considering pounding is 0.84 Nm, but when pounding is not included, the maximum bending moment generated is 1.22 Nm. This shows a decrease in maximum bending moment with the inclusion of pounding effects. The bending moment development of the bridge pier when subjected to ground motion Set 3 is shown in Figure 5.

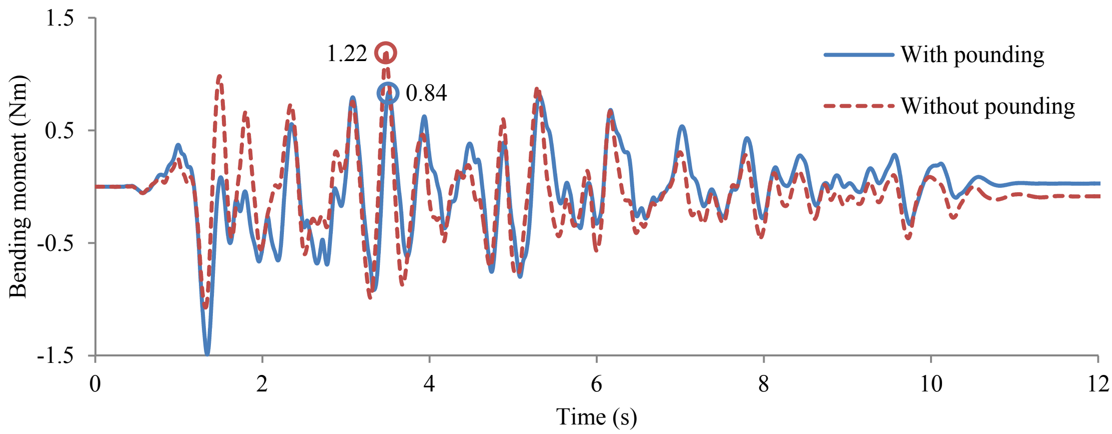

Figure 5. Bending moment of bridge pier subjected to ground motion Set 3 with and without pounding

To further investigate the effects of pounding on the bending moment development of bridges, the maximum bending moments generated in the pier when subjected to different ground motions have been plotted in Figure 6. The plot shows that consideration of pounding can increase and decrease the maximum bending moment generated in the bridge pier depending on the applied ground motion. However, the inclusion of pounding mostly decreases the maximum bending moment generated.

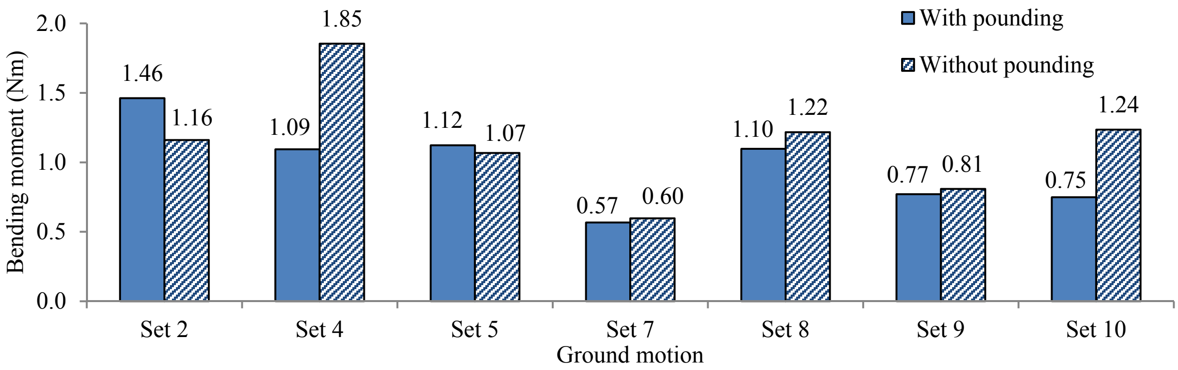

Figure 6. Maximum bending moment generated in bridge pier subjected to different ground motions

Thus, pounding should be considered when designing bridges to give a more realistic representation of the design actions that bridges are likely to experience during major seismic events. This is because although pounding tends to decrease the maximum bending moment generated in the bridge pier, it can in fact either increase or decrease the design actions experienced by the bridge pier, i.e. the design of bridges based on the assumption that pounding does not occur will result in design that are either too conservative or inadequate.

3.2 Effect of plastic hinge development

The effect of plastic hinge development is also investigated. A sufficiently large torque was applied to the artificial plastic hinge so that the hinge capacity would not be exceeded and the pier behaves elastically. A smaller torque of 2.5 Nm was then applied to simulate plastic hinging in the bridge piers.

The bending moment development in the bridge pier when subjected to ground motion Set 1 for the elastic and plastic case is shown in Figure 7. It can be seen that when the piers were elastic, the maximum bending moment generated was 1.32 Nm whereas when plastic hinging was introduced, the maximum bending moment was 1.18 Nm. This means that the development of plastic hinges in bridges could potentially reduce the bending moment generated.

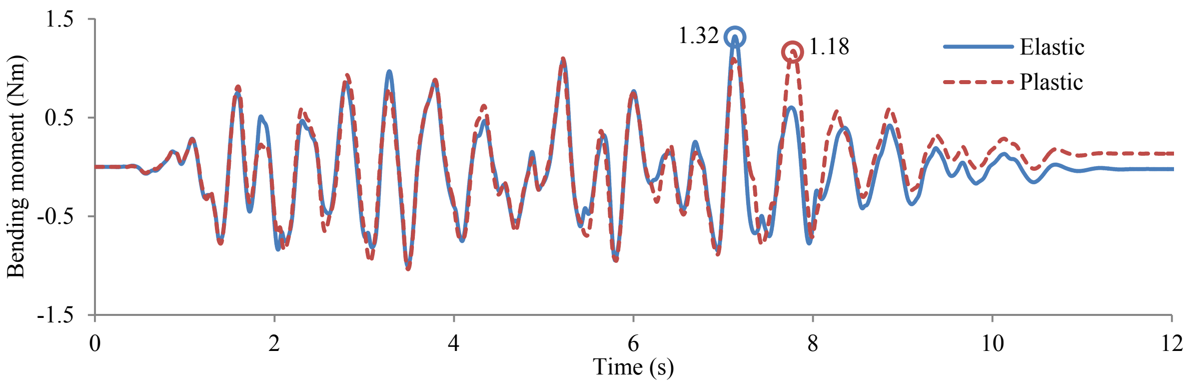

Figure 7. Bending moment of bridge pier subjected to ground motion Set 1 for elastic and plastic cases

When the bridge model was subjected to ground motion Set 2, the bending moment generated increased when plastic hinge was introduced. The bending moment development is plotted in Figure 8. It can be seen that the maximum bending moment generated when the bridge remains elastic is 1.24 Nm but when plastic hinging is allowed, the maximum bending moment generated is 1.46 Nm.

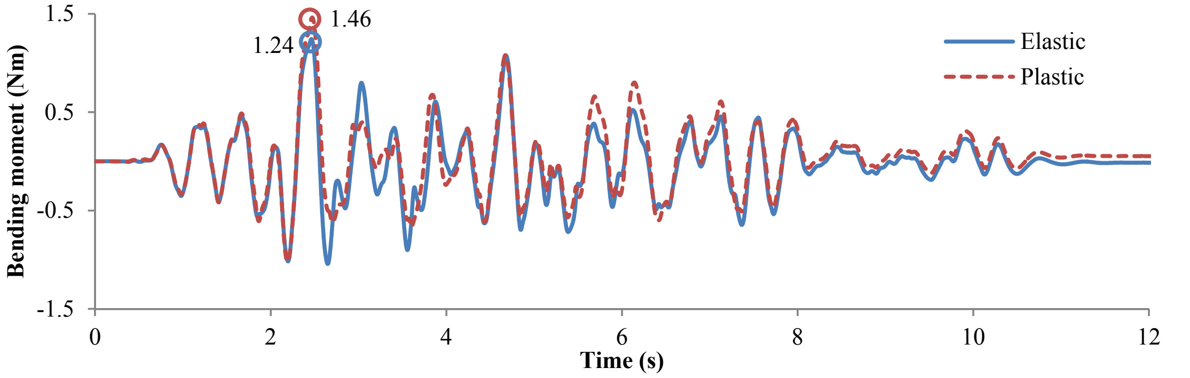

Figure 8. Bending moment of bridge pier subjected to ground motion Set 2 for elastic and plastic cases

However, the increase in bending moment when plastic hinging was introduced only occurred when the bridge model is subjected to ground motion Set 2. From the plot of the maximum bending moment generated in the bridge pier subjected to different ground motions shown in Figure 9, it can be seen that the bending moment is generally decreased when the bridge behaves in a plastic manner.

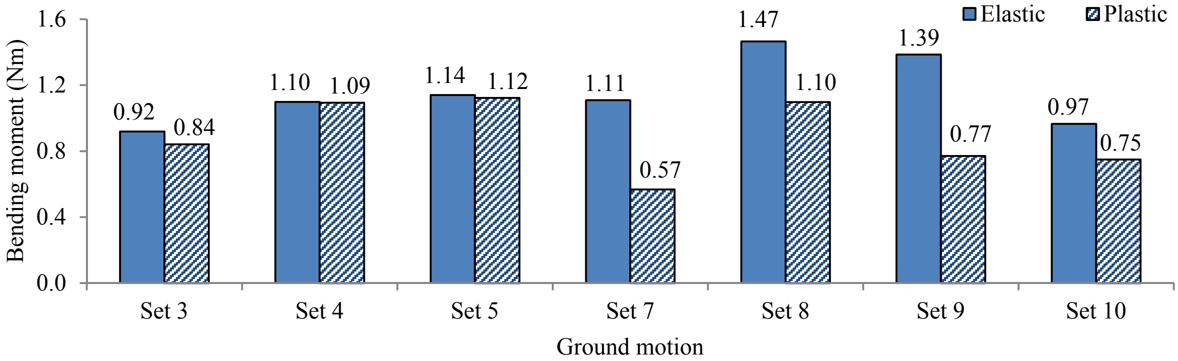

Figure 9. Bending moment development of bridge piers subjected to different ground motions for elastic and plastic behaviour

3.3 Effects of pounding and plastic hinge development

Figure 10 shows the effect of poundings on the bending moment development at the pier support with and without plastic hinge development. For comparison the development without pounding is also considered. A development of plastic hinge reduces the maximum bending moment, whereas depending on the excitation applied pounding can be beneficial or adversarial to the maximum bending moment. It can be seen that the maximum bending moment generated in the elastic case with pounding is 1.32 Nm. In the plastic case without pounding effect the moment is 1.01 Nm. A consideration of both pounding and plastic hinges results in a maximum bending moment around 1.18 Nm.

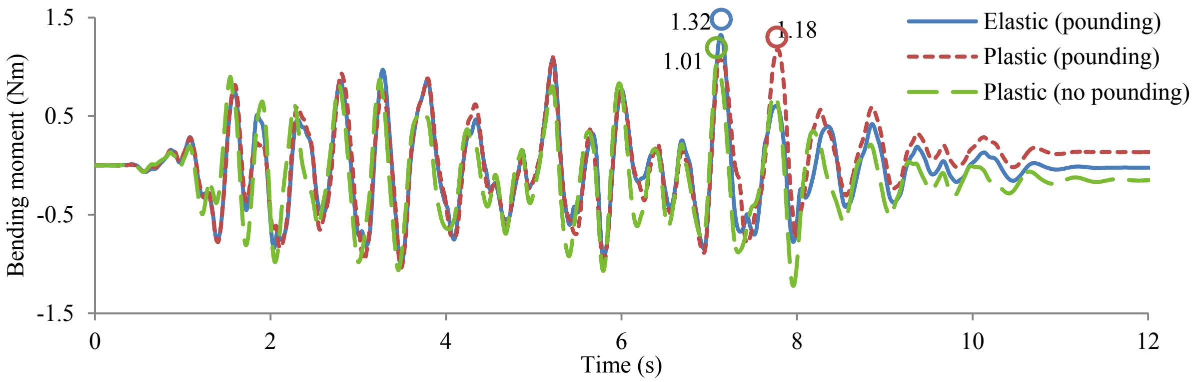

Figure 10. Bending moment development of bridge pier due to ground motion Set 1

The maximum bending moments generated in an elastic bridge pier with pounding, inelastic case with and without pounding when subjected to the different ground motions is shown in Figure 11. It can be seen that allowing plastic hinge to develop reduces the maximum bending moment. Pounding also tends to reduce the maximum bending moment as can be seen in the cases of ground motion sets 3, 4, 7, 8, 9, and 10.

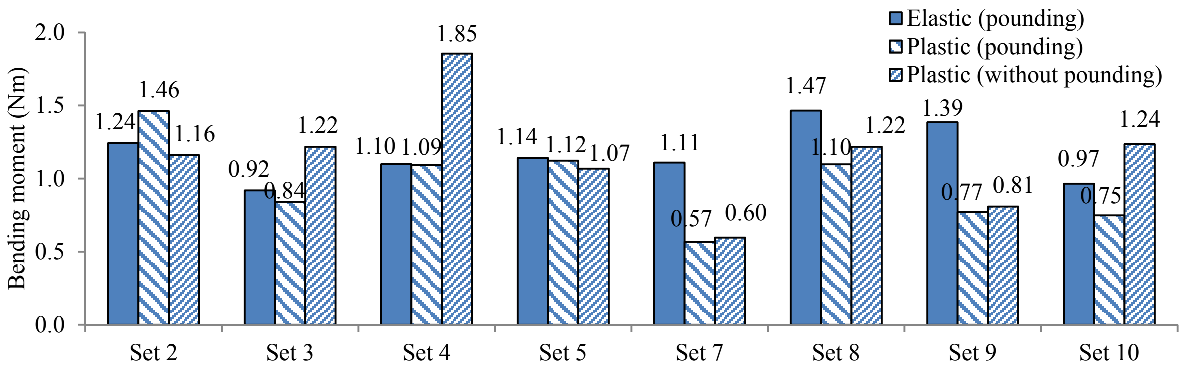

Figure 11. Maximum bending moment of bridge pier subjected to different ground motions

4 CONCLUSIONS

This work addresses the experimental investigations on the effects of pounding and plastic hinge development on bridges when subjected to spatially varying ground motions. It has been found that:

- Pounding between adjacent bridges tends to decrease the bending moment in the bridge pier.
- The bending moment could also increase depending on the ground motion considered.
- The effects of pounding should be included in the design of bridges to prevent overestimation or underestimation of the design actions experienced by the bridge during major earthquakes.
- The occurrence of plastic hinges in bridge piers during seismic events mostly decreases the bending moment generated in the piers.
- Allowing bridges to behave in an inelastic manner during earthquakes could prevent overestimation of design actions and possibly lead to more economic design.

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