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NUMERICAL SIMULATION OF ADJACENT BRIDGE STRUCTURES WITH NONLINEAR SFSI

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Abstract. *Pounding between adjacent bridge structures in earthquakes have been investigated by many researchers in the past. However, most of works is performed with an assumption that the considered structures are fixed at their base. If soil-foundation-structure interaction (SFSI) is considered at all then linear soil behaviour is often assumed. Works including nonlinear SFSI is very limited. In this study the influence of non-uniform SFSI is considered. It is assumed that the left bridge structure is fixed at its base, while the soil of the right structure can behave nonlinearly. Each bridge structure with footing and subsoil is described by four degrees of freedom. A macro element is used to describe the dynamic behaviour of the footing and soil. The results show that nonlinear SFSI can have a beneficial effect on the activated forces in the structures. However, compared to bridge structure with linear SFSI more pounding occasions are observed and structural settlement can take place.*

1 INTRODUCTION

In the event of earthquakes seismic waves propagate and arrive at distant bridge support locations with a time delay. Because of the non-uniform development of soil along the bridge the arriving ground motions at adjacent bridge supports are incoherent. This time delay and coherency loss cause then a non-uniform support excitation. During an earthquake interaction between bridge structure, footing and supporting ground occurs. The local soil at adjacent bridge supports is normally not the same. Consequently, unequal soil-footing-structure interaction (SFSI) will take place. Also because of the different dynamic properties of adjacent bridge structures, strong relative movements between neighbouring bridge decks can occur. If the existing gap between the decks is insufficient to cope with the large closing relative movements, pounding will take place. Consequently, damage at girder ends occurs. If the seat length of the bridge deck is inadequately designed then collapse of bridge deck might take place due to insufficient seat length. Even if collapse does not occur, pounding damage can result in a bridge that is functionally disabled.

Bridge damages have been observed in almost all major earthquakes in the past decades, e.g. the 1989 Loma Prieta earthquake [1], the 1994 Northridge earthquake [2], the Kobe 1995 earthquake [3], the 1999 Chi-Chi earthquake [4], the 2008 Wenchuan earthquake [5] and the 2010 Chile earthquake [6]. Figure 1 shows clearly the consequence of strong relative movements at the girder support of the Llacolen Bridge that crosses the Bio-Bio River in Conception. The picture is taken by the authors in one of the field investigations of bridge damages due to the 2010 Chile earthquake.

Figure 1. Relative response induced damage of Puente Llacolen in the 2010 Chile earthquake

Researches on the consequence of relative movements for the seismic performance of bridges have been done mainly numerically. Most investigations have been performed under the assumption of uniform ground excitation [e.g. 7] and without considering the effect of SFSI [e.g. 8]. The significance of the influence of the spatial variation of ground excitations has been confirmed [8-14]. Experimental investigations of the effect of spatially non-uniform ground motions on the development of relative movements between adjacent bridge structures are still very limited [13, 14].

To prevent the occurrence of relative movements most of current design specifications, e.g. JRA [15], Part 2 of Eurocode 8 [16] and most recent CALTRANS [17] recommend that the adjacent bridge structures should have the same or at least similar fundamental frequencies so that the structures will respond to the ground motions mainly in phase. Consequently, relative response between the structures can be avoided or its influence significantly reduces. This is also currently the only suggested measure to prevent pounding damage at the same time to ensure the serviceability of the bridge due to the required small gap of a few centimetres.

Recently, investigations of a possible mitigation measure by installing the so-called modular expansion joints have shown that large relative movements between adjacent bridge structures can be accepted without causing damage to the bridge structures or hinder the functionality of the bridges [10-12].

The significance of nonlinear SFSI has been identified [18-21], however, only very limited works have been performed. This study addresses the influence of unequal SFSI, especially focuses on the consequence of nonlinear SFSI for the development of relative movements between two adjacent bridge structures.

2 SOIL-FOOTING-STRUCTURE SYSTEM AND GROUND EXCITATION

The bridge structures considered are assumed to have the same height of 9 m (Figure 2(a)). Figure 2(b) shows a simplified model of the bridge structures. The multiple bridge piers are described by a collective bridge pier. Each footing is assumed to be rigid with a size of 10 m. The mass of each bridge structure and its footing is assumed to be the same and has the values of 1000 t and 500 t, respectively. The fundamental frequency of the left and right bridge structures with an assumed fixed base is 1.5 Hz and 1 Hz, respectively. Both structures have the same material damping of 5 %.

In the considered cases the supporting ground can be uniform or non-uniform and can behave nonlinearly. The dynamic behaviour of the footing including plastic deformation of subsoil is described based on soil constitutive models as a macro element with a lumped mass and three degrees of freedom at the centre of the footing [18, 19]. The soil stiffness in the horizontal, vertical and rotational directions is 3.038E5 kN/m, 4.594E5 kN/m and 9.113E6 kNm/rad, respectively. The corresponding damping values are 1.35E4 kNs/m, 2.921E4 kNs/m and 2.44E4 kNms/rad. The soil bearing capacity is described by the strength surface which reflects the soil capability to bear the combined vertical, horizontal and moment loading. In this work a strain-hardening plasticity model for predicting the settlement of shallow foundation on sand proposed by Nova and Montrasio [22] is applied.

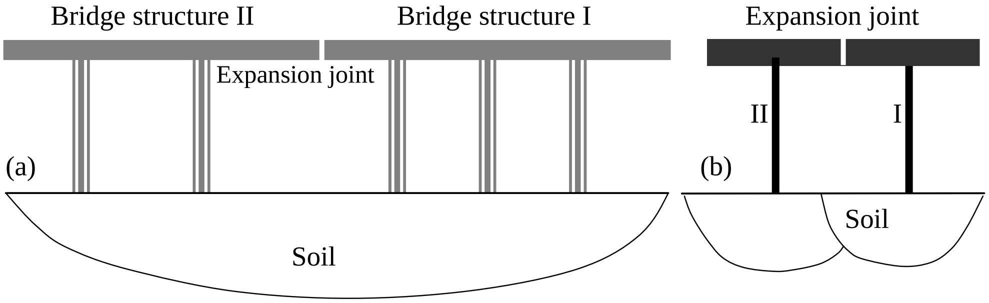

Figure 2. Adjacent bridge structures-foundation-soil system.
(a) MDOF systems and (b) simplified two four DOF systems

To limit the influence factors only linear pounding is considered. The pounding element has the stiffness of 5E6 kN/m. It is assumed that the bridge structures and their footings remain elastic during the entire earthquake loading and only uniform ground excitation is considered [Figure 3].

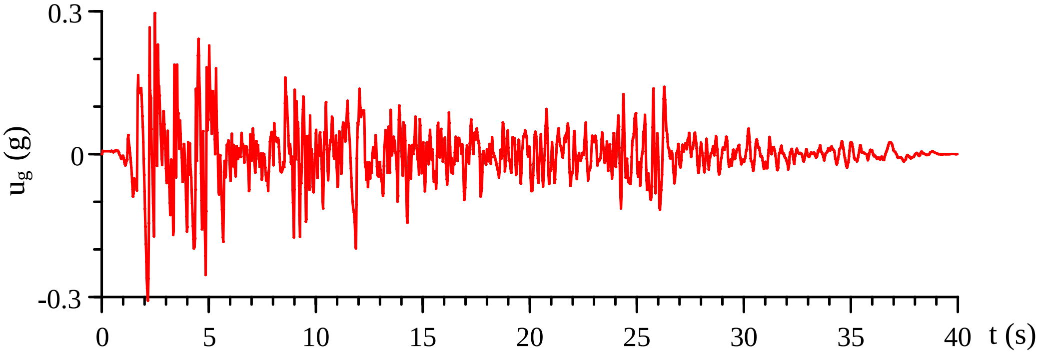

Figure 3. El-Centro ground motions

3 NUMERICAL RESULTS AND DISCUSSION

The effect of linear and nonlinear SFSI on the response of the two adjacent bridge structures can be observed from a comparison of the results with those without considering SFSI. It is assumed that both structures are supported by the same uniform ground. In the case without SFSI, both structures are fixed at their rigid base.

Figures 1(a) and (b) display the time histories of the displacement of the right (u_I) and left (u_{II}) bridge structures, respectively. The solid grey and dark lines are the displacement without SFSI and with linear SFSI effect while the dash line is the displacement with the influence of nonlinear SFSI.

As mentioned earlier the fundamental frequency of the right and left bridge structures with an assumed fixed base is 1 Hz and 1.5 Hz, respectively. As expected the flexible subsoil has stronger influence on the stiffer left bridge structure. The corresponding fundamental frequency of the structures with subsoil is reduced to 0.79 Hz and 1.16 Hz, respectively. In the considered case SFSI has a strong reduction effect on the displacement of the flexible right bridge structure. The maximum displacement without SFSI is 19.58 cm. The maximum displacement with linear and nonlinear SFSI effect reduces to 14.5 cm and 12.69 cm, respectively. In contrast, linear SFSI has an amplification effect on the left stiffer bridge structure. The maximum displacement without and with linear SFSI effect is 10.09 cm and 10.42 cm, respectively. Nonlinear SFSI has always reducing effect and causes a maximum displacement of only 5.97 cm.

From the displacement time histories one can expect that without a consideration of SFSI a realistic pounding potential of bridges cannot be properly predicted, since supporting ground can alter not only the fundamental frequencies of the adjacent soil-foundation-structure systems but also their response amplitudes and consequently the development of relative responses between the adjacent bridge structures.

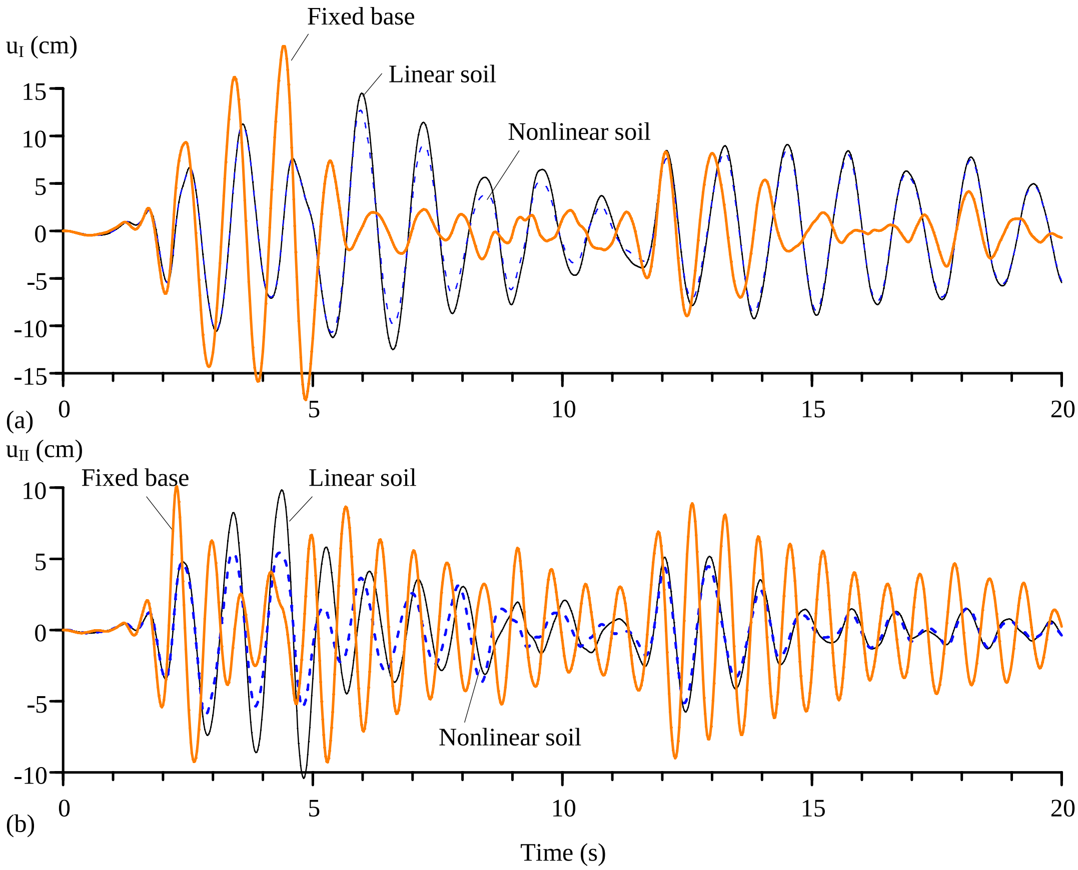

Figure 4. Influence of supporting ground condition on the displacement at (a) the right (u_I) and (b) left (u_{II}) bridge girders.

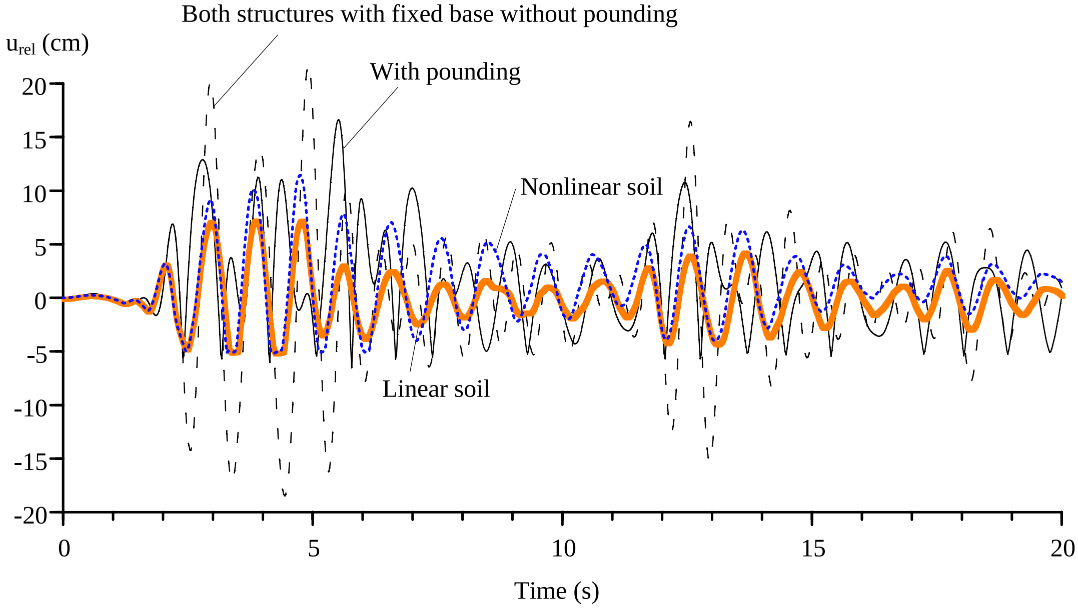

Figure 5. Influence of soil conditions on relative displacement

In Figure 5 the development of the relative displacement u_{rel} is presented. The dash and solid black lines are respectively the development of the relative displacement without and with a consideration of pounding when both bridge structures are assumed to be fixed at their base. The existing gap size of 5 cm can be clearly seen which restricts both girder movements when pounding is considered. The dotted and bold grey lines are respectively the relative displacement with considering nonlinear and linear SFSI effect at the right bridge segment while the left bridge segment is assumed be fixed at the base. Pounding is considered.

From a comparison of the dash and solid thin lines it is apparent that pounding between the adjacent bridge girders reduces the unseating potential of the bridge girders which is indicated by the opening or positive relative girder movement.

The consequence of different soil conditions of the right bridge site can be clearly seen in the pounding development. While an assumption of fixed base bridge structures causes poundings on 18 occasions, when the soil at the right bridge structure remains linear and behaves nonlinearly, poundings only occur on two and five occasions, respectively. It is well known that damage at girder ends is not only influenced by the strongness of the pounding but also by the number of strong poundings. In the considered case SFSI causes a further reduction of the unseating potential which is indicated by smaller positive relative displacement between the adjacent bridge girders. Compared to the linear SFSI case nonlinear soil causes a larger number of pounding occasions and also unseating potential.

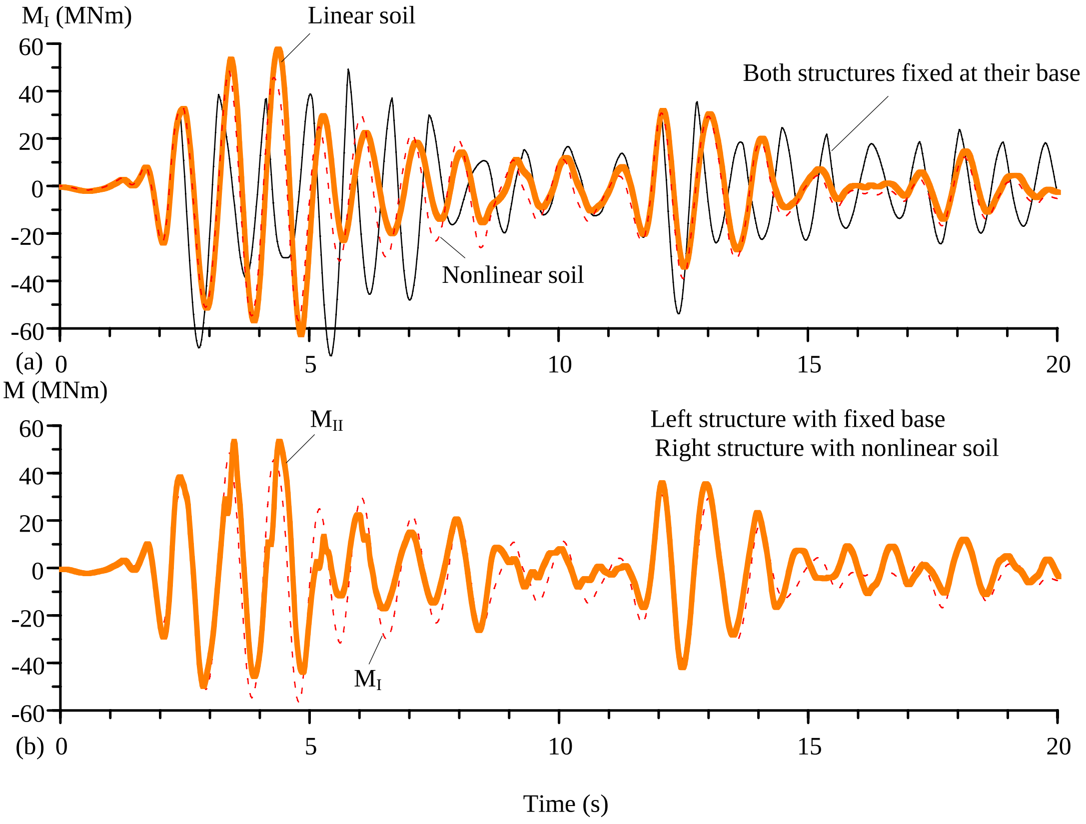

Figure 6. Influence of soil conditions on bending moment development.
(a) M_I and (b) M_I and M_{II} due to nonlinear soil

Figure 6(a) displays the influence of soil conditions of the right bridge structure on the bending moment development at the right bridge support. Pounding effect is considered, and it is assumed that the left bridge structure is fixed at the base. The solid thin line indicates the bending moment development when both adjacent structures are assumed to be fixed at their base. The maximum bending moment is 71.5 MNm. The bold grey and dashed lines are the bending moment when the soil at the right bridge site remains linear and can behave nonlinearly, respectively. The corresponding maximum bending moments are 62.08 MNm and 56.58 MNm. In the considered case the simultaneous influence of nonlinear soil and pounding causes the smallest maximum bending moment.

In Figure 6(b) the bending moment at both bridge supports is displayed. Pounding is considered. They have similar development. The maximum bending moment M_{II} at the left bridge support (bold grey line) is only slightly smaller and has the value of 53.9 MNm. However, the consequence of nonlinear soil deformation can be seen in the residual bending moment M_I (dashed line) at the end of the considered time window.

The results show that if the ground is permitted to behave nonlinearly the activated bending moment in the structures can be reduced significantly. In the considered case even though only one bridge site can have nonlinear soil, as long as a large residual settlement of the structures can be avoided, the nonlinear behaviour of soil can be used to reduce the impact of earthquakes on the structures.

4 CONCLUSIONS

In this work numerical analysis of the effect of soil-foundation-structure interaction (SFSI) on pounding behaviour of two adjacent bridge structures is addressed. Three cases are considered: 1) Both structures are fixed at their base; 2) the left bridge structure has a fixed base and the right structure has a linear soil and 3) the soil at the right bridge site can behave nonlinearly. The gap between the bridge girders is 5 cm. It is assumed that both bridge structures remain elastic during the whole spatially uniform earthquake loading. Each of the bridge structures and its supporting soil are described by four degrees of freedom. For the foundation and subsoil a macro element is used.

In the considered cases the study reveals:

- An analysis without considering SFSI effect will produce more conservative results.
- Even if SFSI is considered only on one of the bridge sites the activated forces in the structures can be reduced. This is also the case in terms of pounding occurrence.
- Nonlinear SFSI can further reduce the activated bending moment at the bridge support. However, the number of poundings is larger than that in the case of linear SFSI.

Additional investigations are necessary to have a better understanding of the interrelation between nonlinear SFSI, pounding behaviour and the characteristic of the bridge structures and loading.

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