ASSESSMENT OF SPATIAL NON-UNIFORM GROUND EXCITATION EFFECT ON NON-LINEAR POUNDING RESPONSES OF MULTI-SPAN BRIDGE

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This study addresses how the non-linear relative bridge girder-pier displacements as well as the relative displacements between the adjacent bridge girders affect damage potential of multi-span bridge structures. Spatial non-uniform ground excitations at the adjacent bridge piers are simulated stochastically based on Japanese design spectrum for a hard-soil site. The study reveals that commonly assumed girder stiffness for the end restraint overestimates the actual effective end-restraint stiffness. The end restraints can reduce the activated forces in the non-linear bridge structures. A consideration of non-uniform ground excitation is essential for a realistic estimation of bridge responses and damage potential.

Key words: *Non-uniform ground excitation, multi-span bridge, pounding response, Japanese design spectrum, non-linear relative displacement*

1. INTRODUCTION

In the past two decades many studies on the effect of relative displacement responses of adjacent structures have been performed. In the case of buildings the goal is a proper determination of required gap to avoid pounding. If pounding is unavoidable, then a suitable measure for reducing the pounding effect should be found. In the case of bridges many earthquakes in the past, like the 1994 Northridge earthquake[1)], the 1995 Kobe earthquake[2)], and the 1999 Chi-Chi earthquake[3)], showed that severe failures often occurred because of large non-uniform ground movements. The resulting large relative displacements between substructure and superstructure and between bridge girders can cause not only pounding but also unseating as well as collapse of the superstructure. To prevent catastrophic failure due to bearing or joint seat loss, an adequate prediction of the required seat length is important, especially in the case of multi-span bridges with expansion joints and movable bearings between piers and girders. The non-linear bearing behaviour can significantly affect the relative substructure-superstructure displacement. The expansion joint in long multi-span bridges can cause large relative girder displacements due to accumulation of girder movements.

Studies on relative bridge girder displacements often neglected the restraining influence of the adjacent girders or abutments. Many of the previous investigations also neglected the influence of the spatial variation of the ground excitation owing to the distant locations between adjacent bridge piers. If it is considered at all, then only identical ground motions with a phase delay are assumed. DesRoches and Muthukumar[4)] and Ruangrassamee and Kawashima[5)], for example, investigated bridge girder responses using single-degree-of-freedom (sdof) systems. The suggestion proposed by the current Japanese design regulation[6)] and many other studies also often based on assumption of uniform ground excitations. Zanardo et al.[7] as well as Chouw and Hao[8, 9] showed in their investigations that spatially varying ground motions can affect the relative girder displacements significantly.

Investigations with considering the effect of adjacent girder or abutment impediments are very limited. In the recent work by Chouw et al.[10] the abutment restraint was considered, however only for a two-span bridge. In all previous mentioned studies the material non-linearity of the bridge structures was not considered. This study considers the simultaneous effect of 1) non-uniform ground motions, 2) adjacent girder or abutment impediments, and 3) non-linear bridge material properties on relative girder as well as substructure-superstructure (girder-pier)displacements. The ground motions are stochastically simulated based on the Japanese design spectrum[11] for a hard-soil site.

2. SPATIALLY VARYING GROUND MOTION AND MULTI-SPAN BRIDGE STRUCTURES

Pounding or unseating potential of bridge girders is determined by the relative displacement between the adjacent girders. In the case of assumed uniform ground excitation adjacent bridge structures with the same dynamic properties will have low pounding potential, since the structures will respond in phase. Consequently, almost no relative displacement will take place. In reality, however, spatially varying ground excitation is likely owing to the wave propagation. Additionally, non-linear behaviour of the elastomeric bearings between the bridge piers and girders can strongly affect the relative displacements between the substructure and superstructure of the bridge. Consequently, they affect the girder relative displacements.

(1) Non-uniform ground excitations

Ground motions at two distant bridge pier foundations can vary strongly from each other, especially when the bridge piers are far apart, because the propagating seismic waves will never be able to arrive at these two locations at the same time, and the soil in the wave path can affect the characteristics of the propagating waves. In the numerical simulation of spatially varying ground motions usually empirical coherency loss functions are applied. These functions are often derived from large number of recorded motions in the dense seismograph arrays such as the SMART-1 arrays [12, 13, 14, 15]. In this study the following empirical coherency-loss functions derived from about 1000 strong motions time histories by Hao[13, 14] are used.

$$\left|\gamma(f, d_{ij}^{l}, d_{ij}^{t})\right| = \exp(-\beta_1 d_{ij}^{l} - \beta_2 d_{ij}^{t}) \exp\{-[\alpha_1(f)\sqrt{d_{ij}^{l}} + \alpha_2(f)\sqrt{d_{ij}^{t}}\,]\,f^2\} \tag{1}$$

where d_{ij}^{l} and d_{ij}^{t} are projected distances in metres between locations i and j on ground surface in the wave propagation direction and its perpendicular direction, respectively; β_1, β_2 are two constants, and $\alpha_1(f)$ and $\alpha_2(f)$ are two functions defined as

$$\alpha_i(f) = \frac{a_i}{f} + b_i f + c_i, \quad i = 1, 2 \tag{2}$$

The parameters β_1, β_2, and a_i, b_i and c_i govern the coherency loss or cross correlation between ground motions at points i and j on ground surface. In this study, the ground motion spatial variation model derived from data recorded at the SMART-1 array during the event 45[14] is employed. Ground motions during the event 45 are considered as highly correlated. Without losing generality intermediately

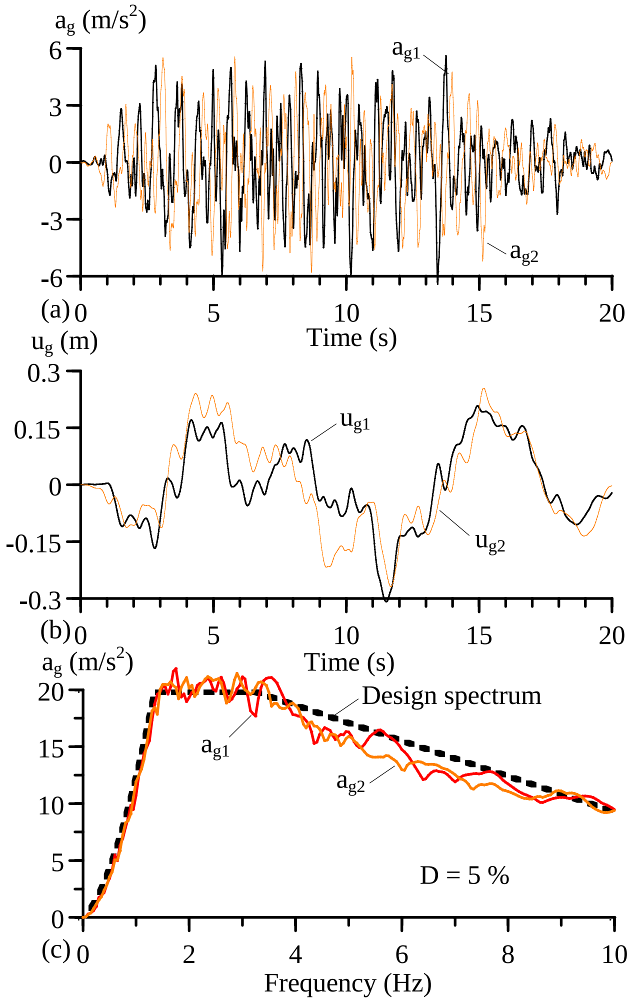

Figure 1(a)-(c). Non-uniform ground motions. (a) Ground accelerations $a_g(t)$, (b) ground displacements $u_g(t)$, and (c) corresponding response spectra with the Japanese design spectrum for hard-soil site.

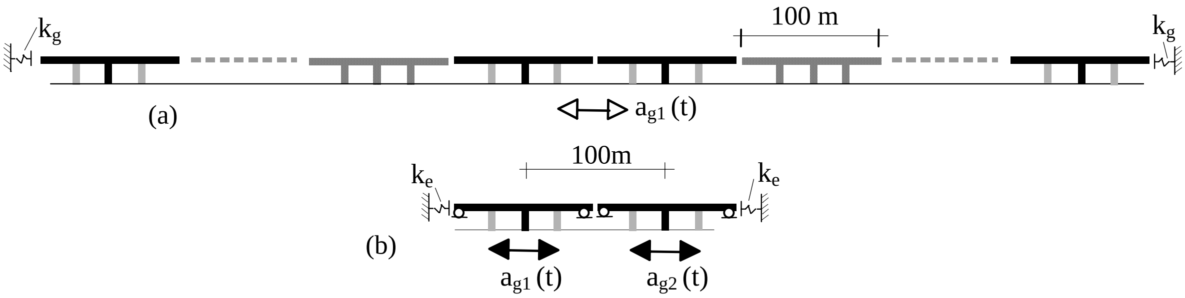

Figure 2(a) and (b). Bridge structures. (a) Multi-span model, and (b) two-span model

cross-correlated ground motions are simulated using following modified empirical coefficients:

$\beta_1 = 3.7\times10^{-4}$, $\beta_2 = 2.24\times10^{-4}$,

$a_1 = 1.19\times10^{-2}$, $b_1 = -1.1811\times10^{-5}$, $c_1 = 1.177\times10^{-4}$,

$a_2 = 1.721\times10^{-2}$, $b_2 = -7.583\times10^{-6}$, $c_2 = -1.905\times10^{-4}$.

The coefficients obtained from Equations 1 and 2 are dimensionless. They were derived from fitting the coherency loss calculated from recorded motions in the SMART-1 array. However, these coefficients are valid only when the distance is in metre and the frequency in Hertz.

In total 20 sets of spatially varying ground motions are simulated. Figures. 1(a) and (b) show one set of the ground acceleration $a_g(t)$ and displacement $u_g(t)$, respectively. The non- uniformity of the ground motions can be clearly seen. A comparison of their acceleration response spectra with the Japanese design spectrum for hard-soil site in Figure. 1(c) confirms that the properties of the ground motions match well with those of the target spectrum.

(2) Multi-span bridge structures

The bridge model consists of multiple identical bridge frame structures as shown in Figure 2(a). Each bridge frame has the same length of 100 m. In the analysis the double-pier bridge structures are approximated as single-pier bridge structures with the same dynamic properties. The properties of the equivalent pier are chosen in such a way that each double-pier bridge structure and the single-pier bridge structure with movable support at both girder ends (Figure 2(b)) have the same fundamental frequency of 0.56 Hz. All bridge piers have the height of 11.5 m. It is assumed that they are fixed at their base. The RC bridge structures are adopted from a published work by Jankowski et al.[16] The equivalent cross section of the RC girder is 8.4 x 2.0 m^2, and the one of the bridge pier 1.5 x 3.6 m^2. The girder thickness is 2.0 m, and the width of the pier in the longitudinal direction is 1.5 m. The Young's modulus of the concrete is assumed to be 27.0 GPa, and uniaxial compressive strength 40 MPa, and those of steel are 200 GPa and 460 MPa,

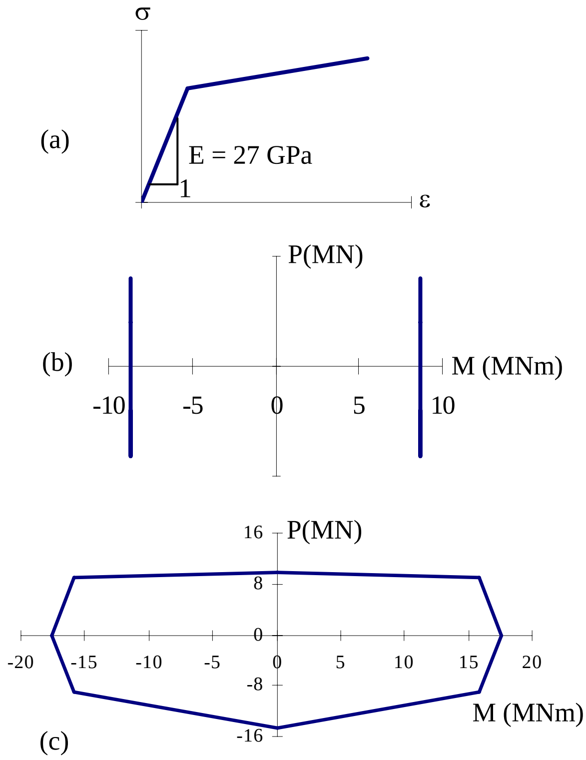

Figure 3(a)-(c). RC pier and girder material properties. (a) Stress-strain relationship, (b) girder yielding surface, and (c) pier yielding surface

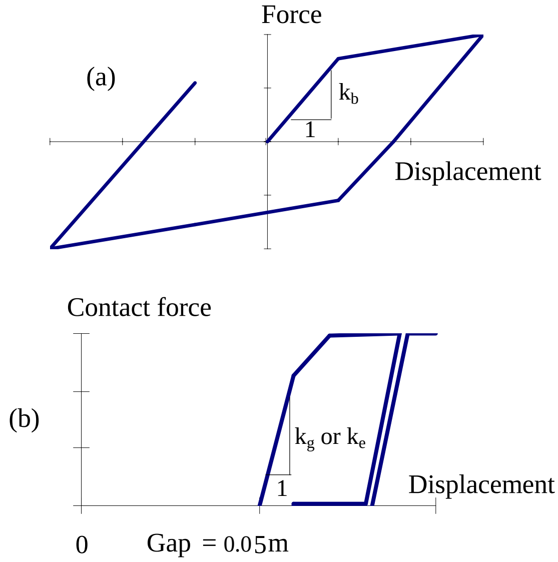

Figure 4(a) and (b). Bearing and impact element stiffness model. (a) Bearing and (b) impact element respectively. The material damping is assumed to be 6 % mass proportional and 1.5 % stiffness proportional. The assumed solid pier has the mass density of 2400 kg/m^3, and the equivalent mass density of the girder with hollow section is 1176 kg/m^3. It is assumed that the girder and pier have 0.6 % symmetric reinforcement ratio with the yielding surfaces of bridge girder and pier defined in Figure. 3. The strain-hardening ratio of RC material is 15 %. The initial horizontal and vertical stiffness k_{bh} and k_{bv} of the elastomeric bearing is respectively 93.192 MN/m and 74664 MN/m with a strain-hardening ratio of 50 %. The bearing starts to behave non-linearly, when the bearing displaces larger than 0.01 m. The impact element is modeled using a spring element. The initial stiffness has the value of the girder stiffness of 9070 MN/m. For the determination of the girder axial stiffness an effective girder length of 50 m is assumed. The impact element and the bridge girder have the same non-linear material behaviour with the first yielding stiffness is 30 % of the initial stiffness, and the second yielding stiffness is only 1 % of the initial stiffness. The girder and the impact element yield when the displacement reaches 0.01 m, and they will have the second yielding at 0.02 m. The relationships between force and displacement of the bearing and the impact element are displayed in Figure 4. The gap at all expansion joints is 0.05 m.

3. NUMERICAL RESULTS

(1) Effective impediment stiffness

The bridge is assumed to have many identical bridge structures. Since it is not practical to include a large number of bridge structures in the analysis, the number of bridge structures that have influence on the response of the middle two bridge structures is determined first by a convergence analysis. In the final analysis only the two middle bridge structures are considered with the equivalent end-restraint stiffness that results in the same responses of the two middle spans. The non-linear calculations are performed using the program DRAIN2DX[17]. In the convergence analysis the number of bridge spans adjacent to the middle two bridge spans is gradually increased. Bending moments and shear forces at the left and right pier supports of the two middle bridge structures are calculated and compared. The convergence is achieved when there is no more change in the obtained bending moments and shear forces with further increase of bridge span number included in the analysis. The effect of adjacent girder restraint is also simulated first with a spring of the girder stiffness k_g (Figure 2(a)). Once the convergence results are determined, the corresponding effective end-restraint stiffness k_e can be defined. It is the stiffness that produces the same bending moments and shear forces in the two bridge structure systems as shown in Figure 2(b). In the convergence analyses only uniform ground excitation is used.

Figure 5(a) shows the development of the maximum non-linear bending moments M_l and M_r at the left and right middle bridge pier supports with the number of the considered adjacent bridge structures. The convergence analysis begins with two middle bridge structures, and the effect of the adjacent bridge structures is modeled by an assumed impediment of the girder stiffness k_g. The analysis continues with an additional bridge structure at each side, and the effect of the further adjacent bridge structures is also simulated by an assumed end restraint of the same girder stiffness. In this considered case the convergence is achieved when in total 8 bridge structures are considered. Even though the bridge structures have identical dynamic properties, and it is assumed that all bridge structures experience the same ground motions, the bending moments at the left and right pier supports are not the same, because the symmetrical bridge structures experience ground excitation with asymmetrical direction. The response of both bridge structures will be the same, if the pounding effect is neglected. If poundings are considered, the first pounding at the left or right girder end or between

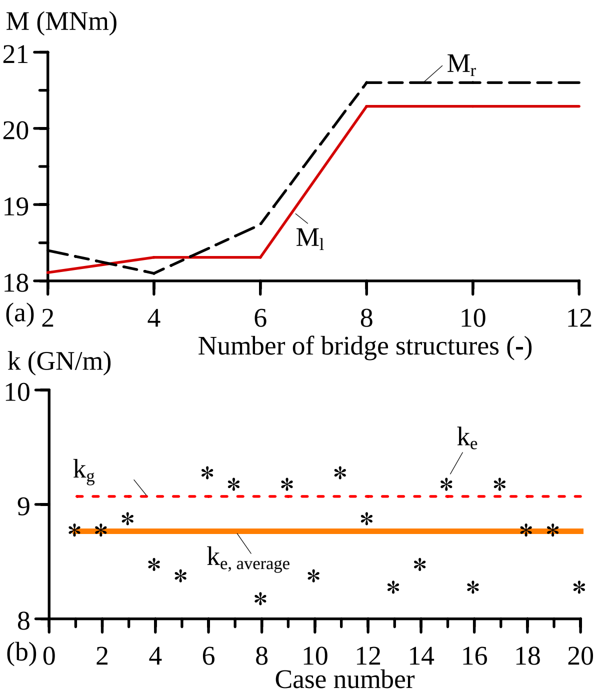

Figure 5(a) and (b). Effect of the number of the considered bridge structures on (a) the bending moment M development, and (b) development of the end-restraint stiffness with the considered cases.

girders will change the subsequent response of both structures. Consequently, both structures will no longer have the same response.

In order to obtain more general conclusion twenty-convergence analyses are performed. The star symbols in Figure 5(b) indicate the obtained effective adjacent impediment stiffness for all twenty cases. The dotted line represents the girder stiffness k_g. A comparison with the girder stiffness k_g shows that the average effective impediment stiffness $k_{e,\,average}$ (bold line) is about 3.4 % smaller. Since the response of the bridge structures is very sensitive to the considered adjacent impediment stiffness, even though this difference is small, it has significant influence on the linear and non-linear bridge responses.

(2) Material non-linearity and end-restraint effect

To have an insight of the degree of the material non-linearity due to the non-uniform ground excitation the influence of the adjacent impediment is neglected first. Since both bridge structures have the same dynamic properties, an assumption of uniform ground excitation -as performed by many researchers in their pounding studies- will cause in-phase response. Consequently, pounding will not occur. Figures 6(a) and (b) show the bending moment M at the left pier support and the impact force F_P between the girders, respectively. The results clearly show the significance of a consideration of the spatial variation of ground motions, because all these pounding responses cannot be observed if uniform ground excitation is assumed. As expected an assumption of linear bridge structure clearly shows larger bending moment. The importance of considering material non-linearity in the analysis can be observed (dotted line). Both linear and non-linear analyses produce almost the same maximum contact force between the two girders, but non-linear response results in more number of poundings. It should be noted that in all the analyses, also in the linear analysis, non-linear impact element is used. Figure 6(c) shows the influence of non-linear material behaviour and pounding on the development of activated horizontal bearing force F_b. In linear bridge structures without pounding (dotted line) and with pounding (thin dark line) clearly larger bearing force can be observed. Pounding causes sudden jump in the bearing force. A consideration of non-linear RC material and non-linear bearings limits the activated bearing forces.

Figure 7 shows the influence of adjacent multiple bridge structures, represented by the effective adjacent girder impediment stiffness k_e, on the bending moment M and shear force Q at the left pier support, bearing force F_b between left pier and girder, and contact force F_P between the girders, respectively. The contact force development in Figure 7(d) shows that the impediment of the girder movement due to pounding with adjacent bridge structures (solid line) causes earlier pounding, and more pounding occasions. The differences in these results clearly show that in order to have more realistic damage analysis the influence of adjacent bridge structures

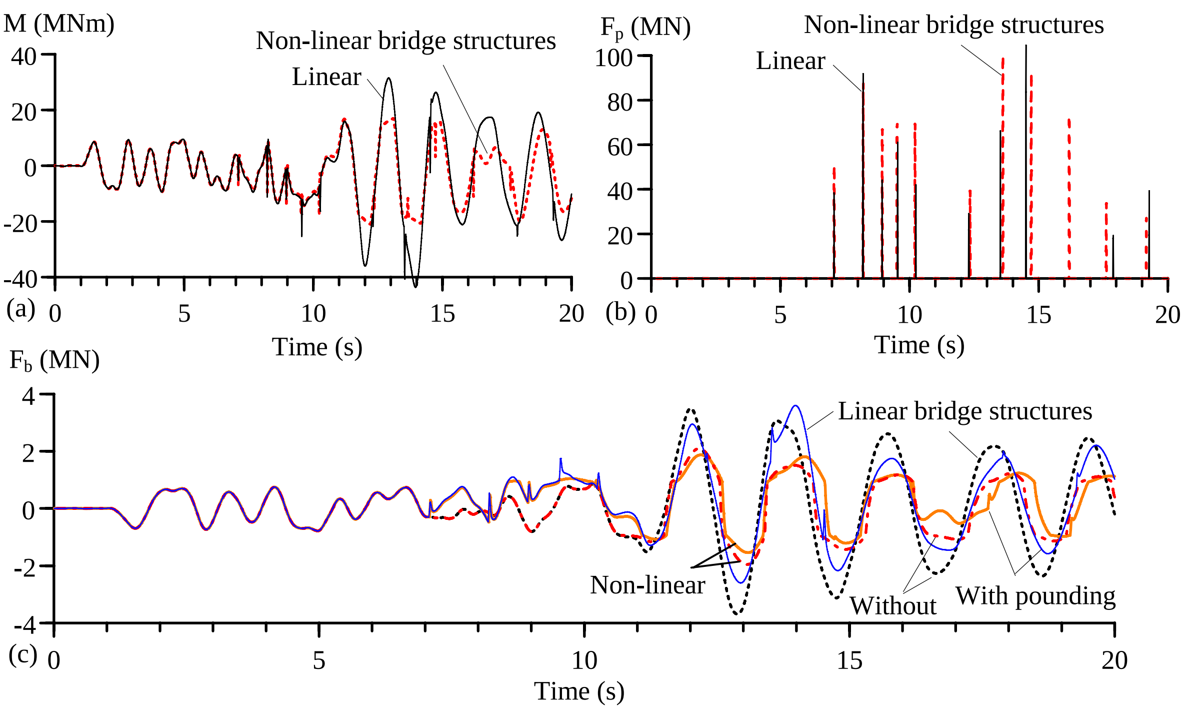

Figure 6(a)-(c). Influence of non-linear material properties on (a) bending moment M at the left pier support, (b) contact force F_p between the girders, and (c) bearing force F_b

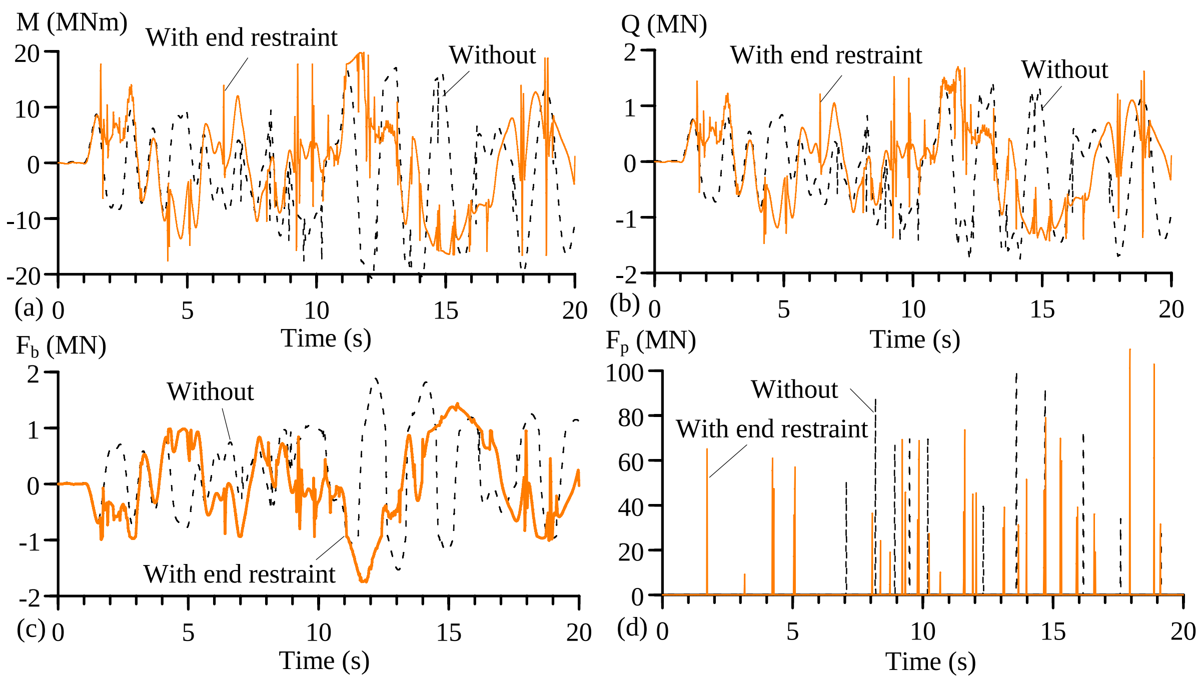

Figure 7(a)-(d). Influence of the end restraints on the activated forces. (a) Bending moment M, (b) shear force Q at the left pier support, (c) bearing force F_b at the left pier top, and (d) contact force F_p between the girders.

must be considered. A neglect of this influence will not be able to provide adequate insight.

(3) Consequence of uniform ground excitation assumption

Indeed, when structures are symmetric and subjected to uniform ground motions, pounding will not occur no matter how large the structural response is, since both bridge structures will respond in phase. However, if the end restraints are considered, the movement of the bridge girders will be limited by the gap between the girder ends and the end restraints (e.g. abutments). Consequently, pounding takes place, when the relative girder movement is larger than the gap size.

Figure 8 shows the influence of spatial non-uniform ground motions on the activated non-linear forces in the bridge structures. Girder relative displacement owing to out-of-phase girder vibrations will only take place, when the adjacent structures have different dynamic properties or in the case of structures with same dynamic properties when the structures are excited by spatially varying ground motions. These results show another significant factor: the impediment effect of the adjacent bridge structures. Even though both bridge structures have the same dynamic properties and experience the same ground excitation, pounding takes place because the gap of 0.05 m at the expansion joint is not sufficient to provide a free movement of the girders. In the considered case the non-uniform ground excitation causes larger maximum pounding force (solid line) than the one

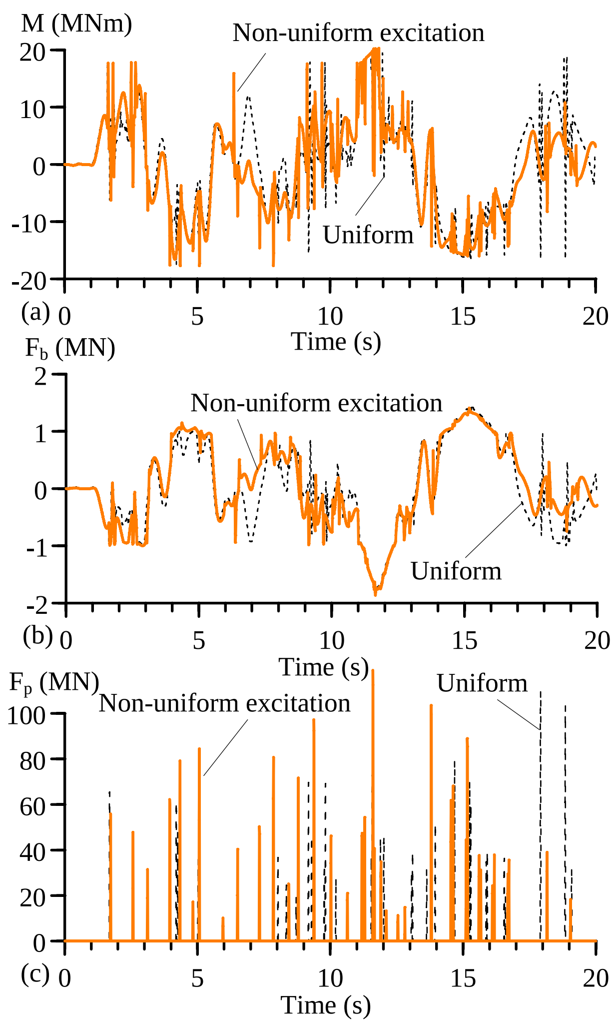

Figure 8(a)-(c). Effect of non-uniform ground excitation on activated force. (a) Bending moment M at the left pier support, (b) bearing force F_B at the left pier top, and (c) contact force F_P between the girders.

Table 1 Influence of spatially varying ground excitations on average activated forces in the non-linear bridge structures

	Uniform ground motions			Non-uniform ground motions		
Restraint stiffness	No restraint	k_g	k_e	No restraint	k_g	k_e
F_p (MN)	No pounding	101.820	105.470	102.370	110.460	109.010
$F_{b,l}$ (MN)	2.029	1.904	1.892	1.948	1.903	1.913
$F_{b,r}$ (MN)	2.029	1.895	1.873	1.907	1.821	1.883
M_l (MNm)	21.690	19.827	21.503	21.292	21.122	21.156
M_r (MNm)	21.690	19.703	21.634	21.217	20.913	21.078
Q_l (MN)	1.840	1.718	1.854	1.831	1.826	1.812
Q_r (MN)	1.840	1.713	1.811	1.812	1.799	1.809

(dotted line) due to uniform ground motions. As shown in Figure 8(a) the strong poundings amplify the bending moment at the pier support, and cause plastic deformation.

This result shows the significance of the combined effect of adjacent girder impediment, non-linear RC material, non-linear bearing behaviour, non-linear impact element, and the non-uniform ground excitation on the bridge responses.

Table 1 gives the average activated maximum contact force F_p, bearing forces F_{bl} and F_{br} between the left and right piers and the girders, bending moments M_l and M_r at the left and right pier supports, the corresponding shear forces Q_l and Q_r, obtained from 20 independent calculations using uniform and spatially varying ground motions.

In the case of uniform ground excitation without considering the adjacent girder impediment no pounding occurs. Unrestrained girder movement causes larger force than the case with adjacent impediment of stiffness k_g as given in the second and third columns.

If the realistic impediment stiffness k_e is considered, larger pounding force, bending moment and shear force at pier supports but smaller bearing forces are observed (fourth column).

In the case of non-uniform ground excitation pounding takes place, even though the adjacent girder impediment effect is neglected (fifth column). Compared to the corresponding results due to uniform ground excitation, the non-uniform excitation causes smaller forces in both structures.

With an additional consideration of the adjacent girder impediment, simulated by using the girder stiffness k_g or the effective stiffness k_e, the results do not follow particular pattern any longer. Compared to the corresponding results caused by uniform ground excitation the activated force can be larger or smaller. Similar observation can be made from a comparison between the non-uniform excitation induced forces obtained using girder stiffness k_g and effective stiffness k_e for simulating the adjacent girder impediment.

4. CONCLUSIONS

Non-linear relative displacements between the superstructure and substructure as well as between girders of two bridge structures were considered. The effect of the adjacent multi-spans of the bridge is simplified using equivalent impediment stiffness. The spatially varying ground motions were simulated stochastically based on the Japanese design spectrum for a hard-soil site and an empirical coherency loss function. In total 40 non-uniform ground accelerations were considered. It should be noted that the numerical results presented in the current paper are valid for the case of expansion joint gap size of 0.05 m only.

The investigations show:

The significance of spatially varying ground excitations is confirmed. All presented results cannot be observed if uniform ground motions and the adjacent girder impediment are not considered.

The girder expansion joints should be considered in the analysis of the relative displacements. The commonly assumed bridge girder stiffness for modeling the adjacent girder impediment effect is in most cases stiffer than it should be.

A consideration of adjacent girder impediment reduces the bridge girder displacements. However, it increases the number of girder poundings. Damages at girder ends due to subsequent strong poundings are therefore likely.

The non-linear bridge structures can significantly reduce the bearing forces F_b (see Figure 6(c)).

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