3D Pounding Analysis Between Decks and at Abutments of a Bridge Structure to Multi-component Spatially Varying Ground Motions

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Abstract

Previous studies of pounding responses of adjacent bridge structures to earthquake loadings are usually based on the simplified lumped mass model or beam-column element model. It has been found that these simplified 1D models can be used to calculate bridge pounding responses with consideration of only the longitudinal excitations. A detailed 3D finite element model is necessary to consider the surface to surface and torsional response induced eccentric poundings. The authors carries out numerical simulation of pounding responses between bridge decks and at abutments of a two-span simply-supported bridge structure to multi-component spatially varying ground motions by using the LS-DYNA explicit finite element code. The bridge components including the bridge girders, abutments, pier, bearings, longitudinal reinforcement bars and stirrups are included in the model. The non-linear behaviours of the concrete and steel rebar material are considered. The damage mechanism of the bridge under seismic pounding is examined. Numerical results show that the 3D FE model provides a more realistic prediction of pounding responses and pounding induced bridge damages than the commonly used lumped mass and the beam-column model.

Keywords: pounding effect, 3D FEM, damage mechanism, numerical simulation

1. INTRODUCTION

Seismic induced poundings between different components of bridge structures were observed in almost all the previous major earthquakes. This is because the gap between adjacent girders or between a girder and an abutment is usually only a few centimetres to ensure a smooth traffic flow, which is not big enough to accommodate the closing relative displacement between the adjacent components. Pounding is a extremely complex phenomenon involving damage due to plastic deformation, local cracking or crushing, fracturing due to impact, and friction when the adjacent components are in contact with each other. To simplify the analysis, most previous studies of pounding responses of adjacent bridge structures were usually based on the lumped mass model (Malhotra 1998; Jankowaski et al. 1998; Ruangrssamee and Kawashima 2001; DesRoches and Muthukumar 2002; Chouw and Hao 2005, 2008) or beam-column element model (Jankowaski et al. 2000; Chouw et al. 2006). It has been proved that these simplified models can only be used to calculate the point-to-point pounding responses under the longitudinal seismic excitation (Bi and Hao 2010). In real bridge structure under seismic loading, pounding could take place along the entire surfaces of the adjacent structures. Moreover, it was observed from previous earthquakes that most poundings actually occurred at the corners of adjacent bridge decks. This is because torsional response of the adjacent decks induced by spatially varying ground motions at multiple bridge supports resulted in eccentric poundings. To more realistically model the surface-to-surface and torsional response induced eccentric poundings, the detailed 3D finite element model is necessary (Bi and Hao 2010). Zanardo et al. (2002) modelled the box-section bridge girders with shell elements and piers with beam-column elements, and carried out a parametrical study of pounding phenomenon of a multi-span simply-supported bridge with base isolation devices. Julian et al. (2006) evaluated the effectiveness of cable restrainers to mitigate earthquake damage through connection between isolated and non-isolated sections of curved steel viaducts using three-dimensional non-linear finite element response analysis. Although 3D FE model of bridge structures were developed in those two studies (Zanardo et al. 2002; Julian et al. 2006), the surface-to-surface pounding were not considered. The pounding phenomenon in these studies was simulated by the contact elements which linked the external nodes of adjacent segments together. In other words, the pounding locations are predefined, whereas in reality the pounding locations constantly change during the earthquake excitations owing to the complex 3D responses of the bridge structures. Zhu et al. (2002) proposed a 3D contact-friction model to analyse pounding between bridge girders. This method conducts searches of pounding locations at every time step, therefore, overcomes the shortcomings of predefining the pounding locations. It, however, could not model material nonlinearities during contacts, and the task to search contact pairs is very time consuming and the searching algorithm is relatively complicated. More recently, Bi and Hao (2010) studied the pounding responses between the abutment and adjacent bridge deck and between two adjacent bridge decks of a two-span simply-supported bridge located on a canyon site by using the explicit finite element code LS-DYNA (2007). The surface-to-surface and torsional response induced eccentric poundings were included in the study, however, the material nonlinearities and pounding induced local damages were not considered.

This paper is an extension of a previous study (Bi and Hao 2010). The detailed modelling of the bridge components including the girders, abutments, pier, bearings, longitudinal reinforcement bars and stirrups are implemented. The nonlinear material behaviours of the concrete and the steel rebar are considered. The damage mechanism of the bridge under seismic pounding is examined.

2. BRIDGE AND SPATIALLY VARYING GROUND MOTION MODEL

2.1 BRIDGE MODEL

The two-span simply-supported bridge located at a canyon site studied by Bi and Hao (2010) is adopted again as the analysing model. Owing to the page limit, only the elevation view of the bridge is shown in Figure 1, the detailed geometry of the bridge can be found in the previous paper.

Constant stress solid elements are employed for all concrete members in this study. By conducting a numerical convergence test on various mesh sizes (30mm, 60mm and 120mm), it is found that the 60mm mesh yields similar results with the 30mm mesh, but result in much less computational time than the smaller mesh. Due to the size of the bridge under consideration and the fact that the effect of pounding is generally localized, the 60mm fine mesh is only applied to a length of 0.96m from each end of the bridge deck and to a length of 0.6m of the abutment. Beyond this region, the mesh size is 2m in the longitudinal direction. To improve the computational efficiency, the reinforcement bars which are considered by the Belytschko beam, are modelled only within the fine mesh region of the concrete with the mesh size of 60mm. The smeared model, i.e., the reinforcements are uniformly distributed over the concrete element, is used in the rest part of the bridge. The longitudinal steel reinforcements with the diameter of 16mm are spaced at 120mm in the bridge girder. The diameter of the other reinforcements (stirrups in the girder, longitudinal, transverse and vertical rebars in the abutment) is 12mm. The spacing distances are 180mm and 120mm for the stirrups in the girder and rebars in the abutment respectively. 8 Neoprene pads are used to model bearing supports of bridge girders on the pier and the two abutments. Three-dimensional solid element is adopted to model the neoprene pads. Figure 2 shows left end of the 3D finite element model of the bridge.

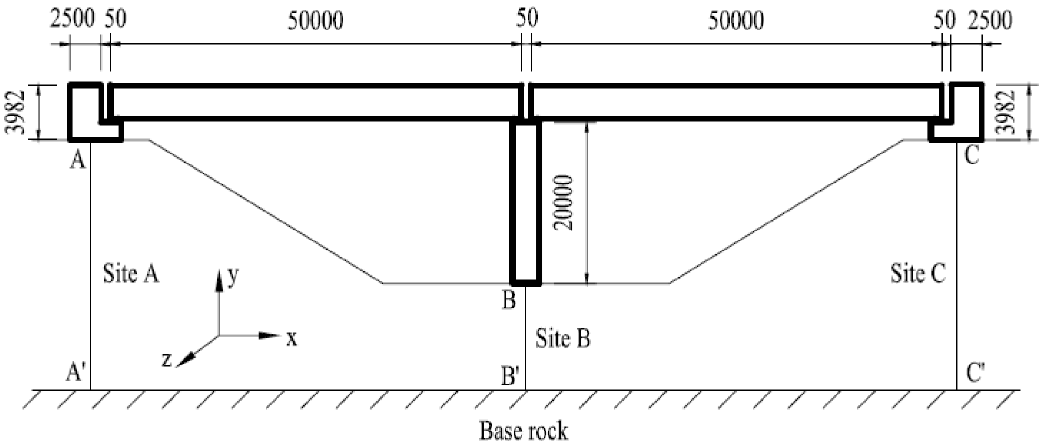


Figure 1. Elevation view of a two-span simply-supported bridge

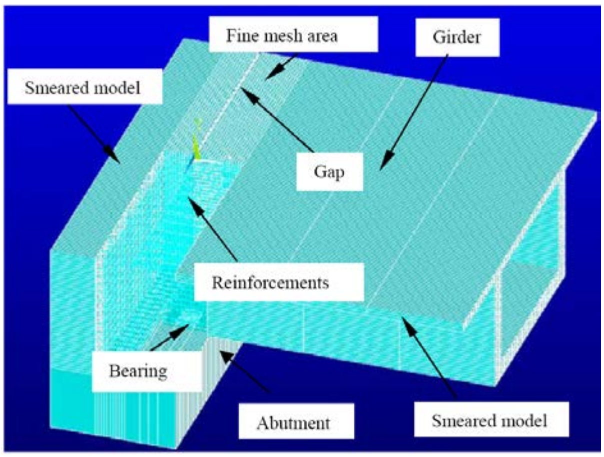


Figure 2. 3D FE model of the bridge

The penalty method is adopted to model the contact interfaces between meshes because of its effectiveness and simplicity for explicit analysis. The contact algorithm *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE in LS-DYNA is employed to simulate the connections between the girders and the neoprene pads and also the impact phenomena between adjacent components of the bridge structure. The dynamic and static Coulomb friction values are both set to 0.2 between these surfaces.

Both CONCRETE DAMAGE REL3 (MAT_72REL3) and PSEUDO TENSOR (MAT_16) material models are utilized to model the concrete in the current study. The CONCRETE DAMAGE REL3 model is employed at places that are subjected to the potential poundings. The PSEUDO TENSOR model is used to model the smeared material at places considered to be undisturbed by pounding effect and hence detail analysis is not needed. In order to avoid computer overflow during calculation, the function MAT_ADD_EROSION is used to eliminate elements that do not further contribute to resisting the seismic loading during the calculation. In the present study, the concrete mesh will be deleted when the principal strain reaches 0.15. PIECEWISE_LINEAR_PLASTICITY (MAT_24) material model is employed for all the steel reinforcements in the bridge. The neoprene pads are modelled using 3D fully integrated solid elements by using the material model MAT_VISCOELASTIC.

The strengths of the structural materials are strain rate dependent as their dynamic properties can be enhanced significantly when subjected to high strain rate impact such as blast or earthquake loads. Current study employs the dynamic increase factor (DIF), a ratio of the dynamic to static strength against strain rate to account for the material strength enhancement with strain rate effect. Owing to the page limit, the strain rate formulas for the concrete and reinforcement are not shown here, which can be found in the relevant studies, such as CEB code (Comite Euro-International du Beton 1990) and Malvar (1998).

2.2 SPATIALLY VARYING GROUND MOTION

It is important to consider ground motion spatial variations in pounding analysis since spatially varying ground motions may result in the torsional response of the bridge structure, which in turn lead to the eccentric poundings between adjacent components of the bridge as mentioned above. Spatially varying ground motions can result from wave passage effect, coherency loss effect and local site effect (Bi and Hao 2011). Previous studies of ground motion spatial variations mainly focused on the wave passage effect and coherency loss effect while neglect the local site effect. For the bridge structure located at a canyon site as shown in Figure 1, local site will amplify the amplitude and filter the frequency contents of incoming motions on the base rock, thus further intensify the ground motion spatial variation effect. It is thus very important to consider the influence of local soil conditions.

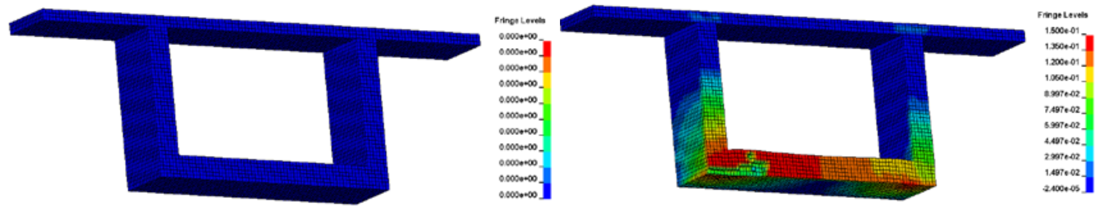
In the present study, not to further complicate the problem, only one soil layer is considered and soil conditions for the three sites are assumed to be the same with the corresponding parameters for the base rock and soil shown in Table I. Soil depths for the three sites are 48.6, 30 and 48.6m respectively. The horizontal in-plane, horizontal out-of-plane and vertical in-plane spatially varying ground motions at different supports of the bridge are stochastically simulated based on the combined spectral representation method and one dimensional wave propagation theory (Bi and Hao 2011), and are applied simultaneously to the longitudinal, transverse and vertical directions of the bridge.

Table I. Parameters for local site conditions.

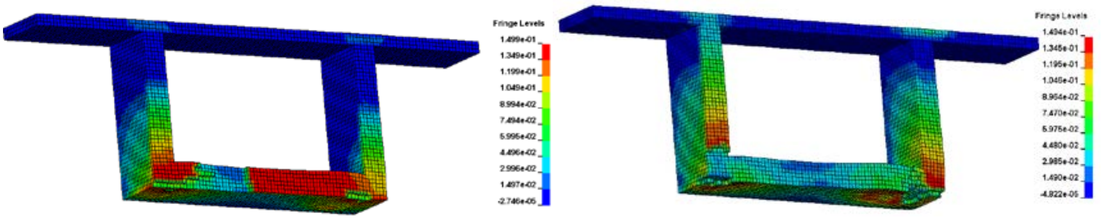
Type	Density (kg/m^3)	Shear modulus(MPa)	Damping ratio	Poisson's ratio
Base rock	2500	1800	0.05	0.33
Soil	2000	320	0.05	0.4

3. NUMERICAL RESULTS

During the earthquake, the adjacent components of the bridge structure will collide with each other. Owing to the page limit, only the pounding prone region on the right end of the left girder is qualitatively examined, while the poundings between bridge deck and adjacent abutment are not shown. Figure 3 shows the snapshots of maximum principal strain contours of the concrete. As mentioned above, the concrete element will be deleted when the maximum principal strain reaches 0.15. As shown in Figure 3(b), the damage first appears on the left bottom corner of the baseplate of the bridge girder at 6.87s, while the first damage appears on the right bottom is at 7.40 s as shown in Figure 3(c). These two figures clearly show the torsional response induced eccentric poundings between bridge decks. This phenomenon, however, cannot be considered by using the simplified lumped mass model or beam-column element model, which illustrates the necessity of using 3D detailed FE model to realistically simulate the earthquake induced pounding phenomenon. When the earthquake ends, almost all the covers on the pounding surface of the bottomplate are damaged as shown in Figure 3(d). The bottomplate itself also suffers serious damage especially near the left and right corners owing to the huge impact force (which is not shown here and it can reach 25MN in the present study). These simulated results are quite similar to the observations in many of the previous major earthquakes as shown in Figure 4, which shows the bottomplates suffered server damages in 1999 Chi-Chi Taiwan earthquake.



(a) 0.00 sec (b) 6.87 sec



(c) 7.40 sec (d) 16.00 sec

Figure 3. Snapshots of bridge girder damage

Ground motion spatial variations can result in larger relative displacement between adjacent components of bridge structures, which in turn lead to the catastrophic damage to the bridge structure. For example, large relative displacement in the longitudinal direction can lead to unseating of bridge spans, while large transverse relative displacement may result in the damage of transverse restrainers as shown in Figure 5. By using the detailed 3D FE model, these damages can also be captured. As shown in Figure 6, the relative transverse displacement between bridge deck and supporting pier reaches 0.32m in the present study. Although the transverse restrainers on the pier are not modelled in the present study, damages are expected under such a large relative displacement. In the present study, the relative displacement between the bridge deck and supporting pier in the longitudinal direction is not as significant as that in the transverse direction. The unseating potential for the studied bridge is not obvious. It should be noted that these relative movements are related to the characteristics of both the bridge structure and the input ground excitations, the unseating phenomenon might be observed for the same bridge under different ground excitations.

Figure 4. Typical pounding damage between bridge decks in Chi-Chi earthquake

(a) longitudinal direction (b) transverse direction

Figure 5. Damages result from large relative displacement between adjacent components of bridge structures in Chi-Chi Taiwan earthquake

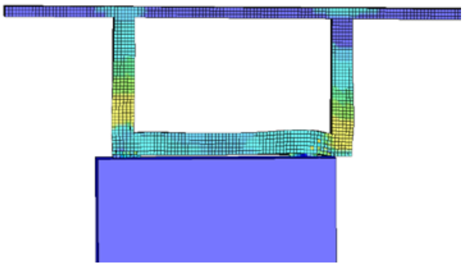


Figure 6. Relative transverse movement between bridge deck and supporting pier

4. CONCLUSIONS

Pounding phenomena of a two-span simply-supported bridge on a canyon site under multi-component spatially varying earthquake excitations is modelled by using the explicit finite element code LS-DYNA based on a detailed 3D FE model. The geometry of the bridge including the bridge girders, abutments, pier, bearings, longitudinal reinforcement bars and stirrups are implemented in the model. The non-linear material behaviours of concrete and steel rebar are considered. Numerical results show that 3D FE model can realistically capture the damage mechanism of the pounding prone regions. The unseating potential and transverse poundings between bridge girders and transverse restrainers can also be considered by using this method.

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