Design of bridges with modular expansion joints for prevention of earthquake-induced girder poundings

Hong Hao[1] and Nawawi Chouw[2]

[1] School of Civil and Resource Engineering, the University of Western Australia, Crawley, WA 6009, Australia

[2] Department of Civil and Environmental Engineering, the University of Auckland, Auckland 1142, New Zealand

Corresponding author email: n.chouw@auckland.ac.nz

Hong Hao is professor of structural dynamics. He received a PhD degree from the University of California at Berkeley. Prior to joining UWA he worked in Seismographic Station in UC Berkeley and Nanyang Technological University in Singapore. His research interests include earthquake and blast engineering, and structural condition monitoring.

Nawawi Chouw is an associate professor. He received his engineering education from Ruhr University Bochum in Germany. Before joining University of Auckland he worked at universities in Europe, Japan and Australia. His interests cover dynamics of soil-structure systems, earthquake and protective engineering, man-made vibrations, vibration reduction and composite structures.

Abstract

Despite of research efforts in the past decades and recommendations provided in almost all seismic design codes, pounding damage of bridge girders has still been observed in many recent major earthquakes. The reason is that in a conventional bridge design the gap of the expansion joint between bridge spans is usually only a few centimetres, therefore girder pounding becomes unavoidable. In this work a new design philosophy using a modular expansion joint (MEJ) is introduced. So far MEJs have been used mainly to cope with large thermal expansion and contraction of long bridges. For a proper design of bridges under strong earthquakes a minimum total gap of a MEJ is essential. The simultaneous effect of spatially varying ground excitations and soil-structure interaction on the total gap of a MEJ -required to eliminate possible pounding- is estimated, and the main influence factors are discussed.

Keywords: bridge girder, near-source earthquake, spatial variation of ground motions, soil-structure interaction, modular expansion joint.

1. INTRODUCTION

Under strong earthquakes pounding can cause heavy damage to neighbouring structures when they are sufficiently close to each other. Current design regulations, e.g. CALTRANS (1999), AASHTO (1998) and JRA (2004), therefore recommend that adjacent structures should have a sufficient separation distance and the same or at least similar fundamental vibration period. The in-phase overall vibrations then prevent the adjacent structures from colliding. This recommendation, however, is made under the assumption that the structures experience the same ground excitation, and their behaviour is determined only by the structural properties. In the case of adjacent buildings an assumption of same ground excitation is justifiable. However, their dynamic behaviour can be affected by the different footing properties and non-uniform ground as well as by the interaction between buildings and subsoil, which may induce out-of-phase responses between adjacent buildings. In the case of bridge structures, besides soil-structure interaction (SSI), inevitable spatially non-uniform ground excitation at the neighbouring bridge pier supports is another factor that may produce out-of-phase responses of adjacent bridge spans. In such a case the current design recommendations can cause an adverse effect (Chouw and Hao, in press). While a minimum distance between buildings is a possible measure for avoiding pounding damage, in the case of bridge structures a large gap between adjacent girders will strongly hinder the passage of traffic. An adjustment of the fundamental frequencies of the adjacent bridge structures is not a suitable approach to reduce out-of-phase responses, because bridge structures will more likely experience spatially non-uniform ground excitation. To overcome this difficulty, in this work a new design philosophy is introduced.

2. NEW DESIGN PHILOSOPHY

Recently, to cope with large thermal expansion and contraction of long bridges more and more modular expansion joints (MEJ) are used. Figure 1 shows two segments of a bridge with a MEJ. The upper figure displays the cross section of the joint in the longitudinal direction of the bridge. The bridge segments are connected by edge beams at both girder ends and by middle beams. Support beams and rubber bearings transfer the traffic loading from the joint to the adjoined bridge girders. To ensure the watertightness of the joint, free and moveable rubber sealing is installed between the beams. The bearings ensure that the beams move uniformly. Details of a MEJ can be found, e.g. in the work by Dexter et al. (2002).

The authors propose to apply the ability of MEJ to mitigate the pounding problems due to large relative movement between the bridge girders. Up to now the suitability of MEJ to mitigate pounding damages of girders under strong earthquakes is unknown. So far investigations of MEJ have been focused mainly on traffic-induced noise (e.g. Ravshanovich et al., 2007) and long-term MEJ fatigue behaviour due to repeated vehicle loading and continuous opening and closing movements of the MEJ beams.

The most significant requirement of a proper design of a MEJ to cope with strong earthquake induced relative movement between bridge girders is the minimum total gap between MEJ beams to prevent pounding. Since the MEJ system ensures a uniform movement between the beams, in the investigation the influence of the rubber sealing is considered to be negligible. Instead, the investigation focuses on the most significant influence factors identified in previous studies (Chouw and Hao, in press):

- characteristics of the spatially varying ground excitation: coherency loss and wave apparent velocities
- ratio of the fundamental frequencies of the adjacent bridge structures
- interaction between bridge structures and subsoil
- combined effect of these factors

The considered left and right bridge structures in Figure 1 have the heights of 12.2 m and 18.3 m, respectively. To focus on the influence factors it is assumed that both structures have very similar fixed-base fundamental frequencies with a ratio f_{II}/f_I of 0.99.

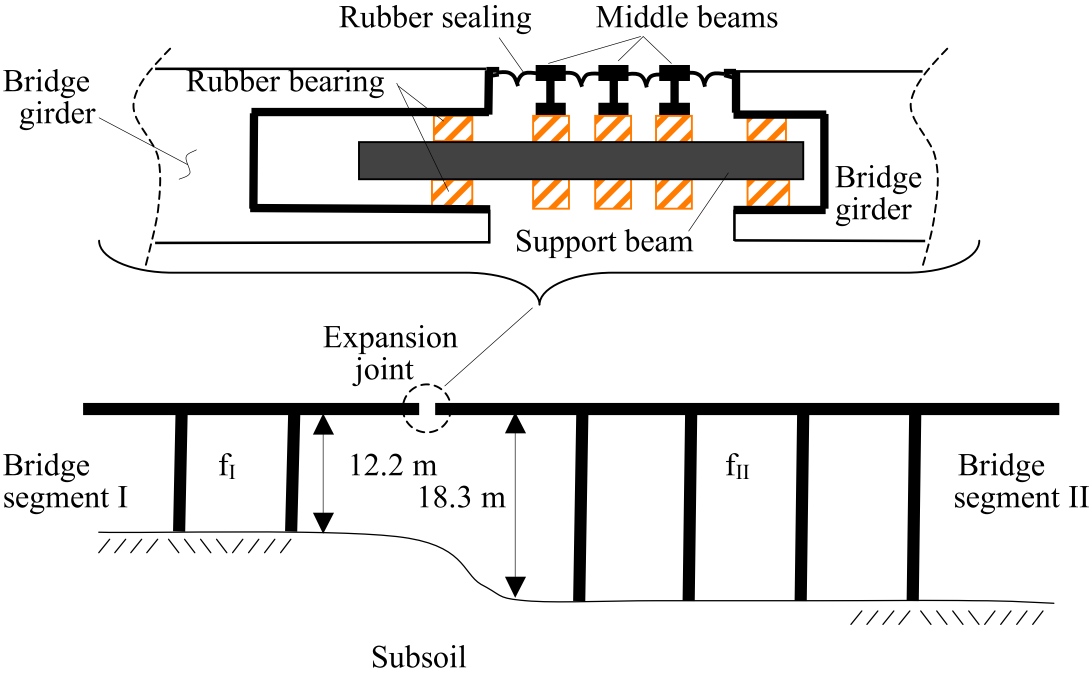

Figure 1 Bridge structures with subsoil and modular expansion joint

The soil is assumed to be a half space with a shear wave velocity of 100 m/s, a density of 2000 kg/m^3 and a Poisson's ratio of 0.33. The bridge structures with their footings and the subsoil are described by finite elements and boundary elements, respectively. Since in the 2D analysis an exact shape function (continuous-mass model) is used, only one finite element is necessary for each bridge pier and each girder. To couple the footing with the subsoil, 8 boundary elements are used to model the supporting soil at each footing-soil interface. The algorithm for the calculation of the girder responses with non-linear soil-structure interaction is described in the reference (Chouw and Hao, in press). For simplicity the piers of the left and right bridge segments are described as a single pier, and the distance between these left and right modeled piers is assumed to be 100 m. Figure 2 shows the influence of the wave apparent velocity c_a on the spatial variation of the ground motions at the two distant bridge pier locations. The ground motions are simulated based on a near-source ground motion model introduced by Ambraseys and Douglas (2003). The dominant frequencies of the simulated ground motions range between 2.5 Hz and 12.5 Hz with the peak ground acceleration of 3 m/s^2. The considered wave apparent velocities c_a are 200 m/s, 500 m/s and 1000 m/s. With increasing wave velocity the delay of the ground motions at the right bridge pier support decreases as the occurrence of the peak motions a_{g1} and a_{g2} shows.

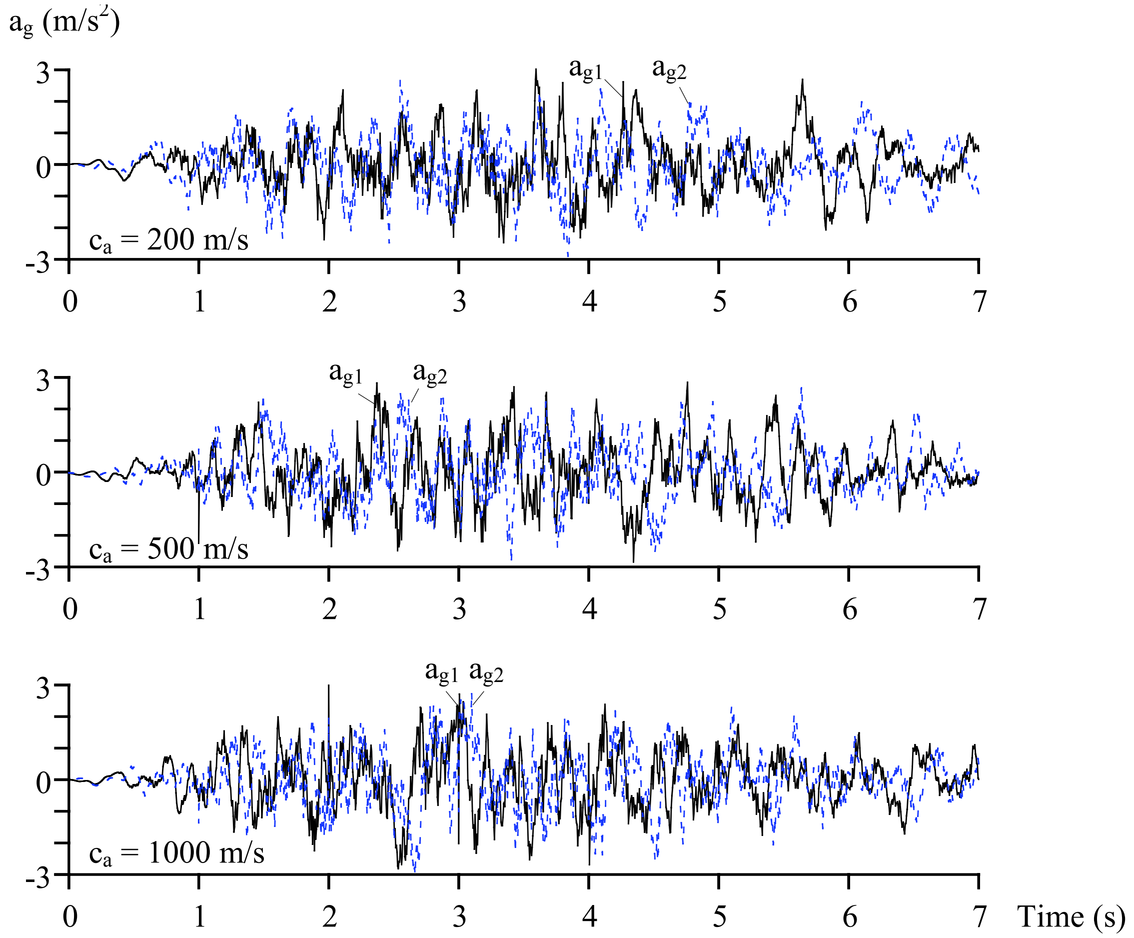

Figure 2 Simulated ground motions with different wave apparent velocities c_a

However, the spatial variation of the ground motions is not only characterized by the time delay but also by the coherency loss. In this study three degrees of coherency loss are considered: weak, intermediate and high. For each parameter of the considered ground motion twenty sets of spatially non-uniform ground motions are simulated. In total 100 sets of ground motions are generated. Details of the ground motion simulation are given in (Chouw and Hao, in press).

3. INFLUENCE FACTORS

Figure 3 displays the combined influence of SSI, the wave apparent velocity c_a and the coherency loss on the mean values of the minimum total MEJ gap required to avoid girder pounding. If fixed-base structures and uniform ground excitation are assumed, the minimum gap g is only 0.59 cm. This is to be expected, because both structures with assumed fixed base have very similar fundamental frequencies ($f_{II}/f_I = 0.99$). If the effect of the subsoil is considered, the required gap is not similar as one might expect. Even though the frequencies of the two structures without considering SSI are similar and both structures experience the same ground excitation, owing to their different structural slenderness both bridge structures interact with their ground differently. The unequal SSI effect causes relative movements, and consequently a much larger minimum required total MEJ gap g of 10.42 cm. In Figure 3 it is indicated as a horizontal solid line.

The results show that an assumption of uniform ground excitation clearly underestimates the minimum total required gap of a MEJ to avoid pounding, especially when the structures are assumed to be fixed at their base. In the case of highly correlated spatially varying ground motions the minimum required gap does not decrease with higher wave apparent velocity c_a.

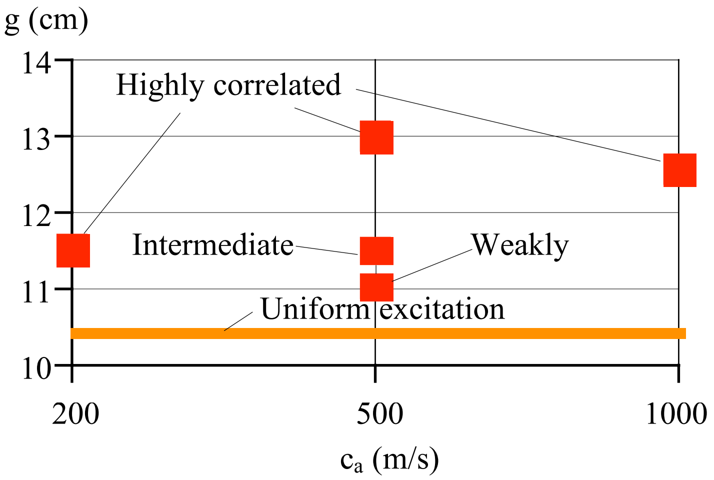

Figure 3 Minimum required total gap g of a MEJ

In the case of the wave apparent velocity c_a of 500 m/s the minimum total gap also does not decrease with less coherency loss (e.g. the highly correlated case) as one would expect. These results reveal that the minimum total MEJ gap cannot be related to a single influence factor, because the combined influence of these factors is dominant. Another influence factor -not considered so far- is the ratio f_{II}/f_I of the fixed-base fundamental frequencies of the adjacent bridge structures. The involvement of this factor in causing relative girder responses is displayed in Figure 4.

To enable a clear interpretation of the considered factors the influence of the structural slenderness is neglected. It is assumed that both adjacent structures have the same height of 9 m. Hence, the relative girder movement due to unequal interaction between bridge structures and subsoil is not considered. As a reference the case of fixed-base structures is also displayed in Figure 4. The results clearly show that the recommendation of current design regulations to avoid relative girder movement by designing structures with similar or equal fundamental frequencies is not adequate, when spatially non-uniform ground excitation does occur. In fact the fixed-base frequency ratio cannot be used as the only design parameter. At the frequency ratio f_{II}/f_I = 1.0 the minimum total gap does not have the smallest value, and this value is definitely not equal to zero. In the investigation it is assumed that the spatially varying ground motions are highly correlated. In both cases, with and without SSI, the influence of the frequency ratio f_{II}/f_I is obvious.

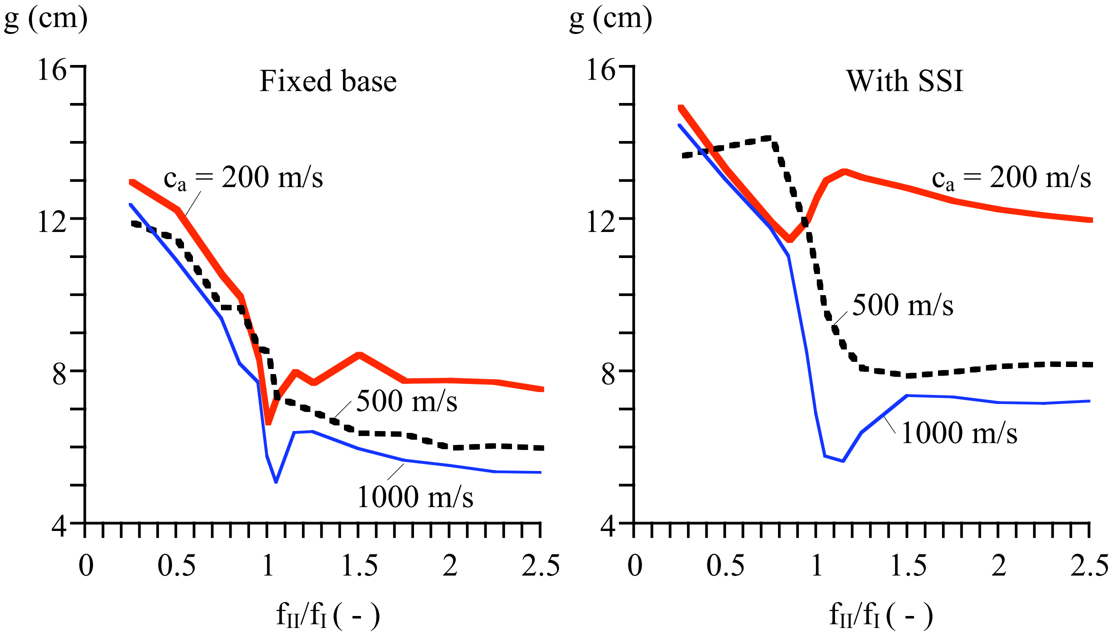

Figure 4 Dependence of the minimum required gap g on the frequency ratio f_{II}/f_I, the apparent wave velocity c_a of the spatially varying ground motions and SSI

In the higher ratio range, f_{II}/f_I above 1.15, the influence of the wave apparent velocity c_a is dominant. As expected the minimum total MEJ gap reduces with increasing wave speed. In the range of lower frequency ratios there is no clear tendency of the influence of the wave apparent velocity. Higher wave speed does not necessarily cause smaller required gap. The minimum gap is significantly affected by the frequency ratio.

A comparison of the results with and without SSI shows that an additional effect of SSI further increases the minimum gap that a MEJ must have to ensure that pounding will not take place.

4. CONCLUSIONS

A new design philosophy for preventing bridge girders from pounding due to strong earthquake is introduced. In contrast to the design of a conventional bridge expansion joint with only a few-centimetre gap, in the new design, modular expansion joints (MEJ) can be installed so that the adjacent bridge girders can have a large relative movement without causing any pounding, and consequently damage to the girders. The most significant specification is the minimum total gap of the joint. The MEJs should then be designed so that the total MEJ gap can cope with the largest expected relative movement.

In this work the influence of the spatially varying ground motions, SSI and their combined effect are discussed.

The investigation shows that:

- The recommendation of current design regulations to adjust the fundamental frequencies of the adjacent bridge structures does not necessarily produce the smallest minimum total gap that a MEJ must have when the ground motions are not uniform and the soil is soft.
- When the frequency ratio of adjacent bridge spans is larger than 1.15 the wave apparent velocity is dominant. The minimum required gap decreases -as expected- with higher wave speed.
- In the lower frequency ratio range the combined effect of ground motion spatial variation, SSI and the frequency ratio governs the minimum required gap.
- In almost all cases SSI causes a larger total gap.

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