1. INTRODUCTION

The usability of bridges after a strong earthquake is undoubtedly important for evacuation, rescue, fire fighting, first-aid supply and other needs for a quick recovery of the affected regions. Although specifications are given in various design codes, damages of bridge structures were still observed in past earthquake events. One most significant factor that controls the safety of bridge structures is the relative displacement between bridge girders. Large relative displacement can cause pounding between the girders and unseating of bridge decks from their supports. Relative displacement between superstructures and substructures is another significant factor, besides the ground motion characteristic, local soil behaviour and bridge support conditions. Despite decades of research efforts most of current design regulations, e.g. US bridge design code [AASHTO, 1998], are still of empirical nature. The objectives of this work are to assess the rationality and reliability of recently published Japanese bridge design code [JRA, 2004] and to identify the influence factors that should be considered in the revision of current design specification.

2. GROUND MOTIONS AND BRIDGE STRUCTURES

The relative displacement spectra in the recently published Japanese bridge design code [JRA, 2004] are determined using 63 strong ground motions recorded in Japan during earthquakes with a focal depth less than 60 km and magnitude equal to 6.5 or larger. To have a similar condition for an evaluation of these displacement spectra ground motions

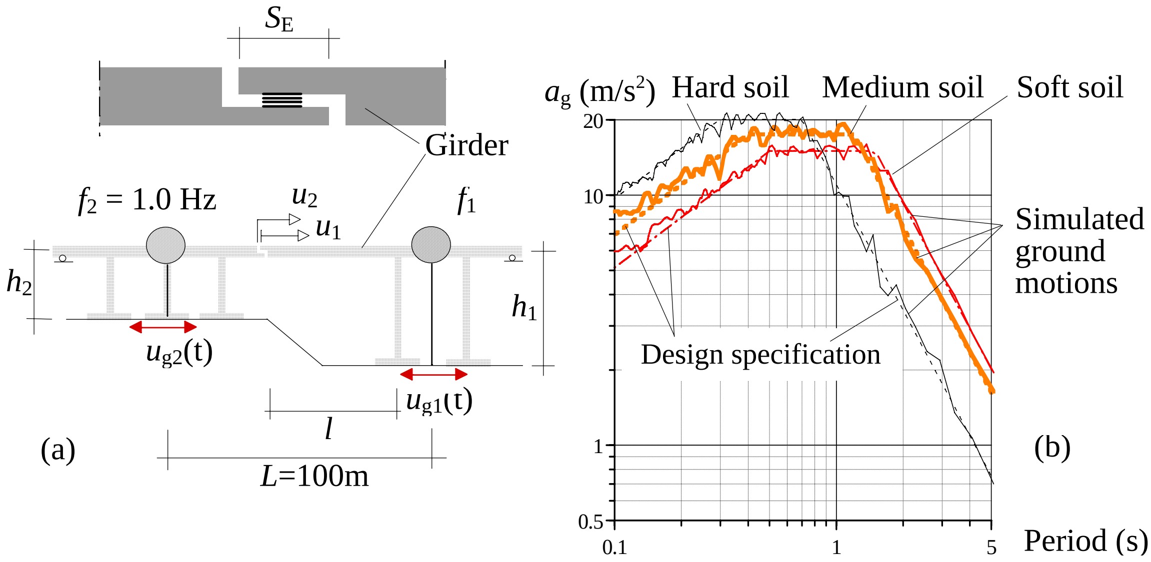

Figure 1(a) and (b). Bridge structures and ground excitation. (a) Simplified model of two bridge segments, and (b) Japanese design spectra and response spectra of the simulated ground motions simulated stochastically based on the Japanese design spectra in Figure 1(b) for soft, medium and hard soil site [JSCE, 2000] are used. In the simulation an empirical coherency loss function developed by Hao et al. [1989] is applied. For simplicity the girder displacements u_2 and u_1 of the left and right bridge structures are described using two single-degree-of- freedom systems (Figure 1(a)). The relative displacement $u_{rel}(t)$ is defined as $u_1(t) – u_2(t)$. The fundamental frequency f_2 = 1 Hz of the left structure is kept constant, while the frequency f_1 of the right structure is varied. It is assumed that the gap between girders is 5 cm. Details of the numerical procedure for calculating the relative displacement of the soil-structure systems with pounding effect are described in the references [Chouw and Hao, 2002 and 2003]. Figure 2 shows the simulated ground motions for hard, medium and soft soil conditions. In total 30 sets of spatially correlated ground motions for each soil conditions are simulated, so that relatively unbiased relative displacement spectra can be obtained. It is assumed that the ground motions are highly correlated, and the wave apparent velocity c_a is 500 m/s. Figures 2(a) and 2(b) show the ground accelerations and their corresponding displacements at the left pier support, respectively. Although the peak ground accelerations (PGAs) for hard, medium and soft soil conditions are almost the same, about 6 m/s^2, the peak ground displacements (PGDs) are very different because of the different frequency content of ground motions for the different site conditions. With increasing soil stiffness the PGD

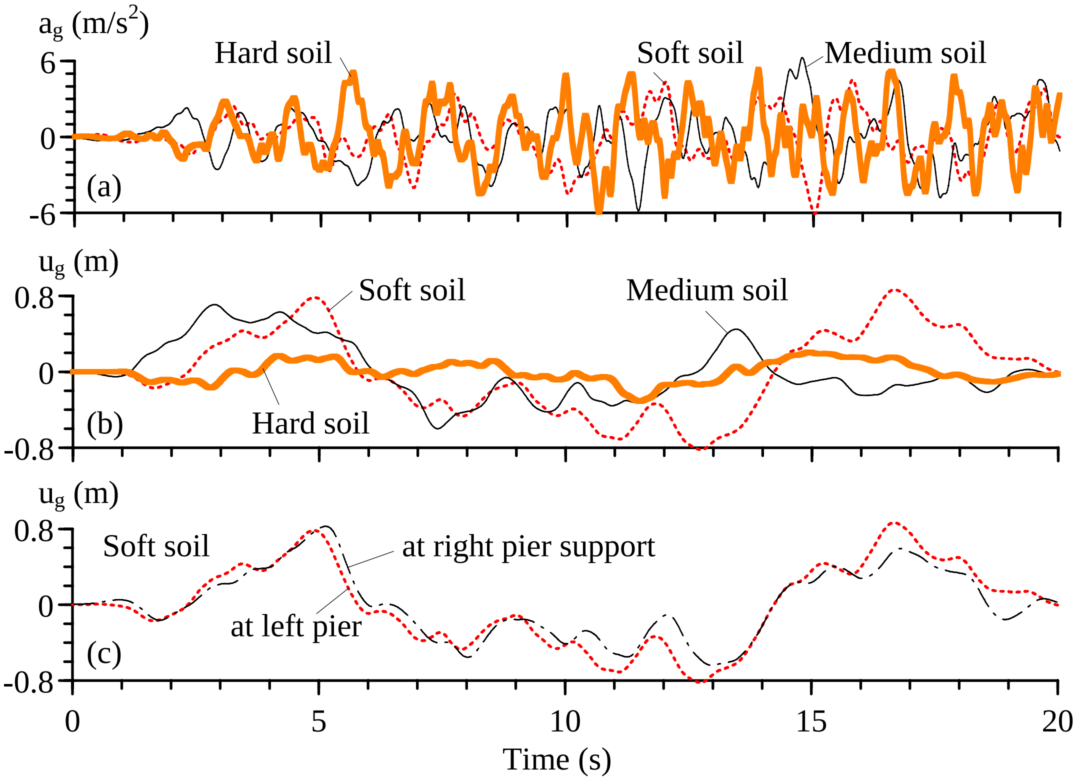

Figure 2(a)-(c). Ground motions. (a) Ground accelerations, (b) ground displacement at left pier support, and (c) non-uniform ground displacements.

decreases. This difference in the ground displacement amplitude can have strong influence on the relative displacement, because it depends on dynamic and also quasi-static response of the adjacent bridge structures. Figure 2(c) shows the ground displacements at the left and right pier supports. Their non-uniformity reflects the quasi-static contribution of the ground motions to the total relative displacement.

3. EVALUATION OF DESIGN SPECIFICATION

3.1 Current Japanese design specification

The seating length S_E at an expansion joint is defined as illustrated in Figure 1(a). The larger value obtained from Equations (1) and (2) should be used. u_{rel} in metre is the maximum relative displacement of the adjacent structures under the strongest ground motions corresponding to the Japanese design spectra in Figure 1(b). In the determination of u_{rel} the effect of unseating prevention measures should not be considered. The Japanese specification is probably the only one so far that considers the influence of spatial variation of ground motions, even only empirically. u_G in metre is the relative displacement of the ground. It depends on the soil strain ε_G and the distance L between the adjacent substructures. For hard, medium and soft soil ε_G can be assumed as 0.0025, 0.00375 and 0.005, respectively. l is the effective bridge span in metre.

$$S_{\mathrm{E}} = u_{\mathrm{rel}} + u_{\mathrm{G}} \geq S_{\mathrm{E,\,min}} \tag{1}$$

$$S_{\mathrm{E,\,min}} = 0.7 + 0.005\, l \tag{2}$$

$$u_{\mathrm{G}} = \varepsilon_{\mathrm{G}}\, L \tag{3}$$

3.2 Relative displacement spectrum

In Figures 3(a) and 3(b) the relative displacement spectrum of the design specification is plotted together with the numerical results due to the uniform and non-uniform ground accelerations for soft, medium and hard soil conditions. In accordance with the design specification only the structural dynamic response without pounding effect is considered. The relative displacement due to each set of ground excitation is normalized by the respective maximum response of the left structure. For the comparison the mean value of the normalized results due to 30 sets of ground motions is applied. The spectrum values in Figures 3(a) and (b) represent then the amplification or reduction of the relative displacement depending on the frequency ratio due to the uniform and non-uniform ground excitations, respectively. Figure 3(a) shows that especially in lower frequency-ratio range the result due to the uniform medium-soil ground motions agrees well with the design spectrum. If the frequency ratio is larger than 1.0, the result due to the hard-soil ground motions matches the design spectrum well. In the low frequency-ratio range below 0.75 the design values clearly underestimate the spectrum values for the soft soil condition.

If non-uniform ground motions are considered, the current design spectrum underestimates, especially, the values in the range around $f_1 / f_2 = 1.0$. Equal fundamental frequencies are supposed to prevent girder relative displacement. The present numerical results indicate, however, that an adjustment of fundamental frequencies to unity -as recommended by many current design regulations, not only the Japanese regulations but also the others like Caltrans [1999]- can cause a relative displacement as large as the maximum displacement of the left structure. If the quasi-static response and soil-structure interaction are considered as well, even larger relative displacement occurs (see the values for the frequency ratios around 1.0 in Figures 5(b) and 6).

Another significant influence factor is the slenderness ratio of the adjacent bridge structures. This effect cannot be observed, if fixed-base structures are assumed. Figure 4 shows the relative displacement without quasi-static responses due to the first set of the

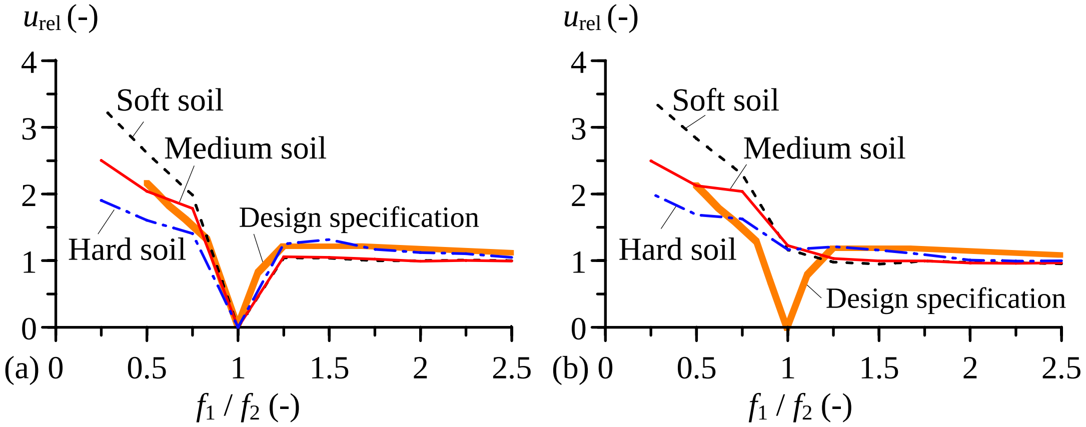

Figure 3(a) and (b). Normalized relative displacement spectra due to (a) uniform and (b) non-uniform ground excitation without quasi-static response and pounding effect ($h_1 = h_2 = 9$ m, $f_2 = 1$ Hz, fixed-base structures)

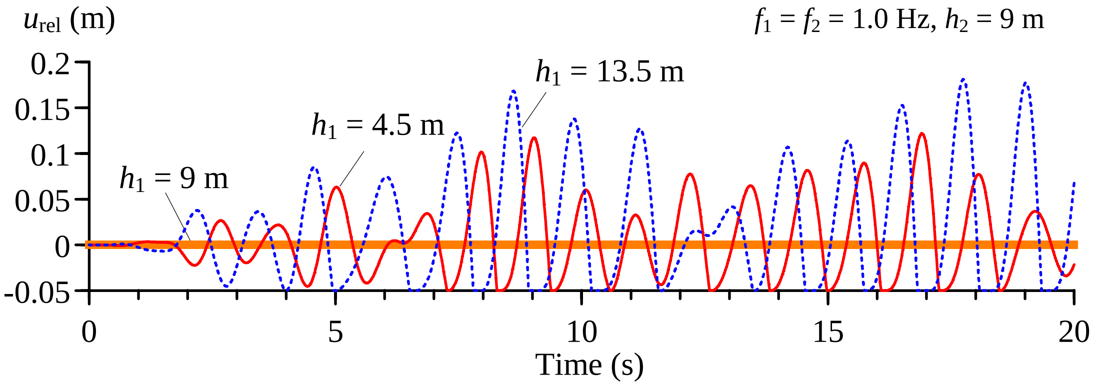

Figure 4. Effect of slenderness ratio on the maximum relative displacement u_{rel}

soft-soil uniform ground accelerations (Figure 2(a)) for different slenderness ratio. The positive and negative relative displacements illustrate how far the girders will move away from and toward each other. Both structures are assumed to have the same fundamental frequency of 1.0 Hz. The pier height of the left structure h_2 = 9 m is kept constant, while the right pier has the height h_1 of 4.5 m, 9 m or 13.5 m. If the relative displacement between adjacent structures is only controlled by their fundamental frequency, uniform ground excitation will cause no relative displacement, because structures with the same fundamental frequencies will respond in phase. The result shows that this is true, only if the structures also have the same slenderness ($h_1 = h_2 = 9$ m). If the structures have different slenderness, they will experience different soil-structure interaction. Consequently, relative displacement occurs. This fact is often ignored in the structural engineering.

Figures 5(a) and 5(b) show the relative displacement spectra due to the uniform and non-uniform soft-soil ground motions, respectively. The soil-structure interaction

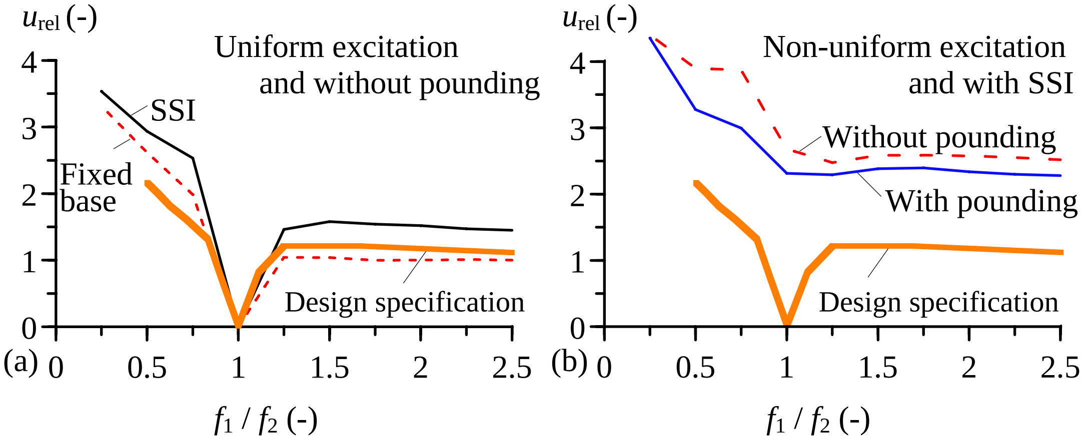

Figure 5(a) and (b). Normalized relative displacement spectra due to (a) uniform and (b) non-uniform soft-soil ground excitation ($h_1 = h_2$ = 9 m, f_2 = 1 Hz)

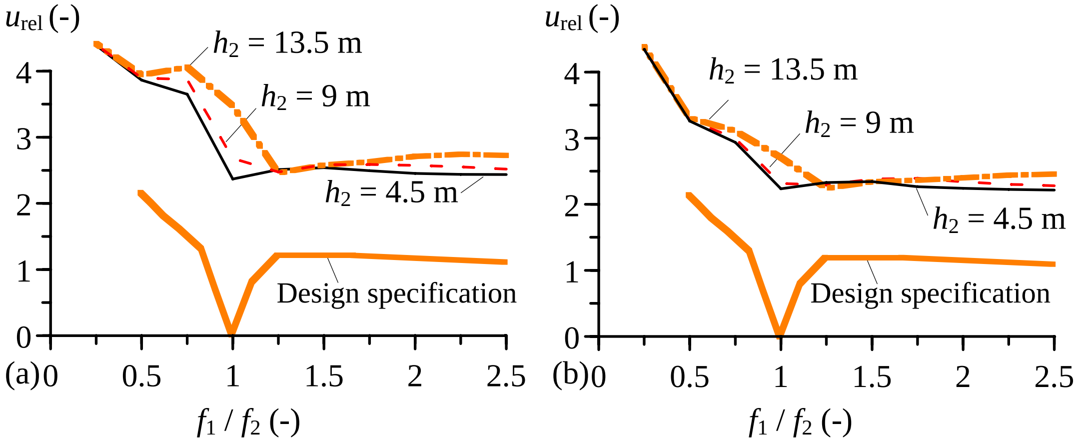

Figure 6(a) and (b). Slenderness influence on required seating length. (a) Without and (b) with pounding effect. (h_2 = 9 m, f_2 = 1 Hz) amplifies the spectrum values (Figure 5(a)). An additional consideration of the quasi-static responses due to the spatially varying ground displacements further amplifies these values (compared solid black line in Figure 5(a) with dash line in Figure 5(b)), especially around the frequency ratio of 1.0. Pounding reduces the values, but not when the neighbouring structure is more flexible, e.g. at f_1 / f_2 = 0.25. The slenderness-ratio influence can be seen in Figure 6. h_1 of 13.5 m causes the largest spectrum values. Pounding reduces the influence of slenderness ratio.

For bridge structures on soft soil with f_1 / f_2 of 0.5 the normalized relative displacement u_{rel} according to the current design specification is 2.15. Assuming that L is 100 m and l is 50 m and applying the mean value of the maximum displacement of the left structure of 0.38 m, the largest required seat length according to Equation (1) is 1.32 m. For h_1 of 4.5 m according to Figure 6(b) u_{rel} is 3.26. The corresponding relative displacement is 1.24 m.

For f_1 / f_2 of 1.0 and h_1 of 4.5 m the relative displacement is 0.88 m corresponding to u_{rel} of 2.33 as shown in Figure 6(b), while the minimum value $S_{\mathrm{E,\ min}}$ of 0.95 m according to Equation (2) is a little conservative. If h_1 is 13.5 m, the minimum design specification value $S_{\mathrm{E,\ min}}$ underestimates the required seat length of 1.03 m corresponding to u_{rel} of 2.46 (Figure 6(b)).

For f_1 / f_2 of 2.5 and h_1 of 4.5 m Figure 6(b) leads to a relative displacement of 0.84 m corresponding to u_{rel} of 2.22, and it is slightly smaller than the minimum design specification value $S_{\mathrm{E,\ min}}$ of 0.95 m.

4. CONCLUSIONS

The current Japan Road Association (JRA) specification is probably the only one so far that considers the influence of spatial variation of ground motions, even only empirically. It also considered the latest research outcome by incorporating the influence of fundamental frequency ratio of the adjacent bridge structures in the determination of the required seating length to prevent bridge girders from unseating. The specification does not consider the following influence factors: the effect of the spatial variation of ground motions, pounding and different soil-structure interaction of adjacent structures.

The evaluation reveals:

The relative displacement response spectrum in current JRA specification is only valid for bridge structures on very hard soil under spatially uniform ground excitations. Current specification provides conservative seat length requirement for stiff structures. If the neighbouring structure is slender and flexible, however, it underestimates the necessary seat length.

In the case of non-uniform ground excitation relative displacement response is expected, even if the adjacent bridge spans have identical vibration frequencies.

Bridge structures with the same fundamental frequency under nearly uniform ground excitation can have relative displacement, if they experience unequal soil-structure interaction effect.

Pounding in general reduces the soil-structure interaction effect.

ACKNOWLEDGEMENTS

The authors wish to thank the Japanese Ministry of Education, Science, Sports and Culture for the support of this research (award number 15560404).

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