# Unequal soil-structure interaction effect on seismic response of adjacent structures

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## ABSTRACT

This contribution addresses the seat length required to avoid unseating of bridge girders under strong earthquakes. In the investigation simulated ground motions according to the Japanese design spectrum for soft soil site are applied. The analysis of two adjacent bridge structures is performed using a combined finite element and boundary element method. The results reveal that current design specifications can strongly underestimate the required seat length, especially when the adjacent bridge structures interact unequally with their common ground.

## 1 INTRODUCTION

In spite of a large number of investigations in the past decades and implementations of their outcomes in design specifications to avoid and to mitigate the consequence of relative bridge girder movements, damage has still been observed in major earthquakes, like the 1994 Northridge earthquake or the 1999 Chi-Chi earthquake. Figure 1 displays the consequence of insufficient girder seat length for one of many bridges with damages related to relative girder movements in the 1995 Kobe earthquake. The main reason for knowledge gap in current design specifications is that the recommendations are based on research outcomes which neglected the influence of soil-structure interaction.

**Figure 1: Bridge with insufficient seat length (1995 Kobe earthquake)**

## 2 CAUSES OF UNEQUAL SOIL-STRUCTURE INTERACTION

Unseating of bridge girders will take place when the opening relative movement between adjacent bridge structures exceeds the available seat length. The cause of relative girder responses is not only the different dynamic behaviour of the adjacent structures. The other cause is the spatial variation of the ground excitations of the adjacent bridge supports due to wave propagation and non-uniform soil conditions. In recent years this influence factor becomes a research topic of many researchers. Another factor that is often neglected in the investigation is the dynamic interaction between the bridge structures and their supporting subsoil.

From Equation (1) the influence of subsoil on the fundamental period of the bridge structure-soil system can be estimated.

$$\tilde{T}_n = T_n \sqrt{1 + \frac{k_n}{k_{nx}}\left(1 + \frac{k_{nx}\, h_n^2}{k_{n\phi}}\right)} \qquad (1)$$

where $\tilde{T}_n$ and $T_n$ are the period of a bridge segment with subsoil and with an assumed fixed base, respectively. $k_n$ , $k_{nx}$ and $k_{n\phi}$ are the bending stiffness of the bridge segment, the static soil stiffness for horizontal and rocking movements of the assumed rigid bridge footing, respectively. The subscript $n$ is the number of the bridge segment, and $h_n$ is the height of the bridge structure. It is assumed that the effect of the vertical soil stiffness is negligible. It should be noted that in reality the soil stiffness depends on the vibration frequencies of the footing (see e.g. Sieffert & Cevaer, 1992). Equation (1) shows that even if the supporting soil of the two adjacent bridge segments in Figure 2 has the same properties ($k_{1x} = k_{2x}$ and $k_{1\phi} = k_{2\phi}$) and the bridge structures have the same fixed-base fundamental period ($T_1 = T_2$), the different heights ($h_1 \neq h_2$) will cause different system periods. Consequently, each bridge segment will respond differently, even if both structures experience the same ground excitation. The change of the system properties also affects the other dynamic property: the overall system damping. Equation (2) is an empirical formula for estimating the damping of a bridge structure-soil system.

$$\tilde{\beta}_n = \beta_{sn} + \frac{\beta_n}{\left(\tilde{T}_n / T_n\right)^3} \qquad (2)$$

where $\tilde{\beta}_n$ , $\beta_{sn}$ and $\beta_n$ are the damping of the bridge structure-soil system, subsoil and bridge structure with an assumed fixed base, respectively. $\beta_{sn}$ includes both soil material damping and radiation damping due to wave propagation from a vibrating bridge footing. In reality, $\beta_{sn}$ is not a constant value but frequency dependent. In the case of soft soil $\tilde{T}_n$ is greater than $T_n$ . The interaction between bridge footing and soil reduces the effectiveness of the structural damping $\beta_n$ of the bridge. If the radiation damping is small, the overall damping of the bridge structure-soil system becomes less than that of the bridge structure with an assumed fixed base. Different influence on overall damping means possible relative responses due to different development of responses of the adjacent structures, and consequently possible increase of unseating potential.

To prevent bridge girders from unseating current design regulations, e.g. AASHTO (1998), CALTRANS (2001) and JRA (2004) recommend that adjacent bridge structures should have the same or at least very similar fundamental periods so that the adjacent girders will respond to the ground motions in phase and consequently unseating will not take place. In reality, however, in addition to soil-structure interaction (SSI) contribution because of the distance between the adjacent bridge pier supports, the ground motions at adjacent bridge supports experience time delay due to propagation of seismic waves from one support to neighbouring support. Because the soil along the bridge is normally non-uniform the ground motions are not coherent. This spatial variation of ground excitations will just cause out-of-phase responses of adjacent structures with same frequency (Chouw & Hao, 2008). To focus on SSI effect spatially varying ground motions is not considered in this study. It is assumed that both bridge structures have the same excitation and the soil is a uniform half space with the properties as given in Figure 2. For the numerical analysis the bridge structures and subsoil are described by a combined finite element and boundary element method (Chouw, 1994). The algorithm for non-linear soil-structure interaction is described in Chouw (2002) and Chouw & Hao (2008).

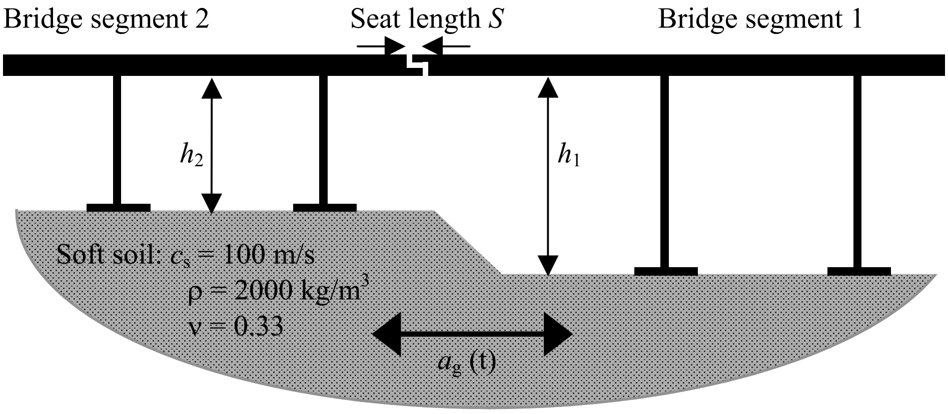


**Figure 2: Adjacent bridge structures**

## 3 CONSEQUENCE FOR STRUCTURAL RESPONSE

In the study the Japanese design spectrum for soft soil is considered (JSCE, 2000), and 20 ground motions are simulated. Figures 3(a) and 3(b) show the design spectrum with the dominant frequencies between 0.65 Hz and 2 Hz and a simulated ground motion time history, respectively.

Figure 4(a) shows the relative displacement between the girders of bridge structures with the same fixed-base fundamental frequency of 1 Hz due to the ground motions displayed in Figure 3(b). It is assumed the girder gap is 5 cm and SSI is taken into account. As expected, the bridge girders have no relative response if both adjacent structures have the same height ($h_1 = h_2 = 9$ m), because both structures interact with the ground in the same way. It is not the case when both structures have different heights. The different SSI causes relative response between the adjacent girders. The activated pounding forces are displayed in Figure 4(b) which reflect the damage potential of the girders. The results show that an assumption of fixed-base structures will provide a wrong understanding of safety. While a fixed-base assumption will produce no

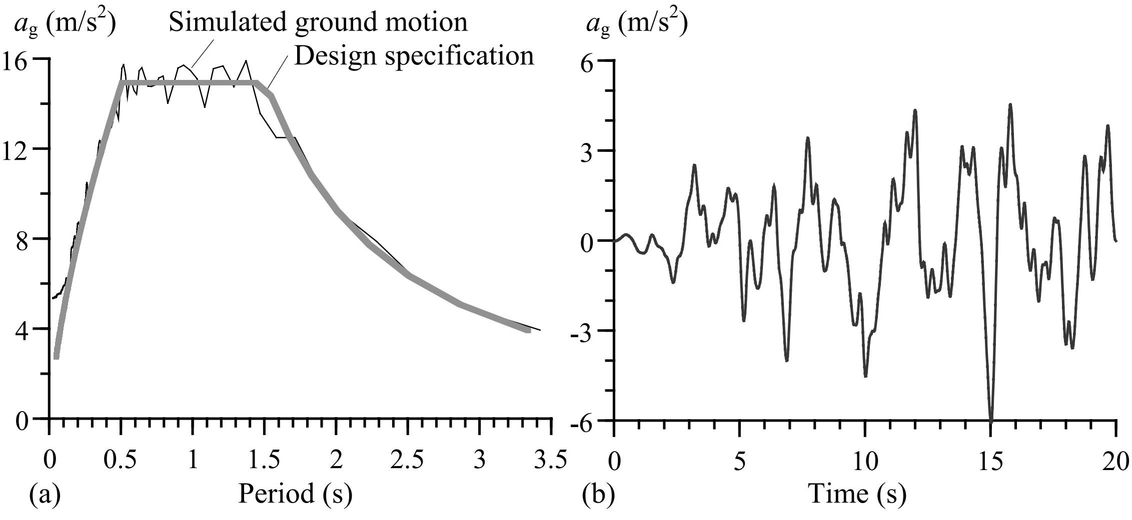


**Figure 3: Earthquake loading.**
**(a) Japanese design spectrum for soft soil and (b) simulated ground motion time history**

relative response due to in-phase responses of the adjacent structures, a consideration of unequal SSI clearly reveals the damage potential due to girder poundings.

Figure 5 shows the influence of SSI on the mean value of the seat length *S* required to prevent girder from unseating. It is assumed that both adjacent bridge structures have the same height of 9 m. The seat length *S* is normalized by the maximum girder displacement of the bridge segment 1. The results in Figure 5(a) clearly show that when both adjacent structures have the same fundamental frequency ($f_2/f_1 = 1$) no seat length is required. This is also the case when SSI is considered, because equal SSI does not contribute to relative responses between the adjacent girders. This result corresponds well with the recommendation of current design specifications.

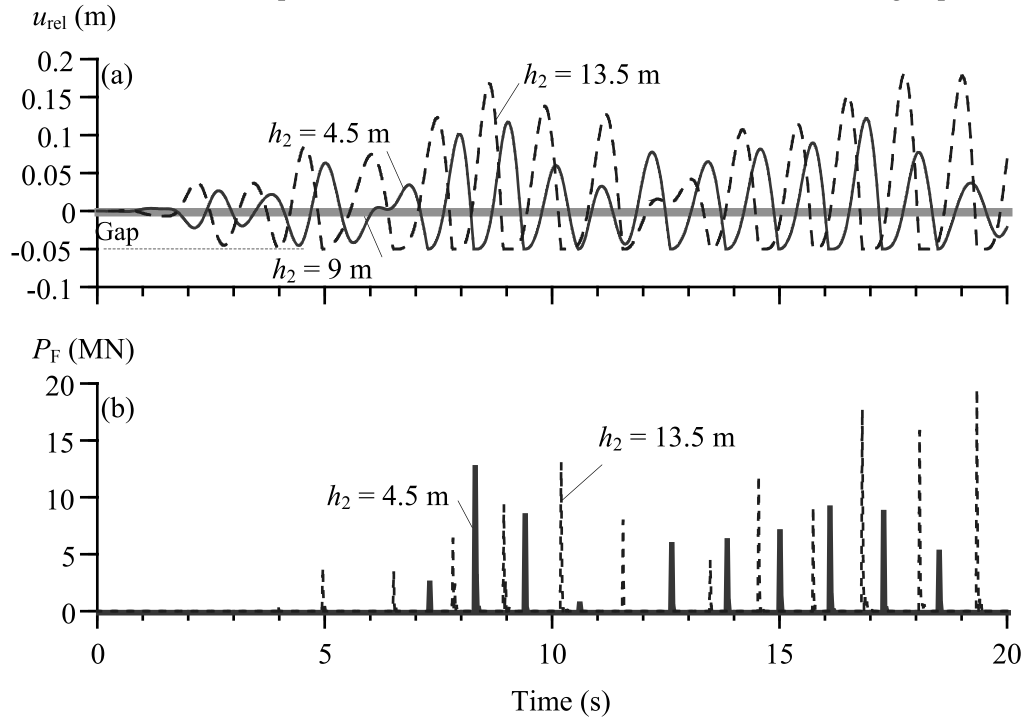


**Figure 4: Consequence of unequal soil-structure interaction for the relative response of adjacent bridge structures.**
**(a) Relative displacement $u_{rel}$ and (b) Contact force $P_F$**

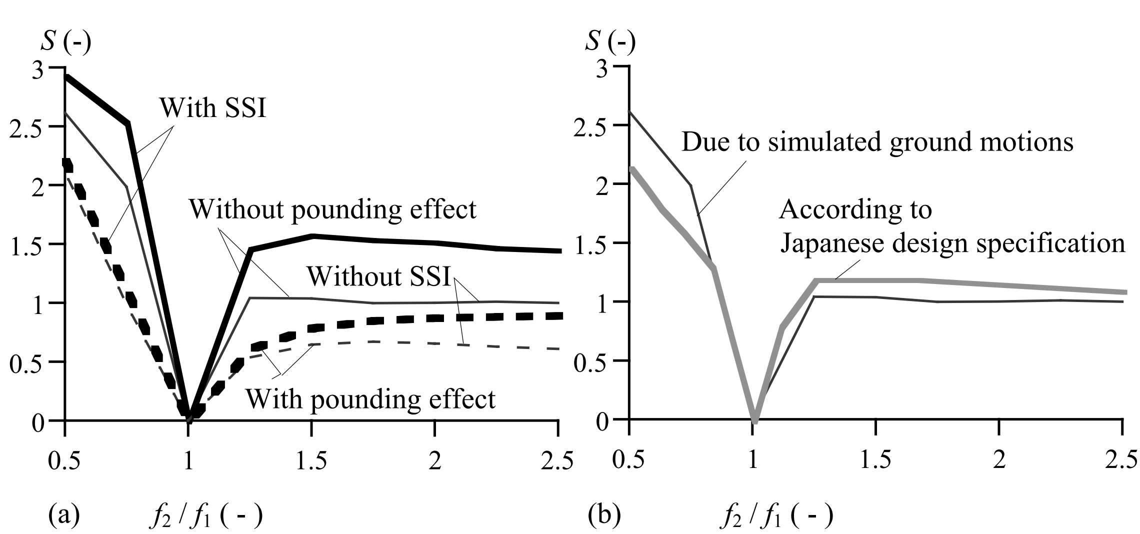


**Figure 5: Required seat length *S*. (a) Influence of soil-structure interaction and pounding and (b) Comparison with Japan design code values**

Bold and thin lines in Figure 5(a) are the results with and without SSI, respectively. Solid and dash lines are the results without and with pounding effect, respectively. In general, SSI increases and pounding reduces the required seat length. In the Japanese design specification the beneficial influence of pounding is not considered. Instead, the seat length is provided without pounding effect. In Figure 5(b) the seat length according to the Japanese design regulation (JRA, 2004) and that due to the simulated ground motions are presented. While in the lower frequency ratio range, $f_2/f_1$ below 0.83, the seat length according to the Japanese design specification is smaller than those obtained in this study, in the higher frequency ratio range, $f_2/f_1$ larger than 1, the values according to the design specification are larger.

Figure 6 shows the influence of unequal SSI on the mean values of the normalized seat length $S$ required to avoid girder unseating. It is assumed that the first bridge segment has the height $h_1$ of 9 m and a fixed-base fundamental frequency $f_1$ of 1 Hz. For the case of equal structural height ($h_1 = h_2$) the results without considering SSI is also presented as a thin solid line. The results shows that equal SSI will provide results as recommended by current design specifications: no seat length is required, when both adjacent bridge structures have the same fixed-base fundamental frequency. However, it should be noted that this result is correct, only when the same ground excitation of both bridge structures can be assumed. If both structures experience different ground motions, this recommendation of equal fundamental frequency of the adjacent structures will just cause an adverse effect (Chouw & Hao, 2008).

If the adjacent bridge structures have different heights, unequal SSI will cause girder relative responses. Even though both structures have the same fixed-base fundamental frequency, the different interaction causes then seat length required to prevent the girders from unseating. Indeed, in the case of $h_2$ = 4.5 m the smallest seat length still can be achieved (solid grey line), when both bridge structures have the same dynamic properties. In the case of $h_2$ = 13.5 m the smallest seat length can be obtained when both structures have the frequency ratio $f_2/f_1$ = 1.25 and not when $f_2/f_1$ = 1.

The results show that the recommendation of current design specifications to adjust the properties of adjacent structures, so that they have the same or similar fundamental frequencies is insufficient, because other significant influence factors, the spatial variation of the ground motions and SSI, are not taken into account. In the considered case, while according to design recommendation no seat length is necessary, the unequal SSI reveals that a seat length of 0.85 ($h_2$ = 4.5 m) or even 1.6 ($h_2$ = 13.5 m) times the maximum adjacent girder displacement is required if girder unseating should be avoided.

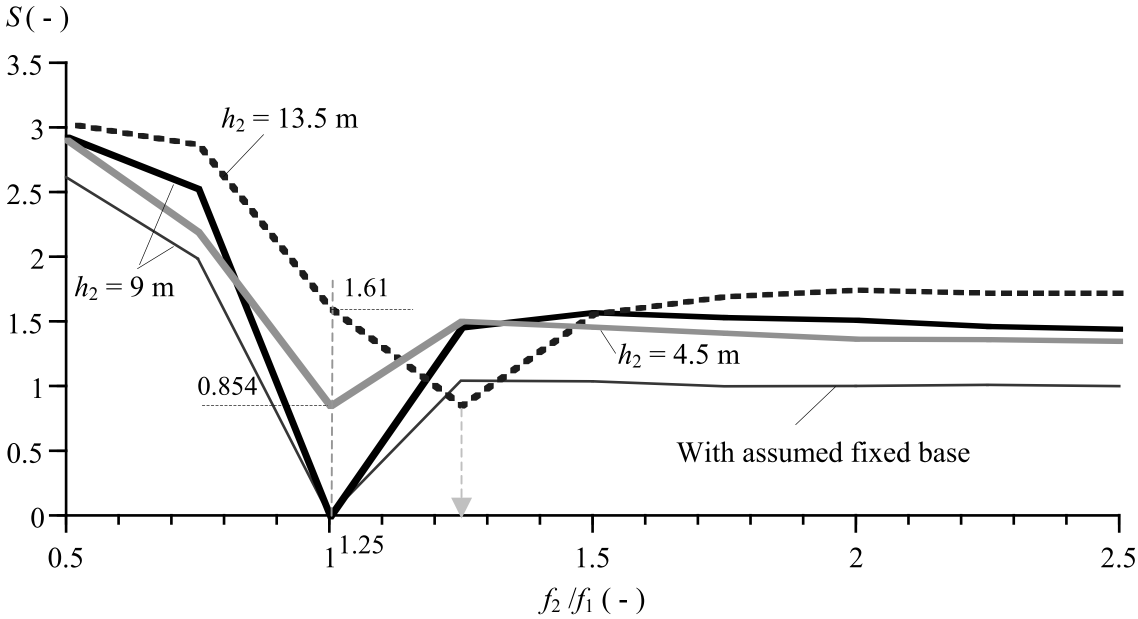


**Figure 6: Influence of unequal soil-structure interaction on the required seat length *S***

## 4 CONCLUSIONS

The numerical investigation focused on the influence of unequal soil-structure interaction of two adjacent bridge structures on the seat length required to prevent unseating of bridge girders under strong earthquakes. In the analysis simulated ground motions according to the Japanese design spectrum for soft soil site are applied. The results obtained are compared with the necessary seat length according to current Japanese design specification.

The following results cannot be obtained when fixed-base structures are assumed as performed in current common practice:

- The assurance of unseating prevention by adjusting the fundamental frequencies of adjacent bridge structures as recommended by current design specifications is confirmed when equal soil-structure interaction can be ensured.
- When both adjacent bridge structures interact with the subsoil unequally, a bridge girder seat length is required.
- When unequal SSI occurs, same fixed-base fundamental frequency of adjacent bridge structures must not necessarily results in the smallest seat length.

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