RELATIVE DISPLACEMENT RESPONSE SPECTRA WITH POUNDING EFFECT

Anat RUANGRASSAMEE[1] and Kazuhiko KAWASHIMA[2]

[1]Student member of JSCE, Graduate student, Dept. of Civil Eng., Tokyo Institute of Technology
(2-12-1, O-okayama, Meguro-ku, Tokyo 152-8552, Japan)
[2]Fellow member of JSCE, Dr. Eng., Professor, Dept. of Civil Eng., Tokyo Institute of Technology
(2-12-1, O-okayama, Meguro-ku, Tokyo 152-8552, Japan)

This research was conducted to investigate the relative displacement with pounding between two adjacent structures. Two bridge segments connected at a joint were idealized as two equivalent-linear single-degree-of-freedom systems. The results from series of analyses were presented in the form of response spectra, called as *relative displacement response spectra with pounding effect.* It is found that the pounding can cause the amplification of relative displacement between two bridge segments. To withstand the effect of pounding, a longer seat length should be provided to support a deck. The value of the seat length can be realized by the application of the relative displacement response spectra with pounding effect.

Key Words : *Relative Displacement, Response Spectrum, Gap, Pounding*

1. INTRODUCTION

On January 17, 1995, the Hyogo-ken Nanbu earthquake wrecked people's lives and caused devastative damage to civil engineering structures in the vicinity of Kobe City. According to post-earthquake investigations, it was found that many bridges suffered from unseating of decks from supports[1)]. The unseating of bridge decks is undesirable because it leads to the loss of function and harms the safety of human life. After the occurrence of a large earthquake, the important bridges treated as the main lifeline for emergent transportation are expected to withstand and be able to serve their functions.

This research is conducted aiming to investigate the relative displacement between two adjacent bridge segments with consideration of pounding. A simplified analytical model is developed for such a purpose. The results from series of analyses are presented in the form of the response spectra, called as *relative displacement response spectra with pounding effect* and *normalized relative displacement response spectra.* The investigation on the influences of ground motion characteristics, natural periods, mass ratios, and gaps is performed. Finally, the formulation of the normalized relative displacement response spectra is proposed for the design of seat lengths.

2. ANALYTICAL MODEL

To investigate dynamic responses of a bridge with the consideration of pounding, a simplified analytical model is developed. Two bridge segments connected at a joint are idealized as two linear single-degree-of-freedom systems as shown in Fig. 1. The systems are referred to as System 1 and System 2. Systems 1 and 2 are separated by a gap Δ_G. Two systems are subjected to the same ground motion $u_G(t)$, neglecting spatial variations of ground motions along the longitudinal direction of the bridge. The natural periods of Systems 1 and 2 are denoted as T_1 and T_2, respectively. The damping ratios of Systems 1 and 2 are defined as h_1 and h_2, respectively. The lumped mass of System 1 is m_1, and that of System 2 is m_2. As shown in Fig. 1, the displacement responses without pounding of Systems 1 and 2 are defined as $u_1(t)$ and $u_2(t)$, respectively. The displacement responses with

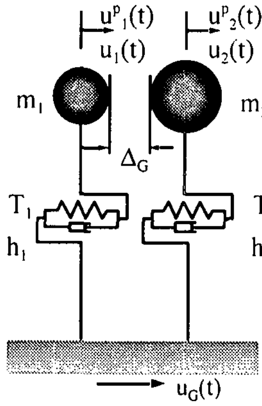


Fig. 1 Idealized model

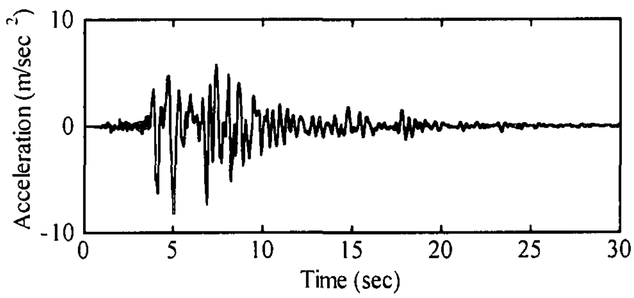


Fig. 2 Ground acceleration of the JMA Kobe record

pounding of Systems 1 and 2 are defined as $u_1^P(t)$ and $u_2^P(t)$, respectively. In the analysis, the pounding between Systems 1 and 2 is taken into account by the application of the laws of conservation of energy and momentum[2)].

3. PARAMETERS IN ANALYSIS

If the gap Δ_G separating Systems 1 and 2 is sufficiently large, the pounding will not occur. The minimum gap required to prevent pounding can be determined from the maximum relative displacement in closing direction, $\max[u_1(t)-u_2(t)]$. If the gap is smaller than the maximum relative displacement in closing direction, the pounding will occur unavoidably. The seat length is evaluated from the maximum relative displacement in separating direction (referred shortly as maximum relative displacement); that is, $\max[u_2(t)-u_1(t)]$ for the case without pounding or $\max[u_2^P(t)-u_1^P(t)]$ for the case with pounding.

In this study, the main objective is to investigate the effect of pounding on the relative displacement between two bridge segments. It can be seen that the normalization of some key parameters will lead to the meaningful interpretation of analytical results. The gap Δ_G is normalized as:

$$r_G = \frac{\Delta_G}{\max[u_1(t)-u_2(t)]} \qquad (1)$$

where r_G is referred to as a *gap ratio*. r_G is the parameter indicating whether the pounding occurs or not. If the value of r_G is equal to or larger than 1.0, the pounding does not occur. But if the value of r_G is smaller than 1.0, the pounding occurs. And the maximum relative displacement is normalized as:

$$N_{RD} = \frac{\max[u_2^P(t)-u_1^P(t)]}{\max[u_2(t)-u_1(t)]} \qquad (2)$$

where N_{RD} is referred to as a *normalized relative displacement*. The value of N_{RD} represents the amplification or deamplification of the maximum relative displacement that may occur due to the pounding effect. If r_G is less than 1.0, N_{RD} may be smaller or larger than 1.0 because of the effect of pounding. If r_G is larger than 1.0, N_{RD} is equal to 1.0, showing no pounding and no amplification of the relative displacement. It is worthy to point out that the normalization advantageously eliminates the effect of peak ground accelerations of ground motions.

In this investigation, the natural periods of Systems 1 and 2 (T_1 and T_2) are varied from 0.05 to 3.00 sec with the increment of 0.05 sec to cover the typical range of fundamental natural periods of bridges. The viscous damping ratio of 0.05 is applied for both systems. The value of the damping ratio is typical for reinforced-concrete structures of moderate size. The mass of Systems 1 and 2 (m_1 and m_2) is represented as a mass ratio:

$$r_M = \frac{m_2}{m_1} \qquad (3)$$

The mass ratios of 1, 2, 5, 8, and 10 are used in the analysis. The coefficient of restitution e is assumed as 1.0, neglecting the energy loss in pounding. The gap ratio r_G is varied from 0 to 1.0 with the increment of 0.1. Totally 80 ground motion records are used in

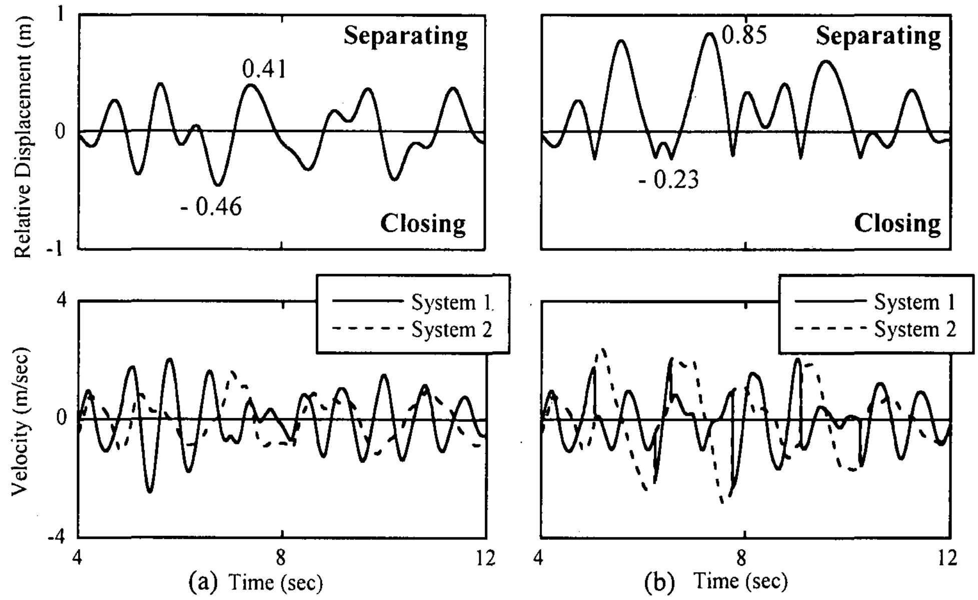


Fig. 3 Dynamic responses without pounding (a) and with pounding (b)

order to clarify the effect of ground motion characteristics. The ground motions were obtained in the free-field condition during earthquakes with magnitudes ranging from 6.6 to 7.9.

4. POUNDING EFFECT FOR A TYPICAL RECORD

Fig. 2 shows the N-S component of the free-field ground acceleration recorded at the JMA Observatory in Kobe City in the 1995 Hyogo-Ken Nanbu earthquake. The earthquake had a magnitude of 7.2 and a focal depth of 14 km. The ground motion record will be referred to as the JMA Kobe record. The peak ground acceleration of the JMA Kobe record is 8.18 m/sec^2. Fig. 3(a) shows the time histories of relative displacement and velocity responses without pounding from the analysis for the JMA Kobe record, T_1 = 0.8 sec, T_2 = 2.0 sec, and r_M = 1. It is found that maximum relative displacement is equal to 0.41 m and 0.46 m in separating and closing directions, respectively. Fig. 3(b) illustrates time histories of those responses with pounding. The gap Δ_G is set equal to 0.23 m, corresponding to a gap ratio r_G of 0.5. It is seen the relative displacement in closing direction is limited to be equal to the gap of 0.23 m. Comparing the relative displacement without pounding and that with pounding, it is obvious that the pounding causes increase in the relative displacement in separating direction. The maximum relative displacement with pounding is equal to 0.85 m, resulting in the normalized relative displacement of 2.07. It is seen that the exchange of velocities occurs at the moment of pounding. It is worthy to point out that the exchange of velocities leads the increase of the relative displacement.

5. ANALYTICAL RESULTS

If the maximum relative displacement for a specific gap ratio is evaluated for various combinations of T_1 and T_2, representation can be done in form of the response spectrum in which X, Y, and Z axes represent T_1, T_2, and the maximum relative displacement. The representation is proposed to be called a *relative displacement response spectrum* (for $r_G \geq 1.0$) or a *relative displacement response spectrum with pounding effect* (for $r_G < 1.0$). The relative displacement response spectrum of the JMA Kobe record is shown in Fig. 4. The relative displacement response spectrum with pounding effect of the JMA Kobe record for $r_G = 0.5$ and $r_M = 1$ is shown in Fig. 5. In the same manner, if the normalized relative displacement for a specific gap ratio is evaluated for various combinations of T_1 and T_2, representation can be done in form of the response spectrum in which X, Y, and Z axes represent T_1, T_2, and N_{RD}, respectively. The representation is proposed to call as a *normalized relative displacement response spectrum.* The normalized relative displacement response spectrum of the JMA Kobe record for $r_G = 0.5$ and $r_M = 1$ is shown in Fig. 6.

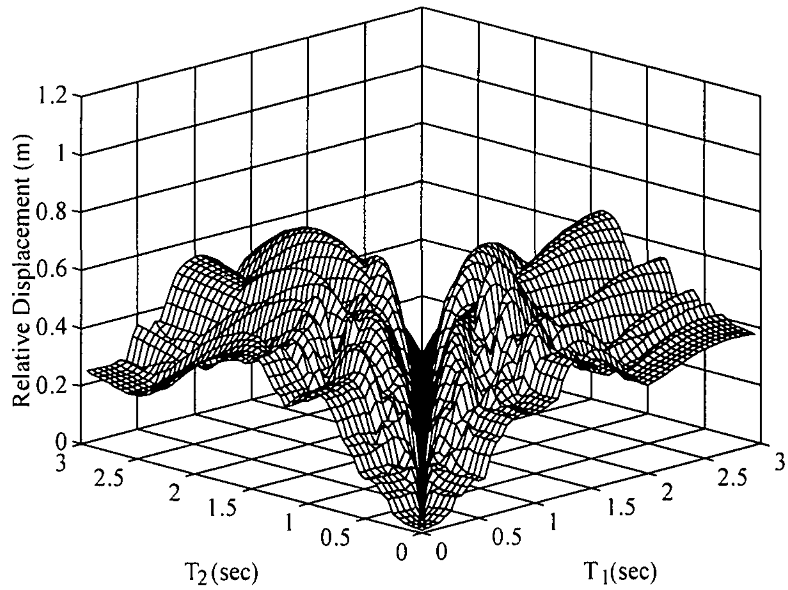


Fig. 4 Relative displacement response spectrum of the JMA Kobe record

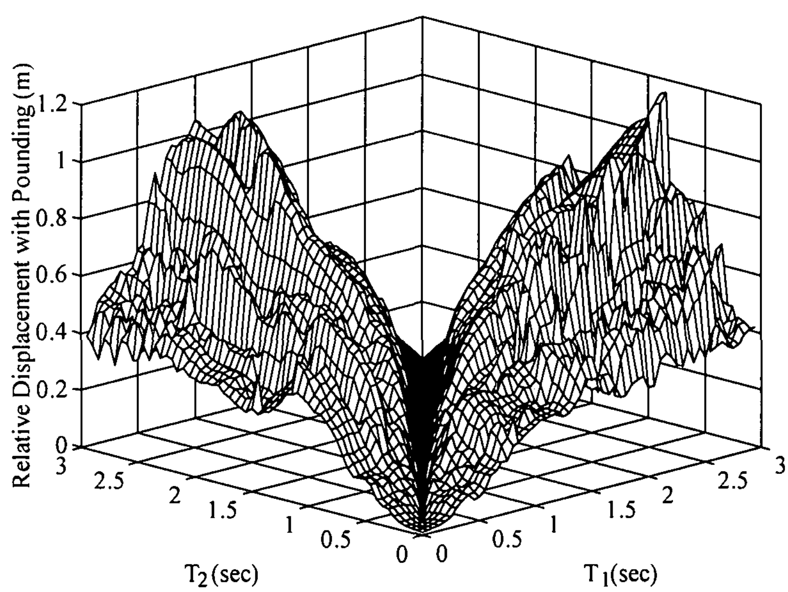


Fig. 5 Relative displacement response spectrum with pounding effect of the JMA Kobe record ($r_G = 0.5$)

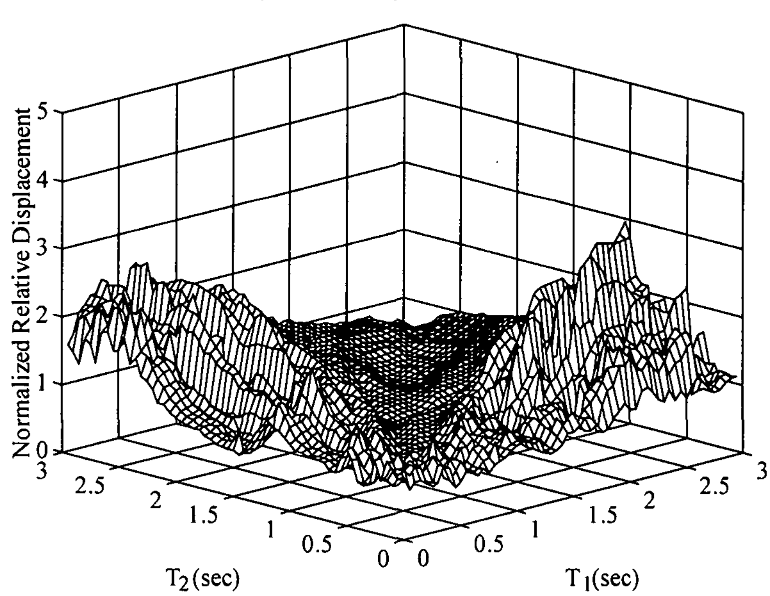


Fig. 6 Normalized relative displacement response spectrum of the JMA Kobe record ($r_G = 0.5$)

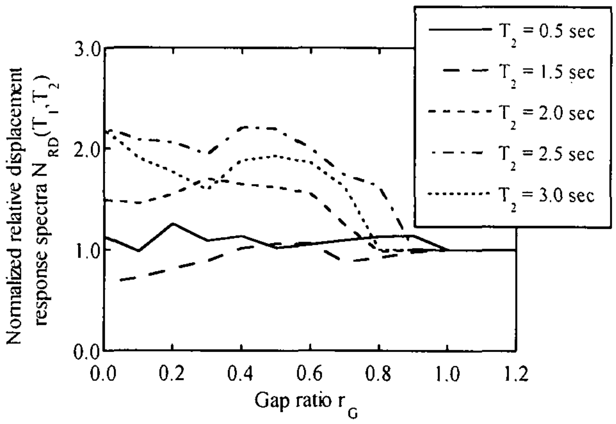


Fig. 7 Normalized relative displacement vs. gap ratio

Fig. 7 shows normalized relative displacement response spectra versus gap ratio for T_1 = 1.0 sec and various T_2. $N_{RD}(T_1,T_2)$ is equal to 1.0 for $r_G \geq 1.0$. It is because there is no pounding between Systems 1 and 2. For $r_G < 1.0$, $N_{RD}(T_1,T_2)$ becomes larger or smaller than 1.0, indicating how much the pounding amplifies or deamplifies the relative displacement. It can be seen that the increase or decrease of $N_{RD}(T_1,T_2)$ occurs at a certain combination of T_1 and T_2. For T_1 = 1.0 sec and T_2 = 2.0 sec, as r_G decreases $N_{RD}(T_1,T_2)$ increases up to about 1.5 at r_G = 0.6, then maintains with slight change of the value.

6. FORMULATION OF NORMALIZED RELATIVE DISPLACEMENT RESPONSE SPECTRA

The effects of ground motion characteristic, gap ratio, mass ratio were investigated. It is found that the effects of earthquake magnitude and epicentral distance are not significant. In addition, it is obvious that $N_{RD}(T_1,T_2)$ tends to increase as r_G decreases and then maintain as r_G becomes less than about 0.6. Consequently, $N_{RD}(T_1,T_2)$ is averaged over all ground motion records and over r_G = 0-0.6. Fig. 8 shows the mean value of $N_{RD}(T_1,T_2)$ for r_M = 1, 5, and 10. For r_M = 1, $N_{RD}(T_1,T_2)$ tends to increase as the difference between T_1 and T_2 increases and reaches the maximum of about 2.0 at T_1 =3.0 sec and T_2 = 0.1 sec. As the mass ratio increases, $N_{RD}(T_1,T_2)$ for $T_1 > T_2$ increases whereas $N_{RD}(T_1,T_2)$ for $T_1 < T_2$ decreases. However, $N_{RD}(T_1,T_2)$ at short T_1 or T_2 is not significantly affected by the mass ratio. The maximum value of $N_{RD}(T_1,T_2)$ is about 3.5 for r_M = 5 and about 4.0 for r_M = 10 at T_1 =3.0 sec and T_2 = 0.5 sec. It is obvious for the case of r_M = 1 that $N_{RD}(T_1,T_2)$ is almost symmetry along the line $T_1 = T_2$. The effect of direction of ground motions becomes less significant after averaging $N_{RD}(T_1,T_2)$ over all ground motions. Consequently, the representation of $N_{RD}(T_1,T_2)$ can be made only for $T_1 > T_2$ or $T_1 < T_2$. For example, $N_{RD}(T_1{=}1.0,T_2{=}2.0)$ for r_M = 5 is corresponding to $N_{RD}(T_1{=}2.0,T_2{=}1.0)$ for r_M = 1/5. $N_{RD}(T_1,T_2)$ will be presented hereafter only for $T_1>T_2$.

From Fig. 8, it is seen that at some combinations of T_1 and T_2, the value of $N_{RD}(T_1,T_2)$ is less than 1.0. It means that the effect of pounding on relative displacement is not significant for such combinations of natural periods. Contour lines of $N_{RD}(T_1,T_2)$ = 1.0 for various mass ratios is shown in Fig. 9. The zone under a particular contour line shows $N_{RD}(T_1,T_2) > 1.0$. It is seen that the larger the mass ratio, the larger the zone of $N_{RD}(T_1,T_2)$ > 1.0. The contour lines of $N_{RD}(T_1,T_2)$ = 1.0 are quite linear. The regression analysis was conducted to determine the estimates of the contour lines as:

$$\frac{T_2}{T_1} = 0.62 + 0.15\log_{10} r_M \qquad (4)$$

When T_2/T_1 is less than $0.62+0.15\log_{10}r_M$, the computation of $N_{RD}(T_1,T_2)$ is necessary since the pounding effect is significant. But when T_2/T_1 is equal to or larger than $0.62+0.15\log_{10} r_M$, the effect of pounding on relative displacement is not significant and $N_{RD}(T_1,T_2)$ is considered equal to 1.0.

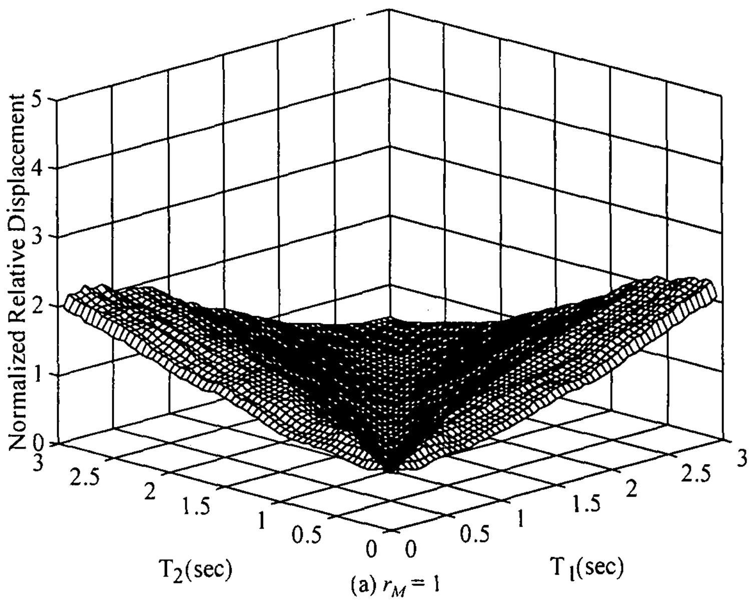
By the regression analysis, the formulation of the normalized relative displacement response spectra can be expressed as:

$$N_{RD}(T_1,T_2) = C_G\left[C_M\left(2.39-2.09\frac{T_2}{T_1}\right)-1\right]\frac{T_1}{3}+1 \qquad (5)$$

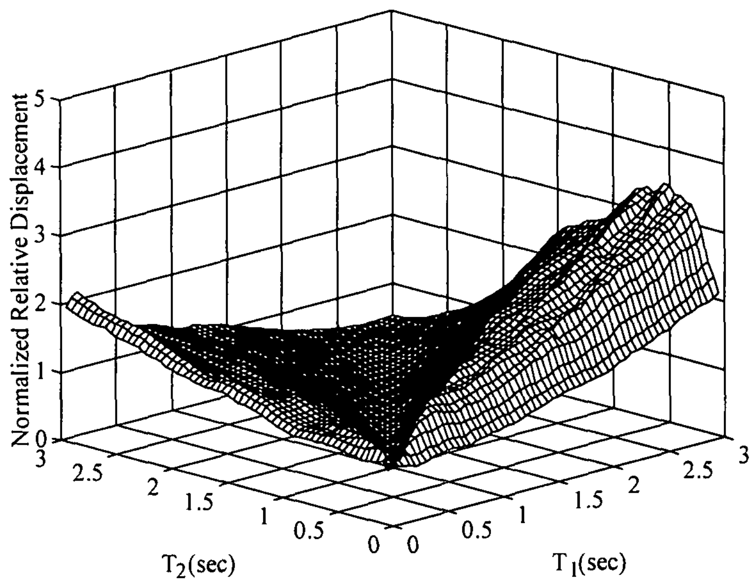
where C_G is a correction factor for the gap ratio evaluated from:

$$C_G = \begin{cases} 1.0 & ; \quad 0 \leq r_G < 0.6 \\ 1.0-5.3(r_G-0.6)^{1.82} & ; \quad 0.6 \leq r_G < 1.0 \\ 0 & ; \quad r_G \geq 1.0 \end{cases} \qquad (6)$$

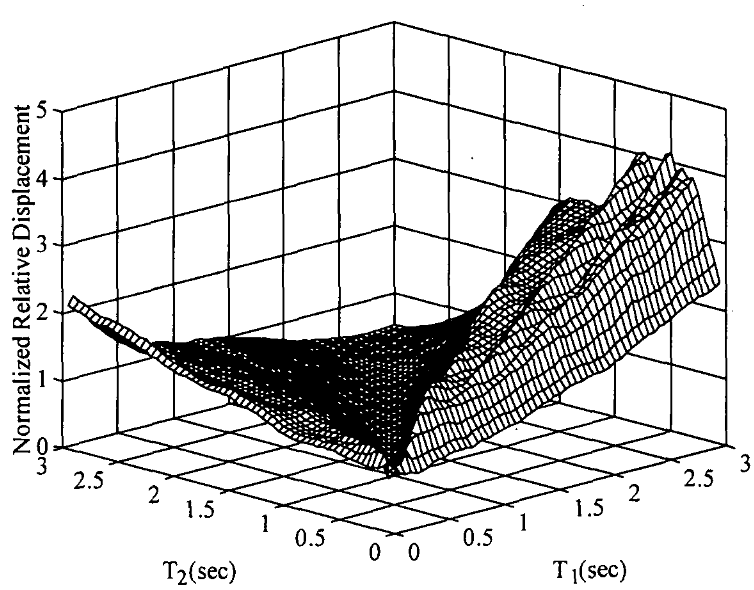
and C_M is a correction factor for the mass ratio which is determined from:



(a) $r_M = 1$



(b) $r_M = 5$



(c) $r_M = 10$

Fig. 8 Mean values of normalized relative displacement response spectra (r_G = 0 - 0.6)

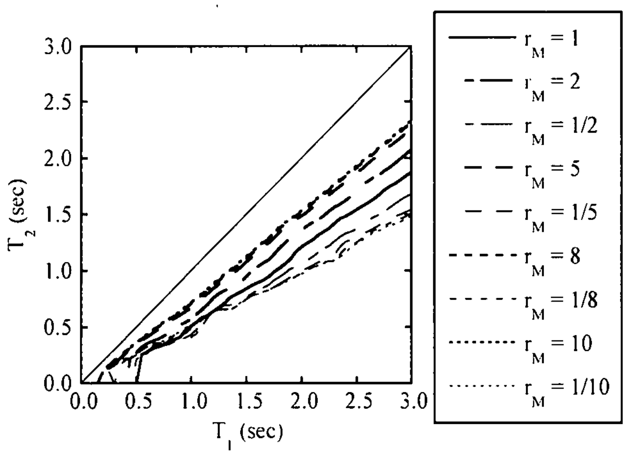


Fig. 9 Contour lines of $N_{RD}(T_1,T_2) = 1.0$

$$C_M = \begin{cases} 1+6(C_{M1}-1)\dfrac{T_2}{T_1} & ; \quad 0 \le \dfrac{3T_2}{T_1} < 0.5 \\ C_{M1}+(C_{M2}-C_{M1})\left(\dfrac{3T_2}{T_1}-0.5\right) & ; \quad 0.5 \le \dfrac{3T_2}{T_1} < 1.5 \\ 1+\dfrac{(C_{M2}-1)}{2.25}\left(\dfrac{3T_2}{T_1}-3\right)^2 & ; \quad 1.5 \le \dfrac{3T_2}{T_1} < 3.0 \end{cases} \tag{7}$$

$$C_{M1} = \frac{2}{2-\log_{10} r_M} \tag{8}$$

$$C_{M2} = \frac{2}{2-\log_{10} r_M - 0.17(\log_{10} r_M)^2} \tag{9}$$

Fig. 10 illustrates the normalized relative displacement response spectra $N_{RD}(T_1,T_2)$ for r_G = 0-0.6 and r_M = 1, 5, and 10 which are determined from Eqs. (4)-(9). Comparing Fig. 10 with Fig. 8, it is seen that the formulation can give a good estimate of the normalized relative displacement response spectra.

7. CONCLUSIONS

To evaluate the maximum relative displacement with pounding effect between two bridge segments with different natural periods, the relative displacement response spectra with pounding effect were proposed. The effect of pounding on the maximum relative displacement was observed for various combinations of natural periods and gaps. Based on analytical results, it can be concluded that:

1) The pounding leads to the amplification of relative displacement between two bridge segments connected at a joint. Consequently, to withstand the effect of pounding, a longer seat length should be provided to support a deck. And the value of the adequate seat length can be realized by the application of the relative displacement response spectra with pounding effect.

2) The amplification of relative displacement tends to decrease as the gap between two systems increases.

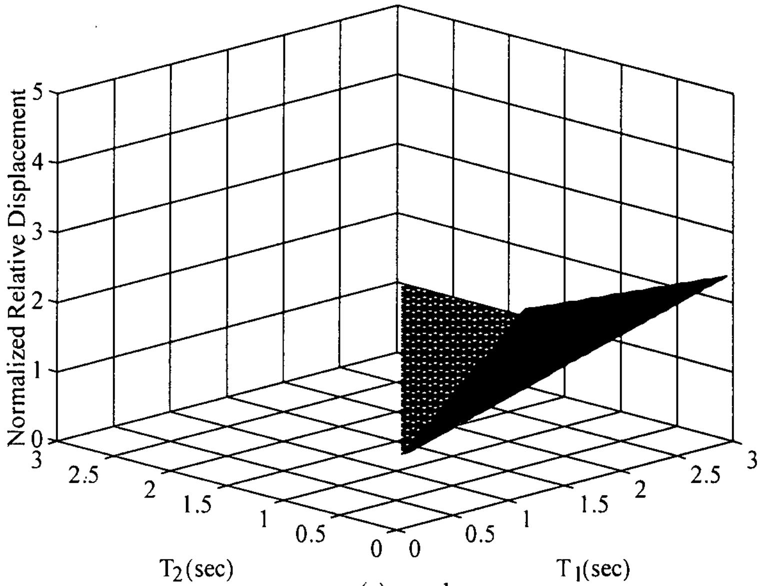
3) The formulation of the normalized relative displacement response spectra is proposed for the design of seat length and shows good agreement with the computed values.

REFERENCES

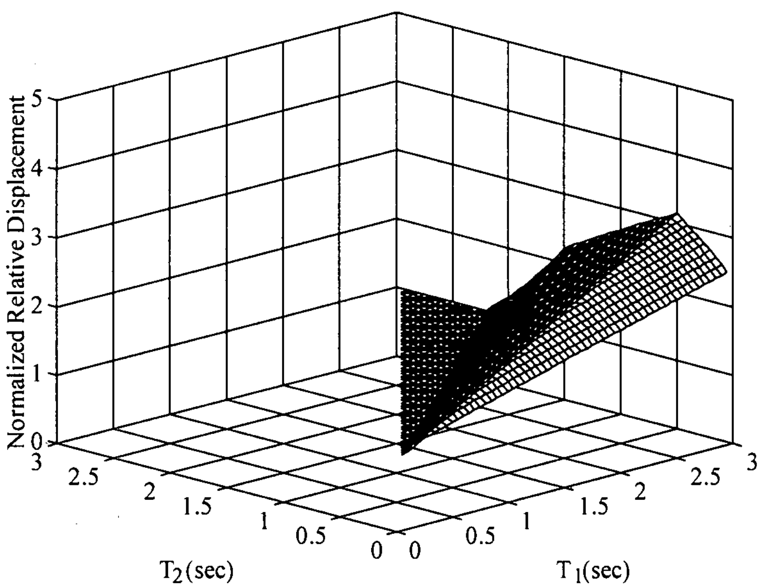
1) Kawashima, K. and Unjoh, S.: Impact of Hanshin/Awaji earthquake on seismic design and seismic retrofitting of highway bridges, *Structural Eng./Earthquake Eng., JSCE*, 13(2), pp. 211s-240s, 1996.

2) Goldsmith, W.: *Impact*, Edward Arnold, London, 1960.

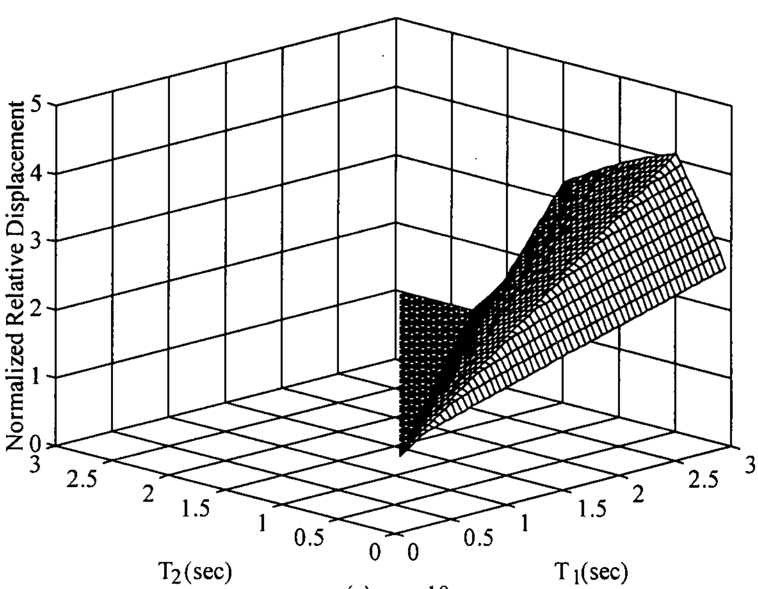
3) Kawashima, K. and Sato, T.: Relative displacement response spectrum and its application, *Proc. 11WCEE*, 1103, Acapulco, Mexico, 1996.



(a) $r_M = 1$



(b) $r_M = 5$



(c) $r_M = 10$

Fig. 10 Normalized relative displacement response spectra ($r_G = 0$ - 0.6) obtained from the formulation