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ESTIMATE AND CONTROL OF RELATIVE DISPLACEMENT BETWEEN ADJACENT STRUCTURES

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ABSTRACT

Peak relative displacement between adjacent inelastic structures can be estimated by so-called inelastic "Spectral Difference (SPD) Method" without conducting time history analysis. Extension of the inelastic SPD method is explained by including the effects of time lag between the support motions as well as those of high viscous damping. The method can be directly applied to estimate the minimum seismic gap to avoid pounding of adjacent buildings. Significant effect of supplemental viscous damping on reduction of the peak relative displacement is parametrically explained by using SPD method. High viscous damping does not only reduce buildings' peak displacements but also promotes their in-phase motion. Likely minimum seismic gap magnitudes are also discussed for conventional buildings pair as well as highly damped buildings pair.

KEYWORDS

Pounding; Building Seismic Gap; Relative Displacement; Spectral Difference (SPD) Method; Time Lag; Effective Period; Effective Damping; Supplemental Viscous Damping.

INTRODUCTION

Pounding of adjacent structures occurs due to their different dynamic characteristics as well as insufficient separation distance between them. Pounding made the buildings' damage worse, and/or caused their total collapse. The 1985 Mexico City earthquake has revealed the fact that pounding was present in over 40% of 330 collapsed or severely damaged buildings, and in 15% of all cases it led to collapse (Rosenblueth *et al.* 1986, Bertero 1985). A survey of pounding incidents in San Francisco Bay area during 1989 Loma Prieta earthquake showed significant pounding cases at sites over 90 km from the epicenter, thus indicating the possible catastrophic damage that may occur during future earthquakes having closer epicenters (Kasai and Maison 1990).

In US, guidelines for required building separation to avoid pounding appeared for the first time in the 1988 Uniform Building Code (UBC). The 1991 National Earthquake Hazards Reduction Program (NEHRP) code also recommends the separation similar to that required by the UBC. The separation specified by these codes are "large" and controversial from both technical (difficulty in using expansion joints) and economical (loss of land usage) views.

Pursuant to this, the writers have been conducting research on the likely minimum building separation considering a variety of earthquakes. As a part of the research, a spectrum approach to estimate the separation, so-called "Spectral Difference (SPD) Method" was developed. The method is more attractive than time history analysis method since: it can explicitly describe the effects of building dynamic properties and ground motions; it is simple to use and requires less computational work, and; it can be in a form readily applicable to the design code.

The SPD method is based on random vibration theory, and it originally considered elastic adjacent buildings by accounting for their periods, viscous damping ratios, and heights (Jeng *et al.* 1992). It was also modified to consider inelastic buildings, by accounting for their hysteresis types and ductility demand (Kasai *et al.* 1996). The method was also modified to consider elastic buildings subjected to seismic travelling wave causing time lag of excitations between the their supports (Jeng and Kasai 1996).

This paper first explains extension of the above work. It discusses further modification of SPD method to consider the case where inelastic structures are subjected to traveling wave, as well as the case where the inelastic structures are retrofitted with supplemental viscous damping device, potentially developing both hysteretic damping and large viscous damping. The SPD method is then used to show significant benefit of supplemental viscous damping in reducing the relative motion as well as required separation to avoid pounding of the buildings. Accuracy of the SPD method is demonstrated by comparing its prediction with dynamic time history analysis results for various generic building pairs. Brief discussion is given regarding likely minimum separations required to avoid pounding for conventional buildings pair as well as highly damped buildings pair. Comments regarding the U.S. code separation requirements are also given.

EXTENDED SPECTRAL DIFFERENCE METHOD

Theory. Consider the relative displacement problem for remotely spaced supports, having the same earthquake excitation with the time lag of $\tau = l/c$ (Fig.(1b)). Where l = distance between the two supports, and c = wave velocity. It is assumed that traveling seismic waves have no decay and distortion between two nearby locations along its path. The difference of total relative displacement $u_{REL,tot}(t)$ of Structures A and B is expressed as:

$$u_{REL,tot}(t) = u_{REL}(t) - u_{REL,g}(t) \approx u_{REL}(t) \quad (1)$$

where, $u_{REL}(t) = u_A(t) - u_B(t)$ is structural relative displacement between two structures and $u_{REL,g}(t) = u_{A,g}(t) - u_{B,g}(t) = u_{A,g}(t) - u_{A,g}(t-\tau)$ is relative displacement between the supports of the structures. Kasai *et al.* (1992) studied response records of an existing bridge subjected to past earthquakes, and showed that the $u_{REL,g}(t)$ tends to be very small compared to $u_{REL}(t)$, as reflected in Eq. 1. The bridge had a short vibration period of only 0.3 sec. Thus, for structures having moderate to longer periods as well as larger $u_{REL}(t)$, the approximation in Eq. 1 would be appropriate. Moreover, for closely spaced structures, such as buildings (Fig. 1(a)), the time lag τ is small, implying $u_{REL,g}(t) \approx 0$ and thus $u_{REL,tot}(t) = u_{REL}(t)$.

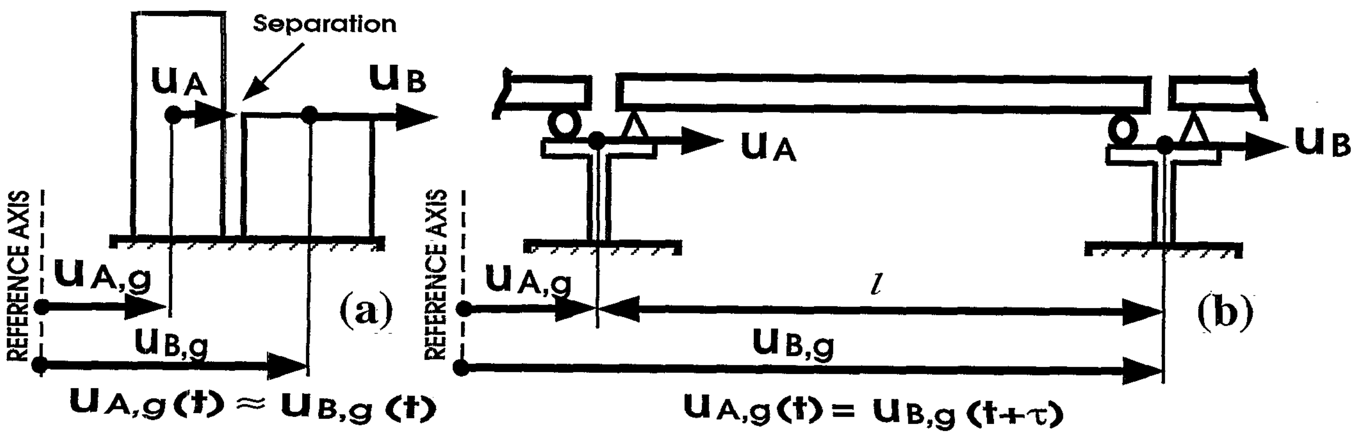

Fig. 1. Relative Displacement Problems

Using the fundamental modes as approximations for the MDOF response of the adjacent buildings, the maximum $|u_{REL}(t)|$, namely u_{REL} is estimated by the SPD method as follows:

$$u_{REL}(SPD) = \sqrt{u_A^2 + u_B^2 - 2\,\rho_{AB}\,u_A\,u_B} \tag{2}$$

where, u_A and u_B = peak displacements at potential pounding location of structures A and B (see Figs. 1(a) and 1(b)), respectively, and ρ_{AB} is the cross correlation-coefficient. Eq. 2 implies that u_{REL} is smaller for higher positive value of ρ_{AB}, and is smaller for negative value of ρ_{AB}. The ρ_{AB} reflects the vibration phase between the two structures considering the effect of time-lagged excitation, and was obtained by Jeng and Kasai (1996) for elastic adjacent structures in terms of their vibration periods and damping ratios. In the present study, such ρ_{AB} will be used for inelastic structures by using the effective periods and effective damping (Kasai *et al.* 1996) as follows:

$$\rho_{AB} = \frac{16\pi^2 T_A^* \sqrt{\xi_A^* \xi_B^*}\;\left[A_1 \cos\left(\tau/T_A^*/\sqrt{1-\xi_A^{*2}}\right) - A_2 \sin\left(\tau/T_A^*/\sqrt{1-\xi_A^{*2}}\right)\right]\; e^{-\xi_A^* 2\pi\tau/T_A^*}}{K_{AB}\sqrt{(T_A^* T_B^*)^3 (1-\xi_A^{*2})}} \quad (\tau \geq 0) \tag{3}$$

$$A_1 = 8\pi^2 \sqrt{1-\xi_A^{*2}}\,\{\xi_A^* T_B^* + \xi_B^* T_A^*\}\,/\{T_A^{*2}\,T_B^*\}$$

$$A_2 = 4\pi^2\,\{(1-2\xi_A^{*2})T_B^{*2} - T_A^{*2} - 2\,\xi_A^*\xi_B^*\,T_A^* T_B^*\}\,/\{T_A^{*2}\,T_B^{*2}\}$$

$$K_{AB} = 16\pi^4\{(T_B^{*2}-T_A^{*2})^2 + 4\xi_A^*\xi_B^*\,T_A^*\,T_B^*(T_A^{*2}+T_B^{*2}) + 4(\xi_A^{*2}+\xi_B^{*2})(T_A^{*2}\,T_B^{*2})\}\,/\,\{T_A^{*4}\,T_B^{*4}\}$$

where, T_A^* and T_B^* = inelastic effective vibration period, ξ_A^* and ξ_B^* = inelastic effective damping ratio of structures A and B, respectively. $\tau > 0$ implies that the structure A is excited before the structures B. The effective period T^*, and effective damping, ξ^* for bilinear and degrading system are obtained through extensive numerical simulations and they are expressed as follows (Kasai and Jagiasi 1996):

$$T^* = T\{\,1 + 0.09(\mu-1)\}\ \text{(Bilinear), or}\qquad T\{\,1 + 0.18(\mu-1)\}\ \text{(Degrading)}\qquad (\mu\geq 1) \tag{4}$$

$$\xi^* = \xi + 0.084(\mu-1)^{1.3}\ \text{(Bilinear), or}\qquad \xi + 0.16(\mu-1)^{0.9}\ \text{(Degrading)}\qquad (\mu\geq 1) \tag{5}$$

where, T = initial elastic vibration period, ξ = initial viscous damping ratio and μ = maximum ductility demand of the structure. Eqs. 4 and 5 were obtained originally by considering the initial damping ratio ξ = 0.03, such that they reflect the effect of high hysteresis damping combined with small viscous damping. However, the present study proposes the use of these equation to treat the case where both high hysteresis damping and high viscous damping develop simultaneously. Later sections will describe reasonableness of such modification.

Trend of Cross Correlation Coefficient. Fig. 2 plots ρ_{AB} vs. T_B^*/T_A^* for $\xi_A^* = \xi_B^* = 0.05$ and 0.20, respectively. Five cases of τ/T_A^* = 0, 1/8, 1/4, 3/8, and 1/2 are plotted.
The following trends are noted:

(1) Under $T_B^*/T_A^* = 1$ and $\tau/T_A^* = 0$, the ρ_{AB} becomes the most positive. This is because the structures having the same effective vibration periods tend to vibrate in-phase, especially when their support motions are identical. Whereas, ρ_{AB} decreases when τ/T_A^* increases, since the differential support motion leads to out-of-phase motion of the structures.

(2) Under $T_B^*/T_A^* \neq 1$ and $\tau/T_A^* = 0$, the ρ_{AB} depends on T_B^*/T_A^* and ξ_A^* (= ξ_B^*). But the effect of T_B^*/T_A^* becomes much less under the higher effective damping case (Fig. 2(b)): Under the high damping, the structures' free vibration is suppressed, and their motions follow closely the support motion. Thus, the vibration period governing the free vibration part of the phase motion becomes less important. High effective damping and identical support motions lead to significant in-phase motion of the structures over a wide range of their effective vibration periods.

(3) Under $T_B^*/T_A^* \neq 1$ and $\tau/T_A^* \neq 0$, ρ_{AB} becomes sensitive to τ/T_A^*. When τ/T_A^* increases, the ρ_{AB} becomes anti-symmetric with respect to $T_B^*/T_A^* = 1.0$, indicating which of the two structures is excited first becomes important. Significant time lag can cause considerable out-of-phase motion of the structures even if they have the similar effective vibration periods and/or high effective damping ratios. The ρ_{AB} varies between -1 and 1, which is not predicted by the other spectrum methods such as square-of-sum-of-squares (SRSS) method ($u_{REL} = \sqrt{u_A^2+u_B^2}$) and absolute sum (ABS) method ($u_{REL} = u_A+u_B$).

However, if the τ/T_A^* is less than about 1/16, the effect of time lag can be ignored. Thus, in most adjacent building cases, τ/T_A^* may be set to zero in Eq. 3.

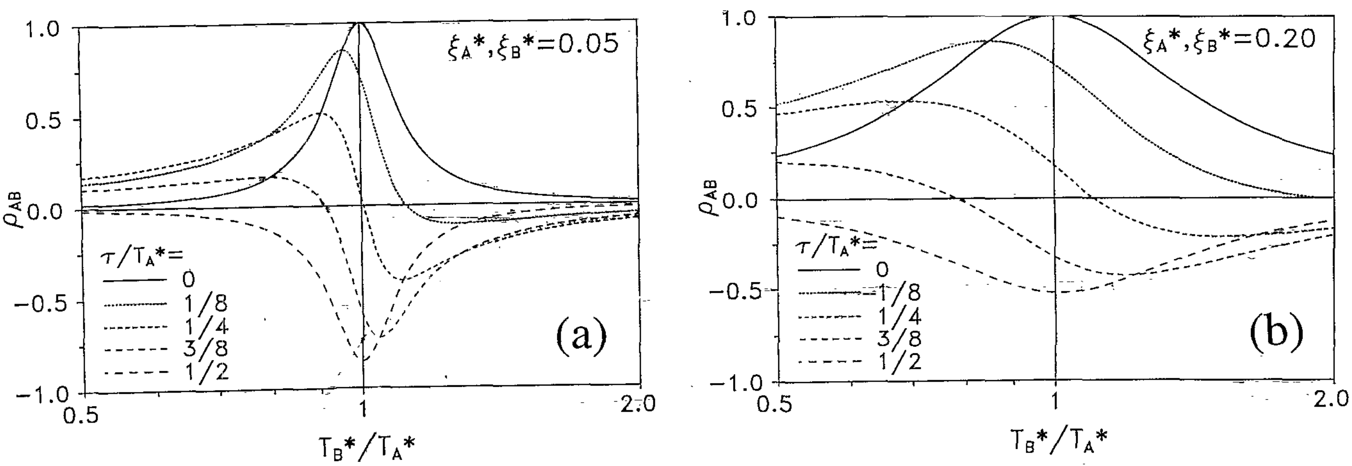

Fig. 2. Variation of Cross Correlation Coefficient for Various Effective Damping Ratios, Vibration Periods, and Time Lags of Support Motions.

Accuracy of Extended SPD Method. Accuracy of the SPD method is demonstrated via extensive numerical simulations. Fifteen different earthquakes are considered, out of which nine are the artificial earthquakes whose spectra are comparable with those given by Structural Engineers Association of California (SEAOC 1990) for different soil types. Remaining six earthquakes are: 1940 El Centro earthquake (0.348g), 1971 Pacoima Dam earthquake (1.170g), 1952 Taft earthquake (0.179g), 1966 Cholame Shandon earthquake (0.434g), 1949 Olympia earthquake (0.280g), and 1965 Olympia earthquake (0.198g). These earthquakes were applied in two directions. Following are the parameters used for the study: 3 different T_A's (0.5, 1.0, and 2.0 sec.), 11 different τ/T_A's (0 to 0.25 with an 0.05 interval, and 0.5, 0.75, 1, 1.5, and 2), 49 different T_B/T_A's (ranging from 0.125 to 8.0 with an equal logarithmic interval), 6 different ductilities (1, 1.5, 2, 3, 4.5, and 6) and 2 hysteresis types (bilinear and degrading). The initial viscous damping ratio ξ_A and ξ_B are set to 0.03. Only a few of these cases are presented in this paper.

Fig. 3 plots the case of $\tau/T_A = 0$. It compares the results from time history analyses with those from the three spectrum methods, SPD, SRSS, and ABS methods. The relationship of T_B^*/T_A^* vs. normalized u'_{REL} ($= u_{REL}/(u_A+u_B)$) of adjacent structures having degrading hysteresis is plotted for $\mu_A = \mu_B = 3$, and $\mu_A = 3$ and $\mu_B = 6$, respectively. Time history analysis result is the average of peak relative displacements due to two directions of earthquake. The u_A and u_B obtained from the time history analysis are used in the three spectrum methods. As seen from Fig. 3 the SPD method agrees closely with the time history results, whereas SRSS method is very conservative especially for $0.7 < T_B^*/T_A^* < 1.4$. The ABS method (i.e., $u'_{REL} = 1$) is overly conservative for very wide range of T_B^*/T_A^* .

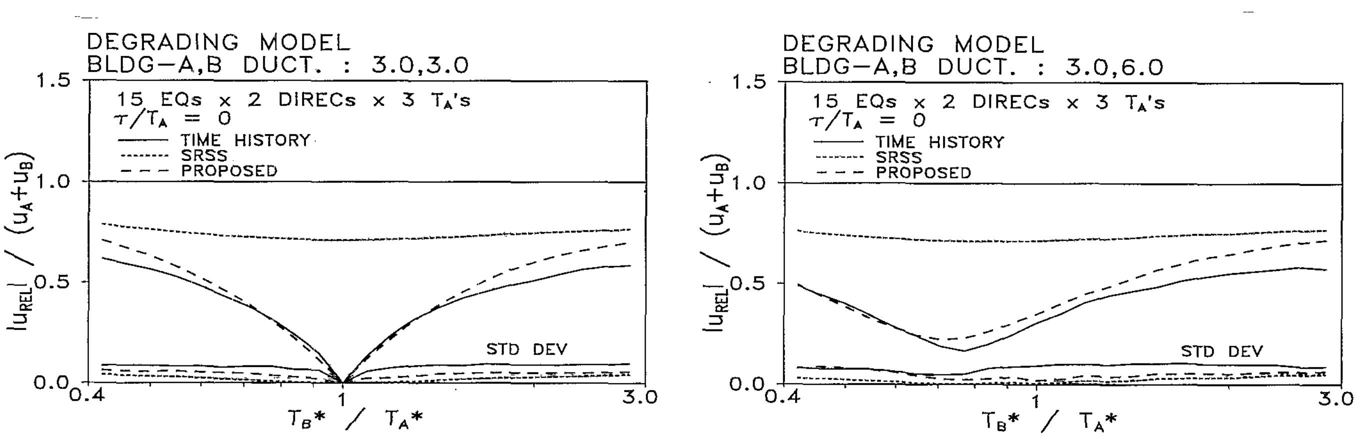

Fig. 3. Normalized Peak Relative Displacement for Zero Time Lag Case.

Figs. 4 and 5 plot the cases of $\tau/T_A = 0.1$ and 0.25, respectively. In contrast to the case of $\tau/T_A = 0$ (Fig. 3), $u'_{REL} \neq 0$ results even when $T_B^*/T_A^* = 1$ and $\mu_A = \mu_B = 3$ (i.e., $\xi_A^* = \xi_B^*$). The u'_{REL} for $\tau/T_A = 0.1$ is somewhat similar to that for zero time lag. The u'_{REL} for $\tau/T_A = 0.25$ is larger than for $\tau/T_A = 0$ for most of the T_B^*/T_A^* values, except for the relatively small values of T_B^*/T_A^* that provides higher ρ_{AB} as shown earlier in Fig. 2(b). The proposed SPD method agrees very closely with time history result, and performs much better than both SRSS method and ABS method for the time lags considered. This trend holds for various other case studies conducted by the writers. In Figs. 3 to 5, the standard deviation (STD DEV) of u'_{REL} is generally lower than 0.1, which implies that u'_{REL} is insensitive to type of the earthquake.

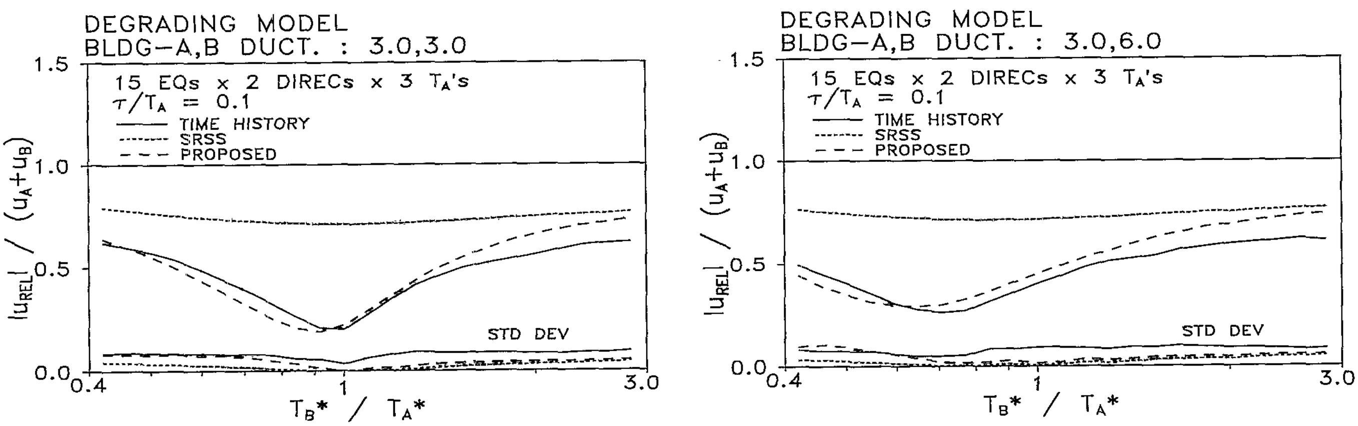

Fig. 4. Normalized Peak Relative Displacement for Non-Zero Time Lag Case ($\tau/T_A = 0.1$).

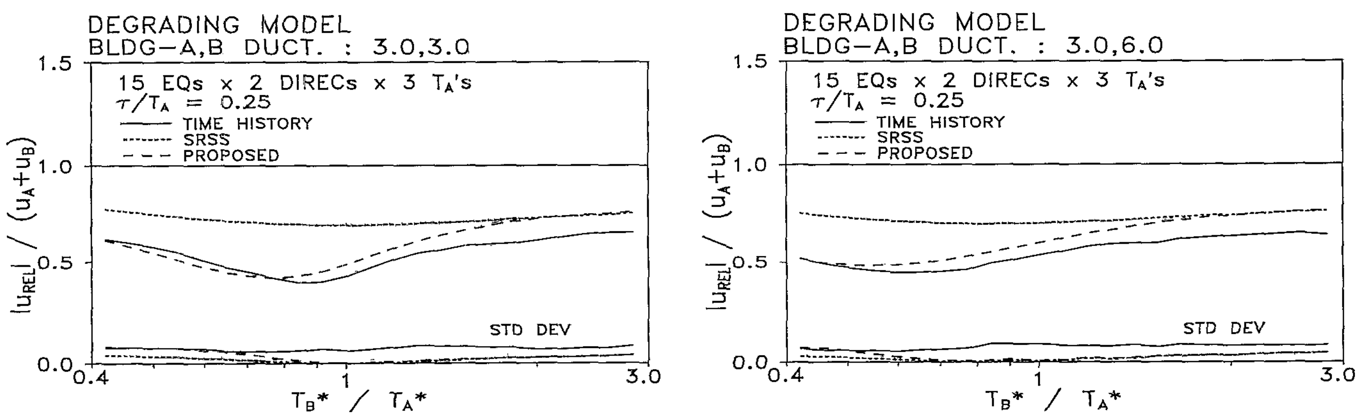

Fig. 5. Normalized Peak Relative Displacement for Non-Zero Time Lag Case ($\tau/T_A = 0.25$).

ESTIMATE OF PEAK RELATIVE DISPLACEMENTS

Practical Implementation of SPD Method. The extended SPD method explained above can be used to calculate the peak relative displacement of adjacent structures for a given earthquake design spectrum. As explained earlier, the effect of time lag can be ignored for calculation of relative displacement of adjacent buildings, but it must be included for the structures having remotely spaced supports. The simplified application of SPD method for estimating u_{REL} of either elastic or inelastic adjacent structures is summarized as follows:

(1) Estimate displacements u_A and u_B at potential pounding location, from linear earthquake spectrum.
(2) Estimate yield displacements $u_{A,y}$ and $u_{B,y}$ at the significant change of structure lateral stiffness.
(3) Obtain ductility demands $\mu_A = u_A/u_{A,y}$ and $\mu_B = u_B/u_{B,y}$ (μ_A and $\mu_B \geq 1$).
(4) Obtain effective periods T_A^* and T_B^* (Eq. 4) and effective damping ratios ξ_A^* and ξ_B^* (Eq. 5).
(5) Obtain cross correlation coefficient ρ_{AB} using Eq. 3.
(6) Obtain peak relative displacement u_{REL}, substituting u_A, u_B, and ρ_{AB} into Eq. 2.

Note that in step (1) the inelastic displacements u_A and u_B are estimated using the elastic spectrum for each earthquake by assuming that they are equal to the maximum elastic displacements (Clough and Penzien 1994). This can cause some errors compared with the case where accurate inelastic displacements u_A and u_B are given (see the previous section), but it does have practical advantage from a view point of SPD method applications. Based on Wu and Hanson's study (1992), the above approach also assumes that the displacement reduction caused by viscous damping for elastic building is similar to that for inelastic building. Accuracy of this approximate approach will be discussed below.

Seismic Gap Required to Avoid Pounding. The magnitude of seismic gap between adjacent buildings is obtained. Many building pairs were studied, but only two building pairs are discussed herein. Adjacent buildings pairs are: (1) 15 story and 10 story concrete moment frames, and (2) 10 story steel and 10 story concrete moment frames. The heights of 15 and 10 story buildings are 180 and 120 feet, respectively. The buildings are assumed to have yield strength $V_y = \Omega V = \Omega C_s W$, where V = required NEHRP seismic design base shear, Ω = overstrength factor, C_s = seismic design coefficient, and W = total weight of the building. In determining C_s, the NEHRP coefficients $A_v = A_a = 0.4$, S = 1.2, and R = 8 are used. The buildings' approximate period T_a is estimated using NEHRP recommendations based on their heights. Overstrength factor Ω of 1.67 is assumed for all building cases. Each pair of adjacent buildings is assumed to have equal viscous damping ratio of either 5% or 20%. The 20% damping case reflects the supplemental damping retrofit for the adjacent buildings to mitigate pounding or reduce the required separation gap. Six earthquakes are used. The earthquakes are the same as those used in the previous section except that 2 times Taft earthquake (0.35 g), instead of Pacoima Dam earthquake, is considered.

Assuming straight line deformed shape of the building, the pounding level maximum displacements are $u_A = 1.5\, S_{d,A}\, H_B/H_A$ and $u_B = 1.5\, S_{d,B}$. Where $S_{d,A}$ and $S_{d,B}$ are the elastic spectral displacements of structures A and B under the given viscous damping ratio, and H_A and H_B are building A and B heights ($H_B/H_A \leq 1.0$), respectively. Based on these, required gap magnitudes are estimated by using SPD method (see the above steps) and SRSS method. The gap required by NEHRP is based on ABS method, i.e., $u_{REL}(NEH) = u_A + u_B$. Note that u_A and u_B are obtained by using the NEHRP design spectrum, and $u_A = 1.5\, D_\xi C_d C_s g(T_{a,A}/2\pi)^2\, H_B/H_A$ and $u_B = 1.5\, D_\xi C_d C_s g(T_{a,B}/2\pi)^2$. The C_d is the displacement amplification factor and it is 5.5 for moment frames. The D_ξ is NEHRP damping reduction factor (1994), and it is 1.0 and 0.64 for 5% damping case and 20% damping case, respectively.

Fig. 6 plots the required separation averaged over six earthquakes for the above two building pairs. In the 5% damping case the buildings yielded under all the earthquakes used, whereas in the 20% damping case yielding occurred at about half of the earthquakes used. Maximum displacement of the building estimated by using NEHRP C_d factor is about 1.5 times the average of the displacements obtained by using the six earthquakes. In contrast, the seismic gap required by NEHRP is about 5 to 7 times the average of time history results under 5% damping, and it is 8 to 9 times under 20% damping. The gap estimated by SRSS method is 2 to 3 times the time history results under 5% damping, and it is about 3 times under 20% damping. The SPD method gives very reasonable estimate for the seismic gap and matches well with the time history analysis results.

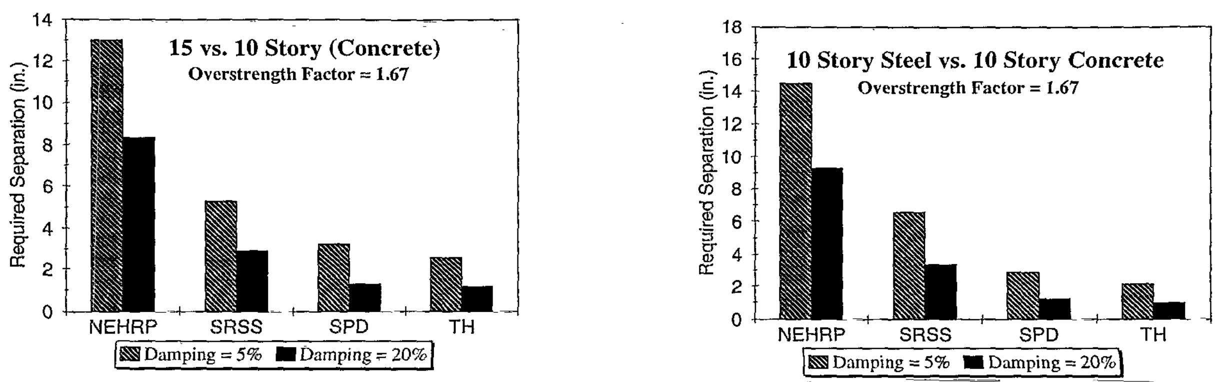

Fig. 6. Various Estimates for Required Seismic Gap Magnitudes.

The SRSS method is conservative due to its inability to consider the in-phase motion that is promoted by either hysteresis damping caused by yielding of the buildings as well as the supplemental viscous damping provided for pounding mitigation. It should be noted that this trend becomes more prominent in the following situations: larger hysteresis damping develops due to larger earthquake or smaller building strength, and; larger supplemental viscous damping is provided to the buildings. Through the writers' additional study by using numerous building pairs, it is found that SRSS method becomes overly conservative and its estimated required gap can be even larger than required by NEHRP.

The writers have been seeking a simplified seismic gap requirement based on Fig. 6 as well as numerous case studies by varying building height, hysteresis type, strength, vibration period, and earthquake. Conservatively, the following gap may be considered under 5% damping ratio for many building pairs so far considered: (1) 0.007 times the total height of the lower of the adjacent buildings for pounding mitigation against the earthquake having half the intensity of the design basis earthquake, and (2) 0.01 times the total height against the design basis earthquake. The second requirement considers increase in hysteresis damping and consequently promoted in-phase motion under the larger earthquake. If a typical height of each story is 12 ft., the second requirement is equivalent to 1.44 inches per story, which is significantly smaller than 4 in. per story suggested elsewhere (FEMA 1988). As an alternative approach, the SPD method can be used including the effects of the various parameters discussed, which can result in even smaller gap requirement.

RELATIVE DISPLACEMENT CONTROL BY HIGH VISCOUS DAMPING

As demonstrated above, increased viscous damping in the building can lead to significant reduction of required building separation, due to reduction of their maximum displacements and promoted in-phase motion. This is parametrically demonstrated by applying the SPD method to an idealized earthquake spectrum having a constant velocity. For brevity, the buildings are assumed to respond elastically against the earthquake. Like the 1988 SEAOC design basis (i.e., major) earthquake spectrum for a stiff soil type, constant velocity of 25 in/sec is assumed under the 5% damping ratio. Accordingly, the spectral displacement S_d = 25 in/sec. x $T/2\pi$. Assuming straight line deformed shape of the building and following the above described steps, the following brief expression for $u_{REL}(SPD)$ is obtained:

$$u_{REL}(SPD) = u_A \sqrt{1 + \{(T_B H_A)/(T_A H_B)\}^2 - 2\rho_{AB}\{(T_B H_A)/(T_A H_B)\}} \quad (6)$$

The analysis is conducted for T_A = 1.0 sec. and for adjacent building damping ratios of 5, 10, 15, 20, and 30%. Since the spectra are derived using 5% damping ratio, damping reduction factors D_ξ given by NEHRP (1994) are used for higher damping cases. Four height ratio's, H_B/H_A, of 0.25, 0.5, 0.75 and 1 are considered. Fig. 7 plots the obtained required separation for some of the above described cases. It can be seen that high damping reduces the required separation effectively . This effect is the most significant when H_B/H_A and T_B/T_A are close to 1.0. For smaller H_B/H_A the reduction of u_{REL} due to higher damping is smaller. It is very interesting to note that regardless of adjacent structure height ratio and damping ratio, $u_{REL}(SPD)$ is nearly minimum for the T_B/T_A close to 1.0. As noted, in the 20% damping case the maximum displacement of the building may be reduced to 0.64 times that of 5% damping case. However, more significant reduction can occur for the required gap due to the promoted in-phase motion of the buildings (Fig. (2b)).

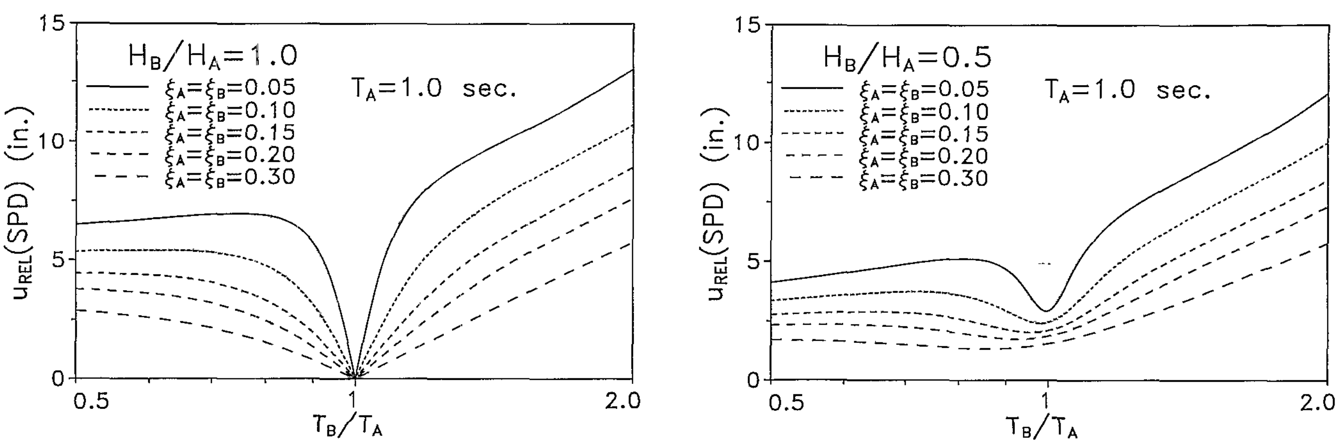

Fig. 7. Requires Seismic Gap Magnitudes between Buildings A and B for (a) Height Ratio = 1.0, and (b) Height Ratio = 0.5.

CONCLUSIONS

The conclusions are as follows:

(1) SPD method based on a response spectrum approach is accurate and is very suitable for the seismic practice compared to time history analysis. The SPD method appears to be accurate for the case where inelastic adjacent structures are subjected to time-lagged support excitations as well as they have high viscous damping ratio.

(2) SPD method is more accurate than other spectrum methods such as the absolute sum (ABS) method and square-root-of-sum-of-squares (SRSS) method. The prediction of SPD method agrees well with time history results. The seismic gap magnitude required by the U.S. code appears to be overly conservative.

(3) Effect of damping on the relative motion of adjacent structures is very significant, since damping does not only reduce the maximum displacement of the structures, but also promotes their in-phase motion. Hence, the use of dampers can be very effective in relative displacement problem such as pounding.

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