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The separation to avoid seismic pounding

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ABSTRACT: A method to estimate the likely minimum building separation necessary to preclude seismic pounding is presented. The method is based on random vibration theory. The accuracy is demonstrated by numerical experiments using 9 artificial and 6 actual earthquake records. The relation between the minimum separation, period, height, and damping are discussed. The effects of inelastic hysteretic building behavior are also discussed.

1 INTRODUCTION

1.1 Pounding Incidents

Investigations into past earthquake damage have shown that collisions between adjacent buildings during earthquakes have been one of the causes of severe structural damage. This collision, commonly called 'structural pounding' occurs during an earthquake when, due to their different dynamic characteristics, adjacent buildings vibrate out of phase and there is insufficient separation distance between them.

Many incidents of seismic pounding have been reported to date. Pounding of adjacent buildings has made damage worse, and/or caused total collapse of the buildings. The earthquake that struck Mexico City in 1985 has revealed the fact that pounding was present in over 40% of 330 collapsed or severely damaged buildings surveyed, and in 15% of all cases it led to collapse (Rosenbluth & Meli 1986). This earthquake illustrated the significant seismic hazard of pounding by having the largest number of buildings damaged by its effect during a single earthquake (Bertero 1985). The writers have surveyed the damage due to pounding in the San Francisco Bay area during the recent 1989 Loma Prieta Earthquake (Kasai & Maison 1991). Significant pounding was observed at sites over 90 km from the epicenter thus indicating the possible catastrophic damage that may occur during future earthquake having closer epicenters.

Continued research is urgently needed in order to provide the engineering profession with practical means to evaluate and mitigate the extremely hazardous effects of pounding. Pursuant to this, the writers are currently conducting a variety of aspects of pounding (Kasai 1992b).

1.2 Code Provisions Regarding Pounding

Past aseismic codes did not give definite guidelines to preclude pounding. Because of this and due to economic considerations including maximum land usage requirements, there are many buildings world-wide which are already built in contact or extremely close to one another that will suffer pounding damage in future earthquakes. The 1988 Uniform Building Code (UBC) based on the 1988 provisions by the Structural Engineers Association of California (SEAOC) gives more detailed requirements for building separations, yet the SEAOC commentary (Section 1H.2.l) indicates the need for research to verify the recommendations. The resulting required separations are "large" and controversial from both technical (difficulty in using expansion joint) and economical (loss of land usage) views.

1.3 Study on Separation

The required separation to preclude pounding can be obtained through dynamic time history analyses of the adjacent buildings involving the calculation of relative displacement between the potential pounding locations of the buildings. An alternative, and more attractive method can be based on the commonly used response spectrum approach. Although response spectrum analysis using modal superposition has been widely applied to estimate the maximum response of a single building (Rosenblueth & Elorduy 1969, Der Kiureghian 1980), it has not been applied to obtain relative displacements between two buildings.

This paper presents the first rational solution to the problem utilizing the concept of response spectrum combination. The method is called the "spectral difference method" (Jeng, Kasai, & Maison 1992). The method can be used for a variety of relative displacement problems.

2 RELATIVE DISPLACEMENT

According to Fig. 1, the relative displacement time history $u_{REL}(t)$ at the potential pounding location of Buildings A and B is expressed as:

$$u_{REL}(t) = u_A(t) - u_B(t) \tag{1}$$

where, $u_A(t)$ and $u_B(t)$ = displacement time histories at the potential pounding locations of Buildings A and B, respectively, which are measured in the direction of the possible pounding. In Fig. 1, pounding occurs when $u_A(t) - u_B(t) > s$, where s (>0) = the separation between the buildings in the at-rest condition. Also, if we exchange buildings A and B in Fig. 1, pounding occurs when $u_B(t) - u_A(t) > s$. Thus, the criterion for the occurrence of pounding is:

$$\max|u_{REL}(t)| > s \tag{2}$$

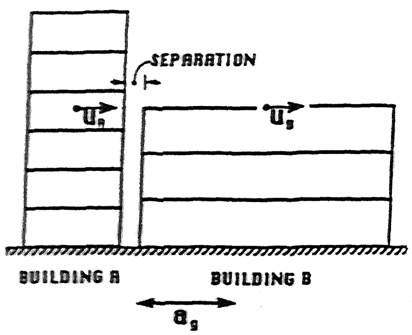


Fig. 1: Relative Displacement Problem.

3 RANDOM VIBRATION THEORY

The method estimates max | $u_{REL}(t)$ | between two linear elastic multiple-degree-of-freedom (MDOF) systems. The following assumptions are made: (1) as commonly assumed in the field of random vibration theory, the earthquake ground acceleration is taken as white noise; and (2) the adjacent buildings are subjected to identical ground motion simultaneously. Based on these and from Eq. 1,

$$E[u_{REL}(t)] = E[u_A(t) - u_B(t)] \tag{3}$$

$$E[u_{REL}(t)^2] = E[u_A(t)^2] + E[u_B(t)^2] - 2\,E[u_A(t)\,u_B(t)] \tag{4}$$

where $E[u_{REL}(t)]$ and $E[u_{REL}(t)^2]$ are first (mean or point estimate) and second (variance) moments of $u_{REL}(t)$, and

$$\begin{aligned} u_A(t) &= \sum_i^{n_A} u_{Ai}(t) = \sum_i^{n_A} P_{Ai}\phi_{Ai,p}Z_{Ai}(t) \ , \\ u_B(t) &= \sum_i^{n_B} u_{Bi}(t) = \sum_i^{n_B} P_{Bi}\phi_{Bi,p}Z_{Bi}(t) \end{aligned} \tag{5}$$

where for Buildings A and B respectively, n_A and n_B = numbers of degree of freedom, $u_{Ai}(t)$ and $u_{Bi}(t)$ = i-th modal displacements at the potential pounding location; P_{Ai} and P_{Bi} = i-th modal participation factors; $\phi_{Ai,p}$ and $\phi_{Bi,p}$ = i-th mass-orthonormalized mode vector components at the potential pounding location; and $Z_{Ai}(t)$ and $Z_{Bi}(t)$ = i-th modal generalized displacements. The method presented herein is based on the difference of spectral quantities of the mode as related to the relative motion between the particular two points in the adjacent respective buildings (Eqs. 3 to 5), thus it is called a "spectral difference method".

Assuming that the ratio between the modal displacement and its standard deviation are constant for all the modes of the adjacent buildings (Der Kiureghian 1980), Eq. 4 can be rewritten as:

$$\begin{aligned} u_{REL}^2 = & \sum_i^{n_A} u_{Ai}^2 + \sum_i^{n_B} u_{Bi}^2 \\ & + \sum_i^{n_A}\sum_{j\neq i}^{n_A} \rho_{AiAj}u_{Ai}u_{Aj} + \sum_i^{n_B}\sum_{j\neq i}^{n_B} \rho_{BiBj}u_{Bi}u_{Bj} \\ & - \sum_i^{n_A}\sum_j^{n_B} \rho_{AiBj}u_{Ai}u_{Bj} - \sum_i^{n_A}\sum_j^{n_B} \rho_{BjAi}u_{Ai}u_{Bj} \end{aligned} \tag{6}$$

where,

$$u_{REL} = \max|u_{REL}(t)| \tag{7}$$

$$\begin{aligned} u_{Ai} &= P_{Ai}\,\phi_{Ai}\,\max|Z_{Ai}(t)| \quad , \\ u_{Bi} &= P_{Bi}\,\phi_{Bi}\,\max|Z_{Bi}(t)| \end{aligned} \tag{8}$$

Note that ρ_{AiAj} (i and j = 1 to n_A) and ρ_{BiBj} (i and j = 1 to n_B) are cross modal correlation coefficients for i-th mode and j-th mode of Building A and Building B, respectively. The coefficients have the same physical meaning as well as mathematical form as the cross modal correlation coefficients commonly used in response spectrum double sum combination (DSC) rules to estimate the response of a single building (Rosenblueth & Elorduy 1969, Der Kiureghian 1980). Note also that ρ_{AiBj} (i = 1 to n_A, and j = 1 to n_B) is a cross correlation coefficient for i-th mode of Building A and j-th mode of Building B as explained below. This coefficient determines the significance of in-phase motion between different vibration modes. The combination rule Eq. 6 is a simplified version of the authors' recently developed Double Difference Combination (DDC) rule (Jeng & Kasai 1992). The Eq. 6 is specifically used as the proposed spectral difference method for estimating relative displacement between structures using earthquake response spectra with an assumption that the structures are under the same ground motion simultaneously. The writers' general DDC rule considers two adjacent structures subjected to multiple support excitations caused by traveling ground waves (Jeng & Kasai 1992), and it departs from the existing spectrum combination rules for a single structure.

Using the fundamental mode as an approximation for the MDOF response of buildings (which is commonly assumed), Eq. 6 can then be expressed as:

$$u_{REL}(DDC) = \sqrt{u_A^2 + u_B^2 - 2\,\rho_{AB}\,u_A\,u_B} \tag{9}$$

where $u_{REL}(DDC)$ = the relative displacement estimated by the DDC method, $u_A = u_{A1}$, $u_B = u_{B1}$, and $\rho_{AB} = \rho_{A1B1}$. The u_A and u_B could be obtained from the earthquake response spectrum. The cross correlation coefficients such as given by Der Kiureghian, and Rosenblueth and Elorduy can be used to obtain ρ_{AB} by replacing their modal indexes by A and B. The ρ_{AB} using the expression given by Der Kiureghian is dependant on T_B/T_A as well as ξ_A and ξ_B, i.e.,

$$\rho_{AB} = \{ 8\sqrt{\xi_A \xi_B}\,(\xi_B+\xi_A T_B/T_A)(T_B/T_A)^{3/2} \} \,/\, \{ (1-(T_B/T_A)^2)^2 + 4\xi_A\xi_B(1+(T_B/T_A)^2)(T_B/T_A) + 4(\xi_A^2+\xi_B^2)(T_B/T_A)^2 \} \quad (10)$$

For simplicity, if $\xi_A = \xi_B = \xi$, Eq. 10 becomes (SEAOC 1988-Appendix 1F Eq.AF-7):

$$\rho_{AB} = \frac{8\xi^2(1+T_B/T_A)(T_B/T_A)^{3/2}}{\{ 1-(T_B/T_A)^2 \}^2 + 4\xi^2(1+T_B/T_A)^2(T_B/T_A)} \quad (11)$$

Two other possible ways of estimating the relative displacement are as follows. The first is the absolute sum (ABS) method (u_{REL}(ABS)).

$$u_{REL}(ABS) = u_A + u_B \quad (12)$$

The second is the square-root-of-sum-of-squares (SRSS) method (u_{REL}(SRSS)).

$$u_{REL}(SRSS) = \sqrt{u_A^2 + u_B^2} \quad (13)$$

Comparisons of the estimates using the DDC, ABS, and SRSS methods are as follows.

The Eq. 12 for u_{REL}(ABS) is obtained if the $-2\rho_{AB}$ of Eq. 9 is replaced by +2. Similarly, Eq. 13 for u_{REL}(SRSS) is obtained if ρ_{AB} is set to zero. From Eqs. 9, 12, and 13, for any T_B/T_A and damping ratio, u_{REL}(DDC) < u_{REL}(SRSS) < u_{REL}(ABS). Further, the u_{REL}(DDC) becomes much smaller if damping is larger, since ρ_{AB} becomes larger. It is also noted that the most significant difference is observed when $T_B/T_A = 1.0$, in which the proposed DDC rule gives:

$$u_{REL}(DDC) = |\, u_A - u_B \,| \quad (14)$$

, which is much smaller than that given by either the ABS or SRSS methods. Numerical comparisons of u_{REL}'s obtained by the above three methods are presented next.

4 ELASTIC ANALYSIS

Example elastic analyses are presented herein to demonstrate the accuracy of the proposed DDC method. For simplicity, it is assumed that the buildings have a constant floor mass at each story level and that they develop straight line lateral deformed shapes due to a seismic excitation. Four different damping ratios (2%, 5%, 10%, and 20%), and four different potential pounding situations (the height of building B is 1.0, 0.75, 0.5, and 0.25 times that of building A) are used. Three cases of T_A (0.5, 1.0, and 2.0 sec.) are considered, and T_B is varied from 0.1 to 4.0 sec. with an increment of 0.1 sec. The 1940 El Centro earthquake (0.348g) is used.

The response spectra and displacement time histories are generated for the two buildings; and then, the required separations to avoid pounding are estimated using the proposed DDC rule and compared with those obtained from time history analyses. The results from the ABS and SRSS rules are also shown for comparison.

4.1 General Trends

Fig. 2 illustrates the case of Buildings A and B having the same height with T_B=1.0 second, $\xi_A=\xi_B$=20%, and potential pounding at the roof level caused by the El Centro earthquake. The u_{REL} obtained from the time history analysis (two values corresponding to the earthquake applied in opposite directions) as well as the u_{REL}'s obtained from the above three rules are shown.

The u_{REL}'s obtained from the time history for El Centro earthquake applied in two directions show agreement except when $T_B/T_A > 2$. The u_{REL}(DDC) obtained from the proposed spectrum method match the u_{REL}'s obtained from the time history very well. Note that when the buildings have similar periods, the required separation is minimum reflecting the influence of in-phase building motions. The u_{REL}(DDC) and u_{REL}(SRSS) are in close agreement when T_A and T_B are well spaced. The u_{REL}(ABS) represents an upper bound of the required separation.

For convenience in presentation, the results are normalized by the values from the absolute sum method (u_{REL} (ABS)). This is termed the normalized maximum relative displacement u^*_{REL} (also called the "normalized required separation"). The results shown in Fig. 2 is presented in the normalized required separation format in Fig. 3.

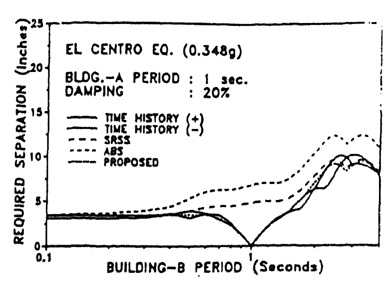


Fig. 2: Required Separation.
(T_A = 1.0 sec., Damping = 20%)

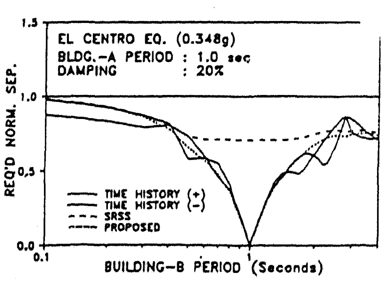


Fig. 3: Required Normalized Separation.
(T_A = 1.0 sec., Damping = 20%)

4.2 Damping

Consider the case of buildings having the same height with T_A = 1.0 sec, and the El Centro record as the excitation. Four different critical damping values are used (2, 5, 10 and 20%). The results for 20% and 5% damping values are shown in Figs. 3 and 4, respectively. For larger damping, the estimate for u^*_{REL} by the DDC rule is far below that by the ABS as well as the SRSS rules for wide range of T_B/T_A (Fig. 3). For smaller damping, the curve falls off rapidly when T_B/T_A deviates slightly from 1.0, and time history analysis, DDC rule, and SRSS rules agree in most cases (Fig. 4).

It should be noted that the actual separation required (u_{REL}) under high damping becomes significantly smaller because of in-phase motion and smaller building displacements due to higher damping. This suggests that increasing the damping of adjacent buildings could be an effective way to mitigate pounding. In addition, hysteretic damping of inelastic structures has the similar effect of reducing relative displacements (required separation) under major earthquakes, as will be discussed in Sec. 5.

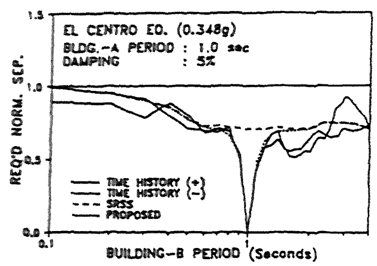


Fig. 4: Required Normalized Separation. (T_A = 1.0 sec., Damping = 5%)

4.3 Building Period

Consider the case of two buildings having the same height which may potentially pound at their roof levels. Three cases are used in which T_A = 0.5, 1.0, and 2.0 sec. It is found that regardless of the value of T_A as well as the type of earthquake, the curves for the different cases are almost identical. This can be explained by considering the idealized case in which both T_A and T_B have the same pseudo-velocity (i.e., the maximum displacement is proportional to the period) as often the situation for multi-story buildings, and that $\xi = \xi_A = \xi_B$. In this case, the u^*_{REL} obtained from the proposed DDC rule can be written as:

$$u^*_{REL}(DDC) = u_{REL}(DDC)/u_{REL}(ABS) = \sqrt{1-2\rho_{AB}T_B/T_A+(T_B/T_A)^2}\,/\,(1+T_B/T_A) \qquad (15)$$

Accordingly, $u^*_{REL}(DDC)$ is now only a function of T_B/T_A and ξ (see also Eq. 11). Therefore, for the idealized case, the ratio T_B/T_A (rather than the individual periods T_A and T_B of the adjacent buildings) and damping ratio influence u^*_{REL}. Extensive parameter study confirms that this trend holds even for real earthquakes. This trend is also a key to the inelastic case to be discussed later.

4.4 Building Height

By assuming the deformed shapes of Buildings A and B during vibration to straight lines, Figs. 3 and 5 show the results from cases where the height ratio, the height of the shorter building (B) divided by that of the taller building, is 1.0 and 0.5 (T_A = 1.0 sec.). The excitation in the El Centro record and 20% critical damping is used. When T_A and T_B are closely spaced, the magnitude of u^*_{REL} strongly depends on the relative height of the adjacent buildings. As discussed (Eq. 14), the case $T_A=T_B$ gives the smallest u^*_{REL} ($=|u_A-u_B|/|u_A+u_B|$), which is depicted by the valley in plots of Figs 3 and 5. If Building B has the same height as Building A, $u^*_{REL}=0$. Further, as Building B height becomes smaller, u_A becomes smaller compared with u_B, thus, u^*_{REL} becomes larger.

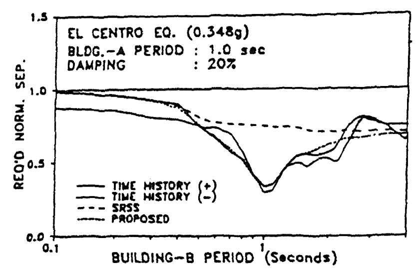


Fig. 5: Required Normalized Separation. (T_A = 1.0 sec., Damping = 20%) (Height Ratio = 0.5)

4.5 Error Analysis

The accuracy of the proposed DDC rule is apparent from the results shown in Figs. 2 to 5. This is further verified by the analysis results of 15 different earthquake records. Thus, in total, 30 different excitations (15 earthquakes x 2 directions) were used for a variety of cases in which T_A = 1.0 sec; T_B varied; building height ratios = 1, and 0.5; and, ξ = 2, 5, 10, and 20%.

The results of the DDC rules agree with that of the time history analysis for all the cases.

5 INELASTIC ANALYSES

5.1 Effective Period and Effective Damping

The effective period of the inelastic building is revealed by the minimum point on the curve of the u^*_{REL} between inelastic building and high damping elastic building of various periods. The effective damping of the inelastic system with a specific ductility is obtained by matching the curve of the u^*_{REL} between two inelastic adjacent buildings of that same ductility ratio with that of the elastic case of various damping ratios. Stiffness degrading and bilinear stiffness (Fig. 6) models are considered for the inelastic systems.(Kasai, Jagiasi & Jeng 1992)

Based on the study results of 15 earthquakes, Eqs. 16

and 17 are proposed for finding the effective period, T*, of inelastic systems for degrading and bilinear stiffness models, respectively.

$$T^*/T = [1 + 0.18\,(\mu - 1)] \qquad (16)$$

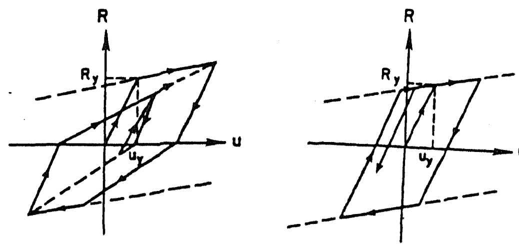
$$T^*/T = [1 + 0.09\,(\mu - 1)] \qquad (17)$$

Where μ is ductility ratio, T is initial period.
Similarly, for the effective damping ξ^* :

$$\xi^* = \xi + 16\,(\mu - 1)^{0.9} \qquad (18)$$

$$\xi^* = \xi + 8.4\,(\mu - 1)^{1.3} \qquad (19)$$

Where ξ is initial damping.



Stiffness Degrading Model **Bilinear Model**

Fig. 6: Hysteresis Models.

5.2 Examples

Example 1. - Two adjacent buildings are considered to have stiffness degrading characteristics. Two cases are considered: (1) the buildings have the same μ (=3.0), and (2) they have different μ's (= 3.0 and 6.0), respectively. Figs.7 and 8 plot required normalized separation with respect to T_B/T_A, as per DDC method, averaged over fifteen earthquakes. The proposed DDC rule results match the time history results very well for the above two cases.

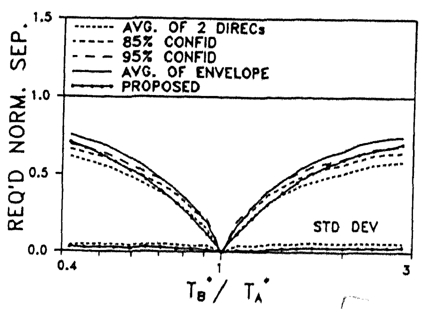


Fig. 7: Required Normalized Separation. (Degrading, μ_A = 3.0, μ_B = 3.0)

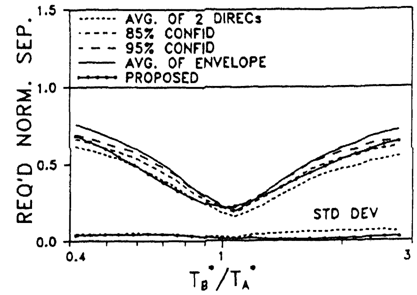


Fig. 8: Required Normalized Separation. (Degrading, μ_A = 3.0, μ_B = 6.0)

Example 2. - The study explained in Example 1 is repeated for adjacent buildings both of which have bilinear hysteresis characteristics. Figs. 9 and 10 show similar results, as presented above.

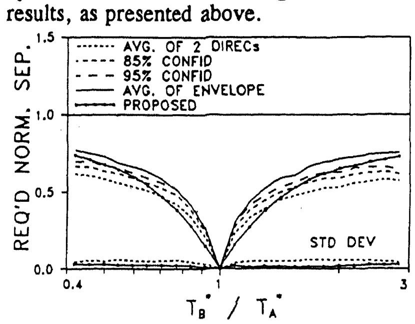


Fig. 9: Required Normalized Separation. (Bilinear, μ_A = 3.0, μ_B = 3.0)

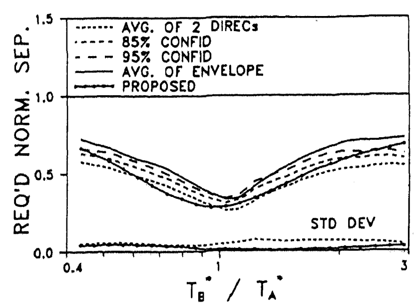


Fig. 10: Required Normalized Separation. (Bilinear, μ_A = 3.0, μ_B = 6.0)

Example 3. - The study explained in Example 1 is now repeated except that the two adjacent buildings have different hysteresis characteristics; Building A has degrading hystresis and Building B stiffness degrading hystresis, respectively. Figs. 11 and 12 and show that the DDC rules also give excellent results for adjacent buildings with different hysteresis stiffness models.

The above obtained results clearly show that the proposed DDC rule can be applied to inelastic as well as elastic response of the buildings.

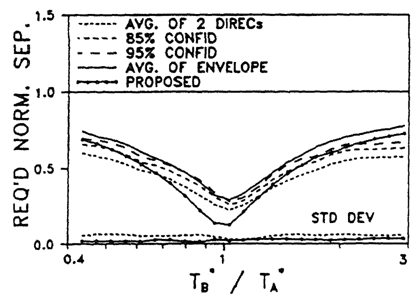


Fig. 11: Required Normalized Separation. (Degrading, $\mu_A = 3.0$, Bilinear, $\mu_B = 3.0$)

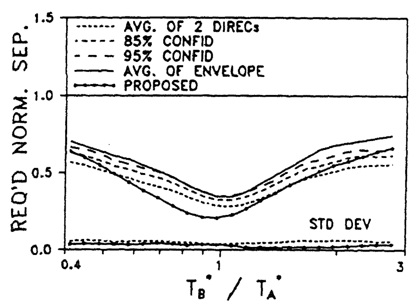


Fig. 12: Required Normalized Separation. (Degrading, $\mu_A = 3.0$, Bilinear, $\mu_B = 6.0$)

CONCLUSIONS

A spectral difference method (DDC rule) to estimate the required separation to avoid pounding is presented in this paper. The conclusions are as follows:

1. The method based on response spectrum techniques is accurate and extremely simple to use. Thus, it is much more suitable for practice as compared with the time history approach.
2. The method can be useful not only for the pounding problem but also a variety of relative displacement problems. For example it can be used to estimate the seismic movements between adjacent bridge segments in order to predict the possibility of falling deck type failure.
3. The method is more accurate than, and gives smaller estimates for the required separation as compared with other spectrum methods, such as the absolute sum (ABS) method as well as square root of sum of the squares (SRSS) method.
4. Effect of damping on the required separation is significant, since damping does not only reduce the maximum displacement of the structures, but also promotes in-phase motion of the adjacent structures. Hence, the use of dampers may be very effective in relative displacement problems.
5. The DDC method can be used for inelastic structures, using effective periods and effective damping. See authors' other papers (Kasai, Jagiasi & Jeng 1992) for further development.

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