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SEPARATION BETWEEN ADJACENT NONLINEAR STRUCTURES FOR PREVENTION OF SEISMIC POUNDING

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SUMMARY

Four existing methods to calculate critical separation distances between adjacent nonlinear hysteretic structures are evaluated through Monte-Carlo simulations, for which seismic excitation is characterized as a nonstationary random process. All the methods use the well-known Double Difference Combination rule, but follow different approaches to calculate the correlation coefficient ρ. Results show that none of the methods evaluated is completely satisfactory in the sense that they are not capable of providing consistently conservative estimates of the critical separation distance for all possible values of relevant parameters. A new method, which consists of using values of parameter ρ derived from empirical estimates obtained through numerical simulations, is then proposed and examined. Results show that the proposed method provides consistently conservative estimates of critical separation distances, the degree of conservatism being slight in most cases. These desirable properties are found to hold for a variety of wide-band seismic excitations.

INTRODUCTION

Seismic pounding occurs when the separation distance between adjacent buildings is not large enough to accommodate the relative motion during earthquake events. Depending on the characteristics of the colliding buildings (Anagnostopoulos [1]), pounding might cause severe structural damage in some cases (Kasai [2]) and even collapse is possible in some extreme situations (Bertero [3]). Further, even in those cases where it does not result in significant structural damage, pounding always induces higher floor accelerations in the form of short duration spikes, which in turn cause greater damage to building contents. For these reasons, it has been widely accepted that pounding is an undesirable phenomenon that should be prevented or mitigated. This is recognized in seismic design codes and regulations worldwide, which typically specify minimum separation distances to be provided between adjacent buildings. For instance, according to the 2000 edition of the International Building Code, minimum separation distances are given by:

$$S = X_A + X_B \qquad \text{(adjacent buildings separated by a property line)} \qquad (1)$$

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$$S = \sqrt{X_A^2 + X_B^2} \qquad \text{(adjacent buildings located on the same property)} \qquad (2)$$

where S = separation distance and X_A, X_B = peak displacement response of adjacent structures "A" and "B", respectively. Equations (1) and (2) are usually referred to as the ABS and SRSS rules, respectively, and are implemented in many seismic design codes and regulations worldwide. Previous studies (Jeng [4], Lopez Garcia [5]), however, have shown that they give poor estimates of S, especially when the natural periods of the adjacent structures are close to each other. In these cases, the ABS and SRSS rules give excessively conservative separation distances, which are very difficult to effectively implement because of maximization of land usage.

A more rational approach was presented by Jeng [4] and can be summarized as follows: Let $U_A(t)$ and $U_B(t)$ be stationary random processes over a finite duration, representing the displacement response of two linear SDOF systems to a Gaussian, zero-mean stationary stochastic excitation $\ddot{U}_g$(t), and let $U_{REL}(t) = U_A(t) - U_B(t)$ be the random process representing the displacement response of the systems relative to one another. It can be shown that $U_A(t)$, $U_B(t)$ and $U_{REL}(t)$ are also zero-mean Gaussian processes (Soong [6]). Assuming that the ratio of the mean peak value to the standard deviation is a constant (a reasonable approximation in the case of stationary Gaussian processes), then the critical separation distance, which is obviously equal to the peak relative displacement response, is given by:

$$S = X_{REL} = \sqrt{X_A^2 + X_B^2 - 2\,\rho\, X_A\, X_B} \qquad (3)$$

where X_A, X_B, X_{REL} = mean peak values of $U_A(t)$, $U_B(t)$ and $U_{REL}(t)$, respectively, and ρ is given by:

$$\rho = \frac{E\{U_A\, U_B\}}{\sqrt{E\{U_A^2\}E\{U_B^2\}}} \qquad (4)$$

where $E\{\}$ is the expectation operator. Equation (4) indicates that ρ is the correlation coefficient for processes $U_A(t)$ and $U_B(t)$. If it is assumed further that the excitation $\ddot{U}_g$(t) is a white noise, then correlation coefficient ρ is given by (Der Kiureghian [7], Grigoriu [8]):

$$\rho = \frac{8\sqrt{\xi_A\,\xi_B}\left(\xi_A + \xi_B\,\frac{T_A}{T_B}\right)\left(\frac{T_A}{T_B}\right)^{1.5}}{\left[1-\left(\frac{T_A}{T_B}\right)^2\right]^2 + 4\,\xi_A\,\xi_B\left[1+\left(\frac{T_A}{T_B}\right)^2\right]\left(\frac{T_A}{T_B}\right) + 4\left(\xi_A^2+\xi_B^2\right)\left(\frac{T_A}{T_B}\right)^2} \qquad (5)$$

where T_A, ξ_A and T_B, ξ_B are natural periods and damping ratios of systems "A" and "B", respectively. Equation (3), together with Equation (5), is usually referred to as the Double Difference Combination (DDC) rule. In the case of more realistic nonstationary wide-band excitations, it has been shown (Lopez Garcia [5]) that, despite the various simplifying assumptions under which it was derived, the DDC rule is much more accurate than the ABS and SRSS rules, although it gives somewhat unconservative results when T_A and T_B are well separated. A correction for these latter cases has been proposed (Lopez Garcia [9]).

In actual case scenarios, a great majority of building structures responds nonlinearly when subjected to strong ground motions. If it is assumed that Equation (3) is still valid for nonlinear systems (an assumption whose basis is weaker than that for linear systems), then all that is needed to extend the applicability of the DDC rule to nonlinear systems is a suitable expression for ρ, for which no closed-form solution valid for hysteretic systems exists. This problem has been the subject of a number of studies carried out by several authors (Filiatrault [10, 11], Penzien [12], Kasai [13], Valles [14]), who have proposed different methods.

The first objective of this paper is to evaluate the abovementioned existing methods to extend the applicability of the DDC rule to nonlinear hysteretic systems. The evaluation is performed by Monte-Carlo simulations, for which the seismic excitation is characterized as a nonstationary random process representative of realistic wide-band excitations. The second objective of this study is to propose values of ρ for nonlinear hysteretic systems empirically obtained from numerical simulations. It will be shown that critical separation distances calculated using the proposed values of ρ are much more appropriate than those obtained following any of the existing methods in the sense that they are much more accurate and they are *always* on the conservative side.

DESCRIPTION OF THE EVALUATION PROCEDURE

In this study, seismic excitation is characterized as a Gaussian, zero mean nonstationary random process $\ddot{U}_g(t)$ whose evolutionary power spectral density function is given by:

$$S_{Ug}(t, \omega) = [e(t)]^2 \; S_g(\omega) \tag{6}$$

where $e(t)$ is the envelope function proposed by Saragoni [15] and calibrated by Boore [16] and $S_g(\omega)$ is given by the well-known modified Kanai-Tajimi equation, i.e. (Clough [17]):

$$S_g(\omega) = S_0 \left[\frac{\omega_g^4 + 4\,\xi_g^2\,\omega^2\,\omega_g^2}{\left(\omega_g^2 - \omega^2\right)^2 + 4\,\xi_g^2\,\omega^2\,\omega_g^2} \right] \left[\frac{\omega_f^4}{\left(\omega_f^2 - \omega^2\right)^2 + 4\,\xi_f^2\,\omega^2\,\omega_f^2} \right] \tag{7}$$

where S_0 = 200 cm^2/sec^3, ω_g = 12.50 rad/sec, ξ_g = 0.60, ω_f = 2.00 rad/sec and ξ_f = 0.70. These values, typical of realistic wide-band excitations, were selected following recommendations found in the literature. The resulting function $S_g(\omega)$ is shown in Figure 1 (left) for positive values of ω only. A total of 200 samples of the process $\ddot{U}_g(t)$ are then generated as explained in Soong [6]. The time duration of all samples is 30 sec, and the corresponding 5%-damped mean pseudo-acceleration response spectrum is shown in Figure 1 (right). It can be seen that the latter matches very well what can be expected in actual case scenarios at sites of firm soil conditions. For illustration purposes, a sample ground acceleration time history $\ddot{u}_g(t)$ is shown in Figure 2 (left), and the corresponding 5%-damped pseudo-acceleration response spectrum is shown in Figure 2 (right).

Nonlinear structures are characterized as SDOF systems having the bilinear force-displacement relationship schematically shown in Figure 3, where force at first yield is given by:

$$F_Y = \frac{m\,SA}{R} \tag{8}$$

where, in turn, m = mass of the oscillator, SA = elastic pseudo-acceleration response and R = force reduction factor. Post-yielding stiffness ratio α and viscous damping ratio ξ are set equal to 0.05.

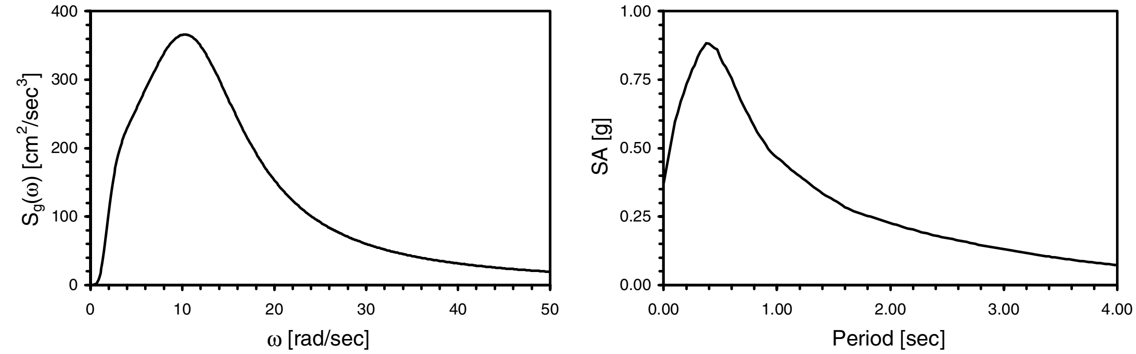

Figure 1: (left) Function $S_g(\omega)$ for $\omega > 0$; (right) Mean SA spectrum of $\ddot{U}_g(t)$ ($\xi = 5\%$)

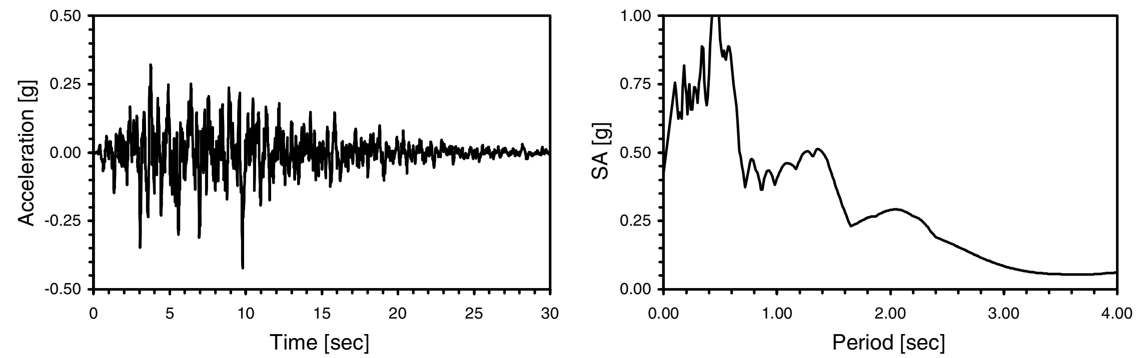

Figure 2: (left) Sample history $\ddot{u}_g(t)$; (right) SA response spectrum ($\xi = 5\%$)

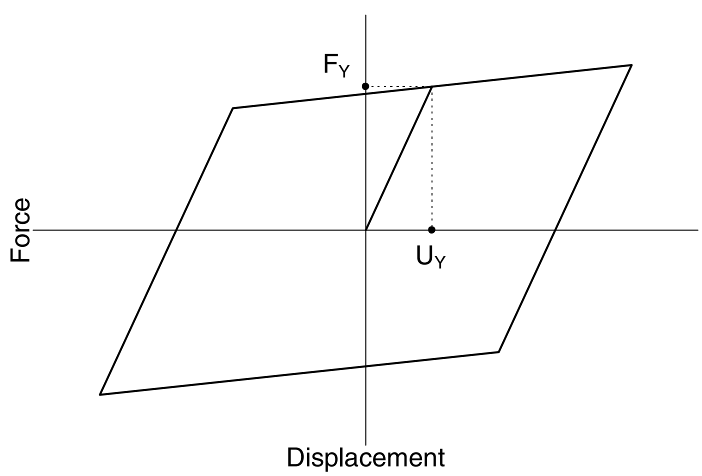

Figure 3: Bilinear force-displacement relationship of SDOF systems

For a given pair of nonlinear SDOF systems "A" and "B" (characterized by T_A, ξ_A, R_A and α_A and T_B, ξ_B, R_B and α_B, respectively), mean peak displacement responses X_A and X_B are first obtained through numerical simulations (nonlinear time history analysis). Equation (3) is then used to calculate S, for which the value of ρ is obtained according to each of the methods examined in this study. Finally, numerical simulations are performed again to calculate the mean peak relative displacement response X_{REL}. Results are expressed in terms of the ratio S / X_{REL}, which are conceptually similar to "capacity/demand" ratios usually used in structural analysis.

APPLICATION OF THE DDC RULE TO NONLINEAR HYSTERETIC SYSTEMS

Method by Filiatrault [10-11]:

Obviously, the simplest approach to extend the applicability of the DDC rule to nonlinear systems consists of assuming that Equation (5), which is valid for linear systems only, is nevertheless at least a decent approximation to the actual correlation between displacement responses of hysteretic oscillators. This approach was first applied by Filiatrault [10] to three pairs of adjacent steel building models, and resulted in separation distances that were conservative by 30% in all cases. The same approach was later applied in the more comprehensive study by Filiatrault [11], which considered reinforced concrete building models, and resulted in values of S exhibiting a high degree of dispersion, ranging from 81% conservative to 13% unconservative. In both studies, the excitation was characterized by small sets of earthquake records.

Examples of results given by the evaluation procedure followed in this study are shown in Figure 4. Each chart shows results for a set of pairs of SDOF systems where the natural period and force reduction factor of system "A" (i.e., T_A and R_A) have a fixed value, the value of R_B is fixed as well, and the value of T_B varies from 0.10 sec to 4.00 sec with 0.025 sec increments. Results shown in Figure 4 exhibit a high degree of dispersion. While estimated separation distances are reasonably accurate when T_A and T_B are well separated, they become increasingly conservative (by more than 50% in some cases) as T_A approaches T_B, and finally become suddenly and markedly unconservative when T_A and T_B are very close to each other. Results for other values of T_A, R_A and R_B are qualitatively similar to those shown in Figure 4 and are not shown for brevity.

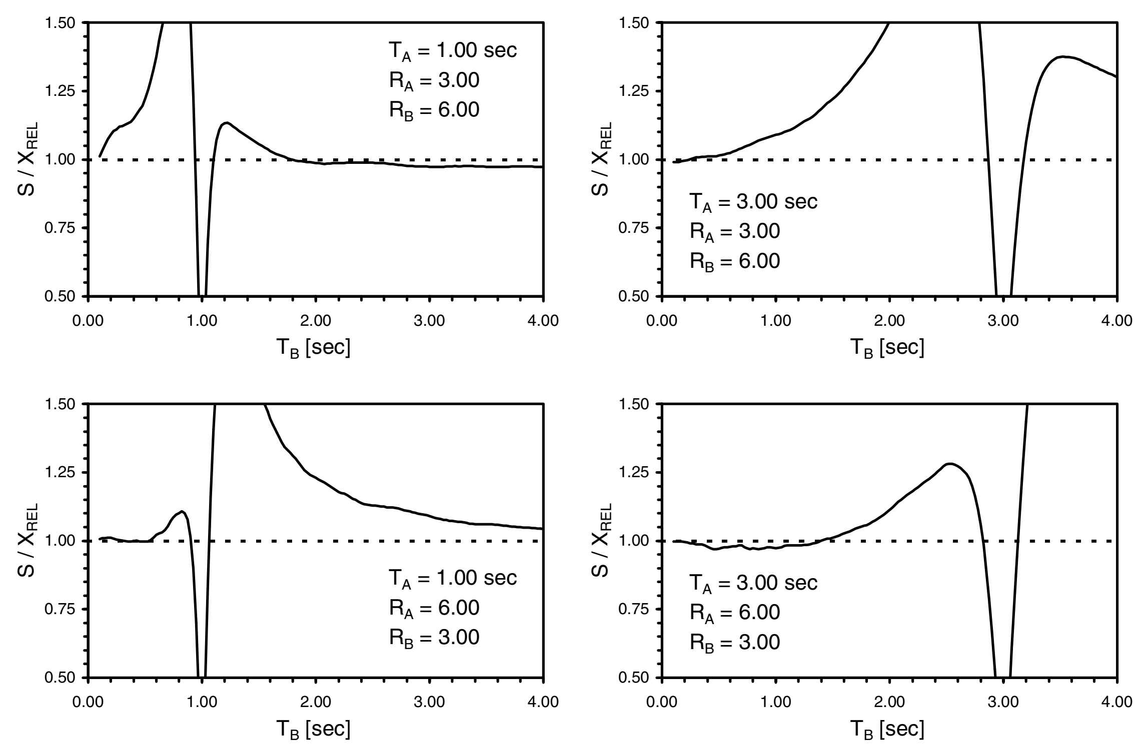

Figure 4: Normalized separation distances obtained by the method of Filiatrault [10,11]

Another possible approach to extend the applicability of the DDC rule to nonlinear consists of using "effective" linear properties, i.e., it consist of assuming that there exists a pair of *linear* systems for which the correlation between their responses is at least a good approximation to the correlation between the responses of the actual nonlinear systems. In other words, this approach assumes that Equation (5) is still valid for nonlinear systems as long as T_A, ξ_A, T_B and ξ_B are replaced by "effective" properties T_{Aeff}, ξ_{Aeff}, T_{Beff} and ξ_{Beff}, which in turn are a function of the characteristics of the actual nonlinear oscillators. While, in principle, the use of "effective" linear properties is possible, determination of T_{Aeff}, ξ_{Aeff}, T_{Beff} and ξ_{Beff} is not straightforward. In what follows, two methods that adopt this criterion are presented and evaluated.

Method by Penzien [12]
According to Penzien [12], effective linear properties are given by:

$$T_{A\,eff} = T_A \sqrt{\frac{\mu_A}{\gamma + \alpha_A\left(\mu_A - \gamma\right)}} \tag{9}$$

$$\xi_{A\,eff} = \xi_A + \frac{2}{\pi}\left\{\frac{\left(\mu_A - \gamma\right)\left(1 - \alpha_A\right)\gamma}{\mu_A\left[\gamma + \alpha_A\left(\mu_A - \gamma\right)\right]}\right\} \tag{10}$$

where μ_A = displacement ductility of system "A" and $\gamma = 0.65$. Substitution of subscript "A" by "B" in Equations (9) and (10) gives the corresponding expressions for T_{Beff} and ξ_{Beff}. It must be noted that, if $\gamma = 1.00$, then Equations (9) and (10) are the well-known formulae proposed by Rosenblueth [18] to linearize the response of individual hysteretic systems. The factor $\gamma = 0.65$ was introduced by Lysmer [19] to calibrate the linearization of the seismic response of soil layers. Results presented in Penzien [12] show that this method gives results that are significantly different from those obtained using the ABS and SRSS rules, but its accuracy was not rigorously examined.

Some representative results of the evaluation performed in this study, calculated using values of μ_A and μ_B equal to mean displacement ductilities, are shown in Figure 5. It can be seen that, in general, this method gives unconservative results. In particular, separation distances S become significantly unconservative, by more than 50% in extreme cases, when T_B approaches a particular value that, depending on R_A and R_B, is either greater or less than T_A. Results for other values of T_A, R_A and R_B are qualitatively similar to those shown in Figure 5 and are not shown for brevity.

Method by Kasai [13]
For the particular case of nonlinear systems having a bilinear force-displacement relationship with a 5% post-yielding stiffness ratio (i.e., the nonlinear hysteretic systems considered in this study), Kasai [13] proposed that effective linear properties be given by:

$$T_{A\,eff} = T_A\left[1 + 0.09\left(\mu_A - 1\right)\right] \tag{11}$$

$$\xi_{A\,eff} = \xi_A + 0.084\left(\mu_A - 1\right)^{1.3} \tag{12}$$

Again, substitution of subscript "A" by "B" in Equations (11) and (12) gives the corresponding expressions for T_{Beff} and ξ_{Beff}. Equations (11) and (12) were obtained from the analysis of results given by numerical simulations and indicate the properties of a linear system whose displacement response relative to that of a nonlinear system characterized by μ is minimized. Results presented in Kasai [13] show that this method gives estimates of S that, while definitely more accurate than those obtained using the ABS and SRSS rules, tend to be on the unconservative side.

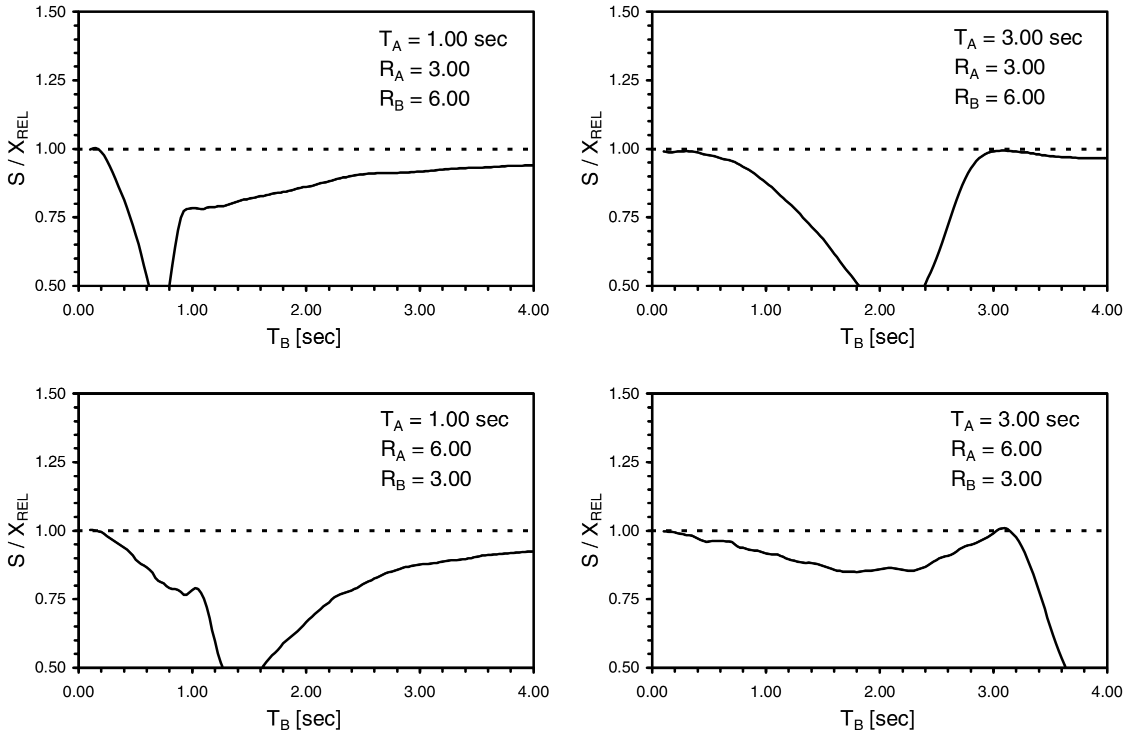

Figure 5: Normalized separation distances obtained by the method of Penzien [12]

The former observation is confirmed by the results shown in Figure 6, which were obtained through the Monte-Carlo simulation described before and using again values of μ_A and μ_B equal to mean displacement ductilities. While still unconservative (up to 25%-30%), separation distances given by the method of Kasai [13] are more accurate than those given by the method of Penzien [12]. This is most probably due to the fact that, while Equations (9) and (10) were derived by linearizing individual systems, relative displacement response was explicitly taken into account when deriving Equations (11) and (12). Results for other values of T_A, R_A and R_B are qualitatively similar to those shown in Figure 6 and are not shown for brevity.

Method by Valles [14]

While no closed-form solution exists for Equation (4) in the case of nonlinear hysteretic systems, values of ρ can still be obtained by numerically evaluating the expectations involved. This approach was followed by Valles [14], whose results were obtained by linearizing the hysteretic term of the equation of motion for bilinear systems rather than by nonlinear time-history analysis. Values of ρ were presented in series of charts for both wide- and narrow-band excitations and for several combinations of values of other parameters. In all cases, however, values of either displacement ductility or force reduction factor were assumed equal in both adjacent structures (i.e., either $\mu_A = \mu_B$ or $R_A = R_B$). For the more general case where either $\mu_A \neq \mu_B$ or $R_A \neq R_B$, Valles [14] suggested that conservative assessments of S are obtained when the value of ρ is taken from the chart valid for the value of either μ or R equal to the lesser of those corresponding to the actual nonlinear systems. This last observation, rather than the values of ρ themselves, is the object of the evaluation approach followed in this study.

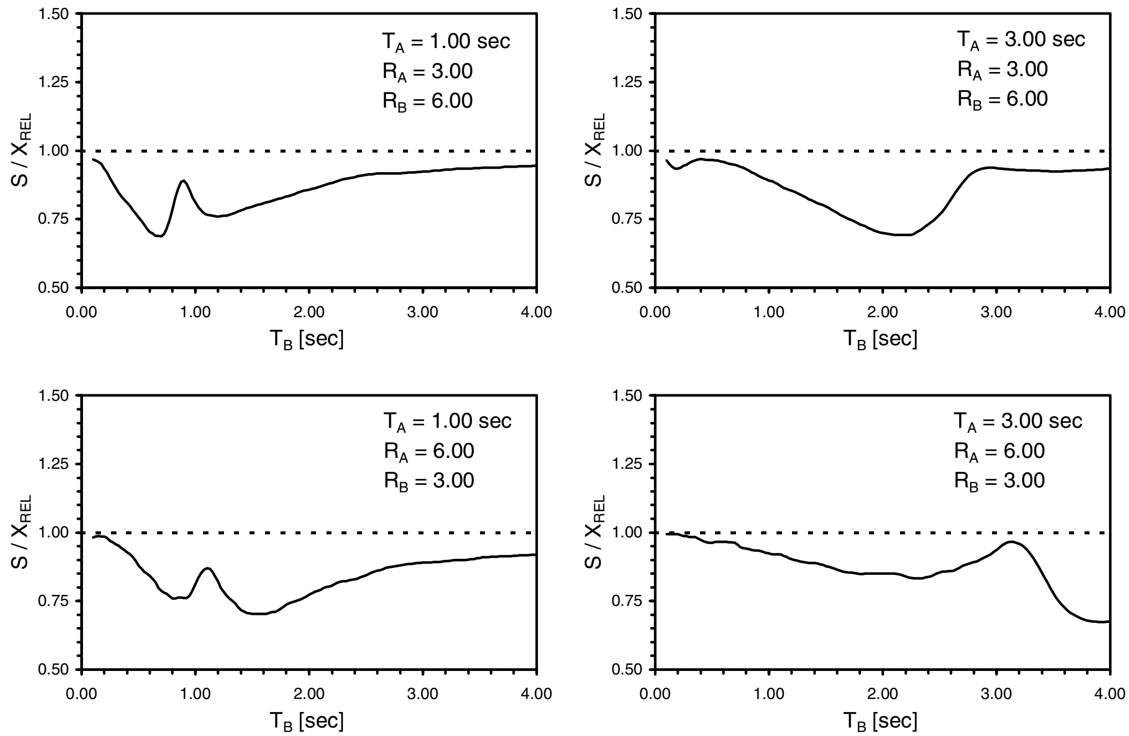

Figure 6: Normalized separation distances obtained by the method of Kasai [13]

For clarity, a complete example of the evaluation procedure for this particular method is described. Monte-Carlo simulations are first performed assuming, for instance, $R_A = 3.00$, $R_B = 6.00$, and the corresponding values of X_A, X_B and X_{REL}, denoted X_{A3}, X_{B6} and $X_{REL3\text{-}6}$ in this particular case, are obtained. Next, a new simulation is performed assuming $R_A = R_B = 3.00 = \min(3.00, 6.00)$, from which "exact" values of ρ for this particular situation, denoted $\rho_{3\text{-}3}$, are calculated using:

$$\rho_{3-3} = \frac{X_{A3}^2 + X_{B3}^2 - X_{REL3-3}^2}{2\ X_{A3}\ X_{B3}} \tag{13}$$

which is derived from Equation (3). Separation distance $S_{3\text{-}6}$ is then given by:

$$S_{3-6} = \sqrt{X_{A3}^2 + X_{B6}^2 - 2\,\rho_{3-3}\ X_{A3}\ X_{B6}} \tag{14}$$

i.e., it is calculated using $\rho_{3\text{-}3}$ rather than $\rho_{3\text{-}6}$, which is not provided in the charts presented in Valles [14]. Finally, separation distances $S_{3\text{-}6}$ are normalized by $X_{REL3\text{-}6}$.

Some representative results of the evaluation procedure described above are shown in Figure 7, where it can be seen that separation distances S are not always conservative. Moreover, they become suddenly and markedly unconservative (by more than 50% in extreme cases) when T_A and T_B are very close to each other. While additional simulations were performed to account for other values of R_A and R_B, the corresponding results are qualitatively similar to those shown in Figure 7 and are not shown for brevity.

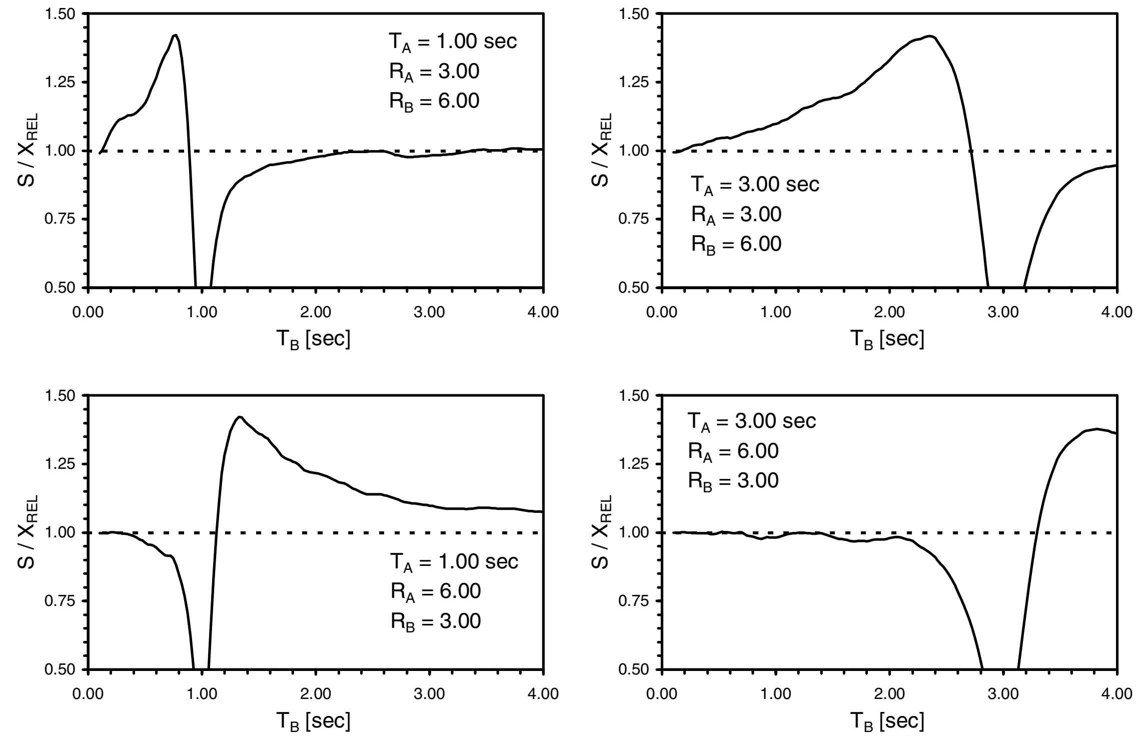

Figure 7: Normalized separation distances obtained by the method of Valles [14]

Summary

The ideal method to calculate critical separation distances should provide results that are consistently conservative but only for a narrow margin. In doing so, the resulting values of *S* effectively prevent pounding while disruption of land usage is kept to a minimum. Since none of the four methods evaluated in this study meets this criterion, there is still a need for a practical yet accurate procedure to extend the applicability of the DDC rule to nonlinear hysteretic systems. In this spirit, an alternative approach is presented and examined in the next section.

EMPIRICAL VALUES OF PARAMETER ρ

Equation (13) may be applied to any pair of adjacent oscillators to calculate appropriate values or ρ, i.e.:

$$\rho = \frac{X_A^2 + X_B^2 - X_{REL}^2}{2\, X_A\, X_B} \tag{15}$$

which is derived by solving Equation (3) for ρ. It is important to note that Equation (15), which indicates a relationship between mean peak responses, does not give the *correlation* between displacement responses of systems "A" and "B". Therefore, the designation "correlation coefficient" is not appropriate for values of ρ calculated using Equation (15). In this study, they are referred to simply as values of "parameter" ρ. Moreover, since they are obtained from numerical simulations, they can suitably be designated as "empirical".

Examples of empirical values of ρ are shown in Figure 8. They were calculated using values of X_A, X_B and X_{REL} obtained by Monte-Carlo simulations for the nonstationary excitation process described before. They are expressed in terms of the period ratio T_1/T_2, where $T_1 = \min(T_A, T_B)$ and $T_2 = \max(T_A, T_B)$. They were obtained considering all the combinations of pairs of nonlinear systems where $T_A = 0.50$ sec, 1.00 sec, … , 3.50 sec and T_B ranges between 0.10 sec and 4.00 in such a way that $T_1/T_2 = k / 100$ (k = 1, 2, … , 100). It must be noted that R_1 indicates the value of R for the system whose natural period is $T_1 = \min(T_A, T_B)$, and that R_2 designates the value of R for the oscillator whose natural period is $T_2 = \max(T_A, T_B)$.

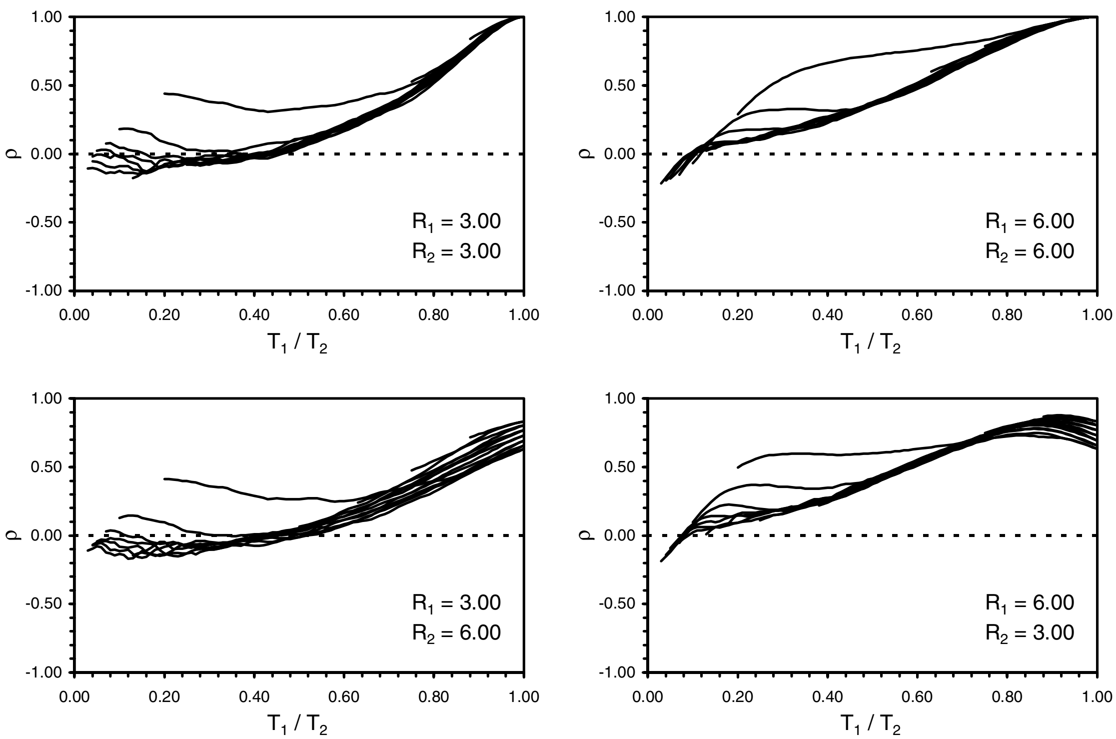

Figure 8: Examples of empirical values of parameter ρ

It can be seen that, for a given value of T_1/T_2, ρ exhibits a significant degree of dispersion only when T_1/T_2 is close to zero (regardless of the values of R_1 and R_2) and when both T_1/T_2 is close to unity and $R_1 \neq R_2$. In the latter case, it was observed that, the lesser the value of T_1/T_2, the lesser the value of ρ. It can also be observed that there is always a line that does not follow the general trend. It was found that this particular line corresponds to the case where $T_A = 0.50$ sec and $T_B < 0.50$ sec, i.e., the only case for which both T_A and T_B are less than the main period of the excitation $T_g \approx 0.61$ sec. It was found that all these observations also apply for other values of force reduction factors and damping ratios.

The qualitative findings described in the former paragraph suggest that, in order to express results in a relatively simple way suitable for routine practical applications, it is possible to characterize parameter ρ as a function of T_1/T_2 regardless of the actual values of the natural periods. In this spirit, it is then proposed that parameter ρ be characterized by "lower envelopes" of empirical values, as indicated in Figure 9. In doing so, the proposed values of ρ should result in consistently conservative estimates of critical separation distances. The degree of conservatism should in general be slight except in the cases mentioned before where the dispersion of empirical values of ρ is significant, for which greater degrees of conservatism can be expected.

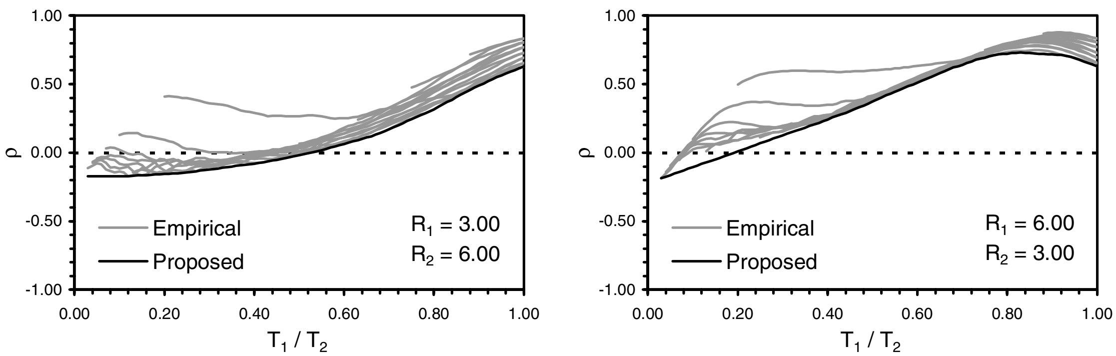

Figure 9: Examples of proposed values of parameter ρ

It was found that, for a given value of R_1, the proposed values of ρ are essentially independent of R_2 for relatively low values of T_1/T_2. As the T_1/T_2 ratio increases, however, influence of R_2 on the value of ρ becomes increasingly important. Qualitatively, this influence depends on whether R_2 is greater or less than R_1, as it can be deduced from the various ρ vs. T_1/T_2 curves shown in Figure 10. It was also found that, while greater damping ratios result in greater values of ρ (same as in the case of linear systems), the general shapes of the ρ vs. T_1/T_2 curves for different combinations of R_1, R_2 are essentially independent of the levels of damping.

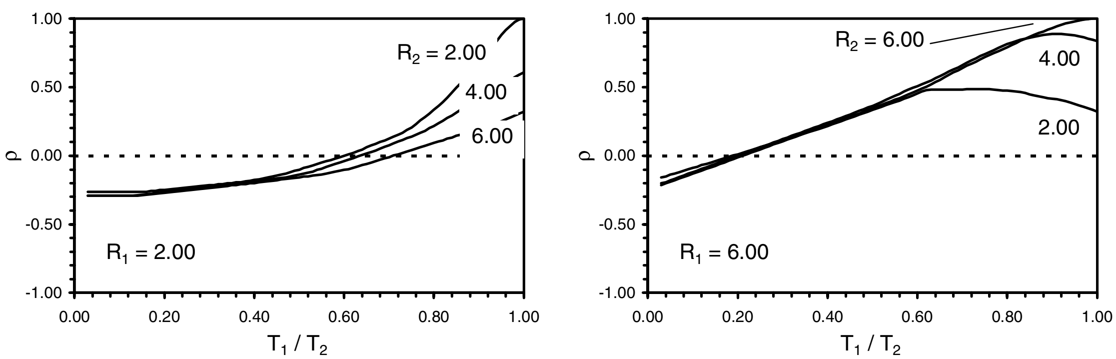

Figure 10: Proposed values of parameter ρ for different combinations of R_1 and R_2

The proposed values of ρ can then be used in Equation (3) to calculate critical separation distances. This approach is evaluated following the same procedure used in evaluating the existing methods described before. Some representative results are shown in Figure 11, where it can be seen that the proposed approach gives consistently conservative results and only for a narrow margin in most cases. As expected, the only exception occurs when both T_A and T_B have relatively large values and are close to each other. In these cases, a significant degree of conservatism is observed. As mentioned before, this is a consequence of ignoring the fact that, when T_1/T_2 is close to unity, larger values of T_1, T_2 result in larger values of ρ. However, even in these cases the proposed approach is much more appropriate than the ABS and SRSS rules, which give results that are far more conservative (Figure 12). Hence, while a lesser degree of conservatism would be desirable, the proposed approach provides separation distances that are much less than those obtained using code-specified methods but that still effectively prevent pounding.

Although care has been taken to ensure that the stochastic excitation used to empirically obtain values of ρ is representative of realistic seismic ground accelerations, there is nevertheless a question about whether the proposed values of ρ provide accurate estimates of S for other possible ground excitations. The proposed approach is then evaluated as described before but using stochastic excitations for which $S_g(\omega)$ is now defined in such a way that the 5%-damped mean pseudo-acceleration response spectra of the resulting processes $\ddot{U}_g(t)$ match the design spectral shapes defined in the 2000 edition of the NEHRP Recommended Provisions for Seismic Regulations for New Buildings and other Structures (FEMA 368). Two design response spectra were obtained for spectral accelerations S_S = 1.50 g and S_1 = 0.60 g and for soil types "B" and "E", whose corresponding spectra have markedly different frequency contents. Response-spectrum-compatible functions S_g (ω), which were obtained by smoothing results of an iterative process, and the corresponding mean pseudo-acceleration response spectra are shown in Figure 13, while sample ground acceleration time histories are shown in Figure 14. Some representative results of the evaluation procedure are shown in Figures 15 and 16. It can be seen that they are qualitatively similar to those shown in Figure 11, although some quantitative differences can be observed (they are somewhat more conservative when T_A = 1.00 sec, and somewhat less conservative when T_A = 3.00 sec). The most important properties, however, are preserved: results are consistently conservative, and the degree of conservatism is negligible or slight in most cases.

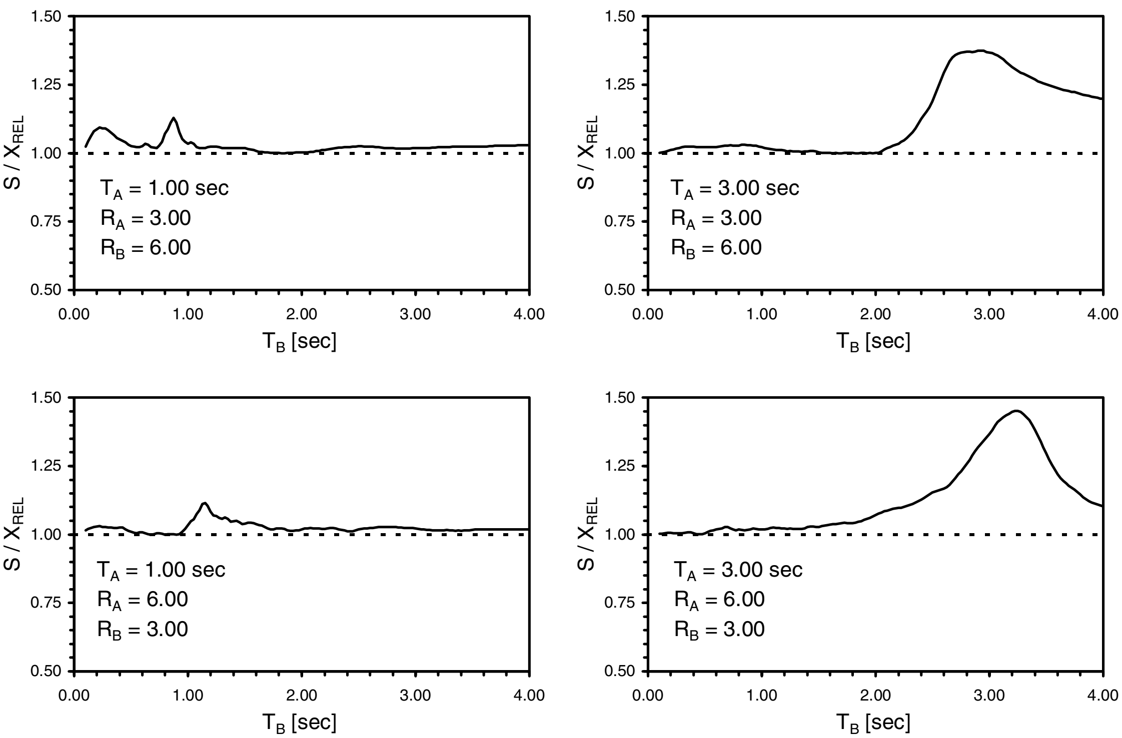

Figure 11: Normalized separation distances obtained using the proposed values of parameter ρ

CONCLUDING DISCUSSION

A new method has been proposed to calculate critical separation distances between adjacent nonlinear hysteretic structures. The method adopts the well-known basic equation of the DDC rule, but uses values of parameter ρ derived from empirical estimates obtained through numerical simulations. When compared to other existing methods, the proposed approach exhibits a number of convenient advantages: (a) it provides consistently conservative results; (b) the degree of conservatism is slight in most cases; (c) in cases where results are non-negligibly conservative, results are nevertheless much less than those given by code-specified equations (i.e., ABS and SRSS rules); and (d) the former properties apply for wide-band excitations in general.

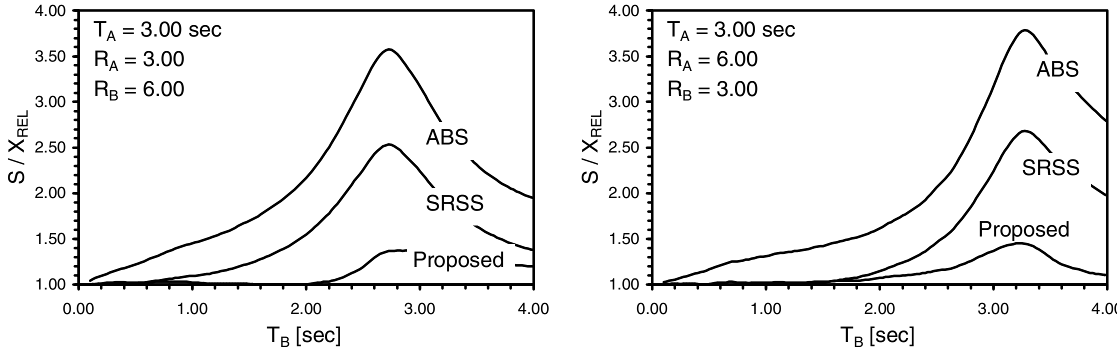

Figure 12: Comparison of normalized separation distances

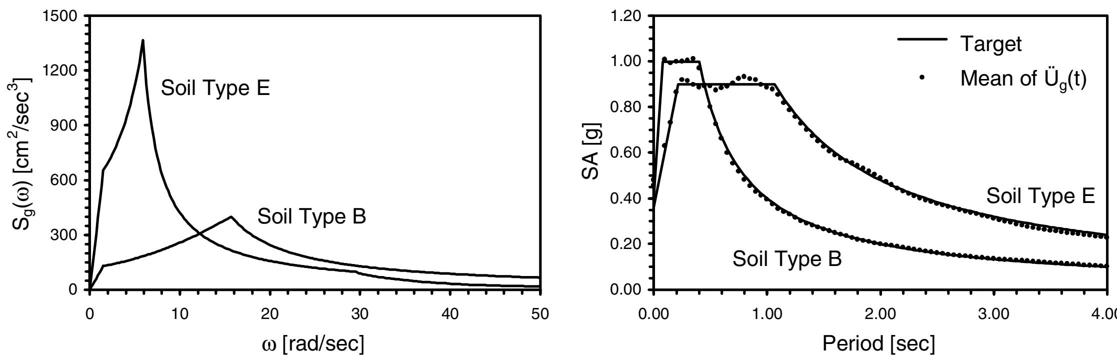

Figure 13: (left) Response-spectrum-compatible functions $S_g(\omega)$; (right) mean response spectra

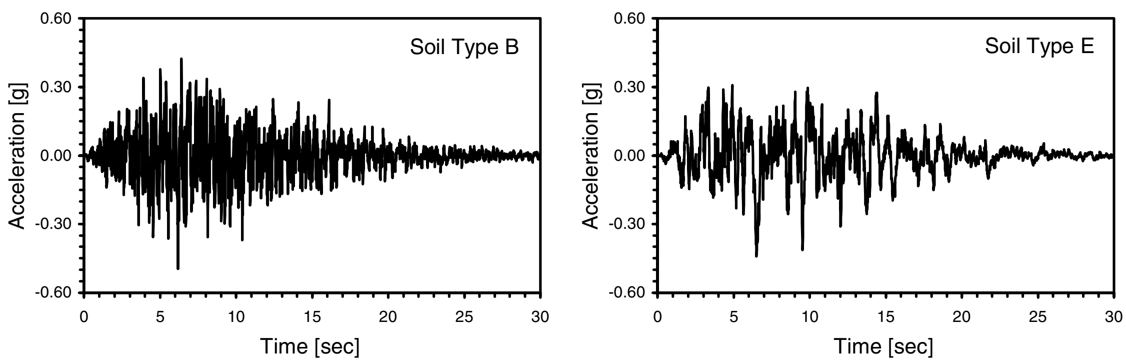

Figure 14: Sample ground acceleration time histories $\ddot{u}_g(t)$

The main disadvantage is the fact that the proposed values of ρ are available only in charts similar to those shown in Figure 10. For practical applications, availability of an analytical expression giving values of ρ as a function of relevant parameters (i.e., $\rho = f\ (T_1/T_2,\ R_1,\ R_2,\ \xi_1,\ \xi_2,\ \alpha_1,\ \alpha_2)$) would be much more convenient. The development of such a function is the subject of an on-going investigation.

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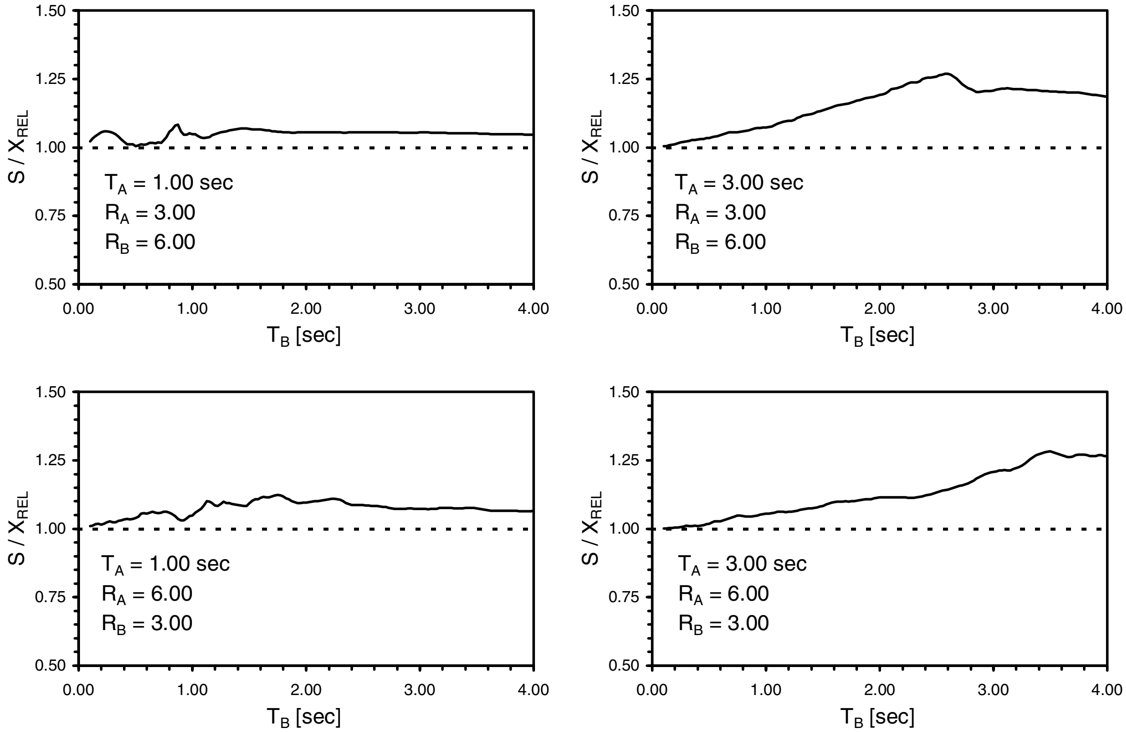

Figure 15: Values of S / X_{REL} for the Soil Type B response-spectrum-compatible excitation

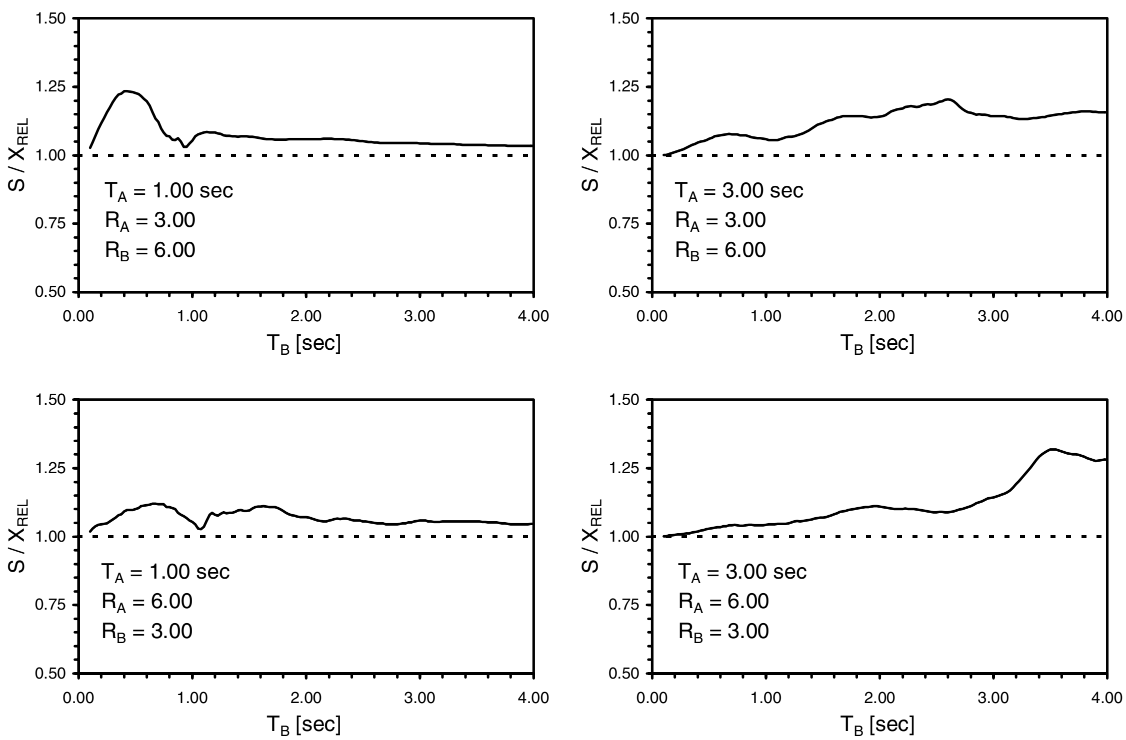

Figure 16: Values of S / X_{REL} for the Soil Type E response-spectrum-compatible excitation

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