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Probability analysis of seismic pounding of adjacent buildings

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SUMMARY

The need to investigate the level of seismic pounding risk of buildings is apparent in future building code calibrations. In order to provide further insight into the pounding risk of adjacent buildings, this study develops a numerical simulation approach to estimate the seismic pounding risk of adjacent buildings separated by a minimum code-specified separation distance during a certain period of time. It has been demonstrated that the period ratio of adjacent buildings is an important parameter that affects the pounding risk of adjacent buildings. However, there is no specific consideration for the period ratio in the related seismic pounding provisions of the 1997 Uniform Building Code. Results also reveal that, for two adjacent buildings, the probability distribution of required distance to avoid seismic pounding fits very well with the type I extreme value distribution. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS: adjacent building; pounding probability; risk analysis

INTRODUCTION

Many cases of structural damage due to pounding between adjacent buildings during major earthquakes have been reported over the past two decades [1–4]. As shown in Figure 1, out-of-phase vibrations can be induced if adjacent buildings have different dynamic characteristics and structural pounding may occur if the separation distance is inadequate.

The methods used in the dynamic analyses of non-linear multi-degree-of-freedom systems under random excitations can be classified into two categories: the theoretical approach and the numerical simulation approach. The main advantage of the theoretical approach is that an exact solution may be obtained. However, its use is frequently limited because of the assumptions made on the analytical procedures. For the past few decades, the numerical simulation

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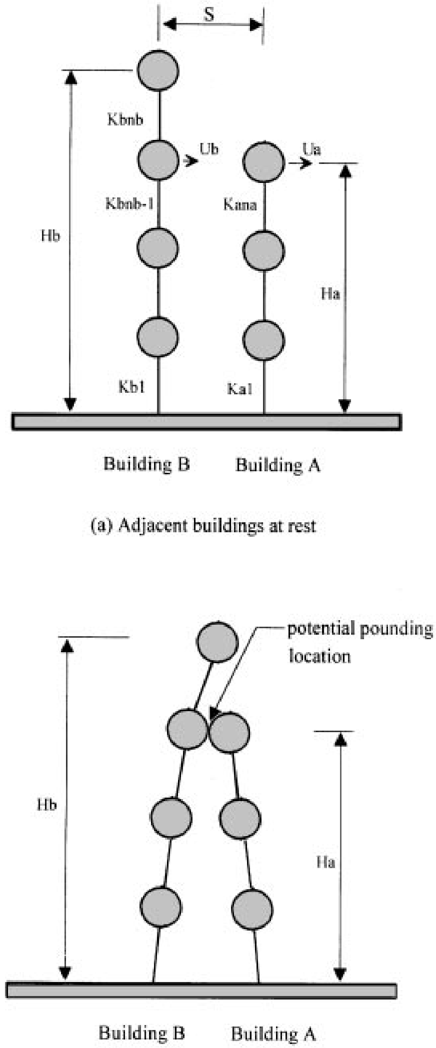


(a) Adjacent buildings at rest

(b) Adjacent buildings at pounding

Figure 1. Analytical model.

approach has gained a wide range of applications in solving responses of non-linear multi-degree-of-freedom systems. In this study, the numerical simulation method is adopted.

Building codes providing a set of minimum technical rules and a legal basis for the practice of structural engineering are intended to ensure safety and play the role of transferring technology from research to practice. Despite significant advances in structural engineering design in recent years, uncertainty induced by structural loads and material strengths, however, gives rise to risk. The writers of building codes frequently address the question: "What is the probability of structural failure during its useful life?”. It is noted that one of the critical objectives of design codes is to restrict the “maximum risk” to a socially acceptable level. The concept and the philosophy of probability-based design have been adopted by recent building codes for many years. The probability, implicated in the seismic provisions of the 1997 Uniform Building Code (UBC’97) [5], that the recommended intensity of earthquake motions at a given location will not be exceeded during a 50-year period is estimated to be about 90 per cent. In other words, a 90 per cent probability of the recommended intensity not being exceeded in a 50-year interval is equivalent to a mean recurrence interval of 475 years or an average annual risk of 0.002 events per year. However, based on a literature survey conducted by the authors, there are no published results on the seismic pounding probability of adjacent buildings. Therefore, the need to investigate the level of seismic pounding risk of adjacent buildings for future code calibrations is quite apparent. In this study, the overall pounding probability of adjacent buildings will be evaluated by combining the results of the seismic hazard analyses and the relations of peak ground acceleration (PGA) and the conditional pounding probability, which means the pounding probability of adjacent buildings subjected to earthquakes with a “specified” PGA.

The main objectives of this study are to provide constructive suggestions for code calibration in the future and to develop a numerical simulation approach to evaluate the pounding probability of adjacent buildings separated by minimum code-specified separation distance during their useful life of 50 years.

LITERATURE REVIEW

In recent years, valuable insights on structural pounding behaviours and formulas for evaluating building separation distances based on linear or equivalent linear procedures have been proposed.

Miller and Fatemi [6] investigated the pounding problem of adjacent buildings subjected to harmonic motions by the vibroimpact concept. Anagnostopoulos [7] analysed the effect of pounding for buildings under strong ground motions by a simplified single-degree-of-freedom (SDOF) model. Anagnostopoulos and Spiliopoulos [8] investigated the response of mutual pounding between adjacent buildings in city blocks to several strong earthquakes. In the study, the buildings were idealized as lumped-mass, shear beam type, multi-degree-of-freedom (MDOF) systems. Westermo [9] applied links to adjacent buildings to reduce the pounding effect. Maison and Kasai [10] modelled the buildings as multiple-degree-of-freedom systems and analysed the response of structural pounding with different types of idealizations. Papadrakakis *et al.* [11] studied the pounding response of two or more adjacent buildings based on the Lagrange multiplier approach by which the geometric compatibility conditions due to contact are enforced. A three-dimensional model developed for the simulation of the pounding response of adjacent buildings is presented by Papadrakakis *et al.* [12].

In the evaluation of building separation, Jeng *et al.* [13] estimated the minimum separation distance required to avoid pounding of adjacent buildings by the spectral difference (SPD) method. Kasai *et al.* [14] extended Jeng’s results and proposed a simplified rule to predict the inelastic vibration phase of buildings based on the numerical results of dynamic time-history analyses. Penzien [15] proposed a formula for evaluating separations of two buildings, based on the procedures of equivalent linearization and the assumptions that the required minimum separation $S_{\text{req'd}}$ is controlled by the first-mode type of responses and that the mode shape of responses is linear. The first writer [16] proposed a theoretical solution based on random vibration theory to predict the statistics of separations of adjacent buildings, assuming linear elastic responses. Hao and Zhang [17] investigated earthquake ground motion spatial variation effects on relative linear elastic responses of adjacent building structures.

BASIC ASSUMPTIONS OF THE PROPOSED APPROACH

To generate artificial earthquake motions for dynamic analysis of structures, the design response spectrum of dense soils and soft rocks (soil profile type Sc of the UBC'97), shown in Figure 2(a), is selected. To simulate the transient character of real earthquakes, the stationary earthquake motions generated from the power spectral density function of dense soils and soft rocks, shown in Figure 2(b), are multiplied by a trapezoidal intensity envelope function, expressed by

$$I(t) = \begin{cases} t/0.15t_{\mathrm{d}} & 0 \leqslant t \leqslant 0.15t_{\mathrm{d}} \\ 1.0 & 0.15t_{\mathrm{d}} \leqslant t \leqslant 0.75t_{\mathrm{d}} \\ t_{\mathrm{d}} - t/0.25t_{\mathrm{d}} & 0.75t_{\mathrm{d}} \leqslant t \leqslant t_{\mathrm{d}} \end{cases} \tag{1}$$

where t_{d} is the time duration and is taken as 30 sec in this study. The earthquake intensity, expressed by the peak ground acceleration (PGA), is taken as 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, 1.0 and 1.2g.

It is assumed that the dynamic response of a building can be well simulated by using the lumped-mass structural system and the excitation can be considered as a non-stationary Gaussian random process with zero mean. The structural system of the buildings investigated in this study is steel moment-resisting frame (SMRF). For simplicity of the numerical simulation, the structure is modelled as a multi-degree-of-freedom shear-type model which exhibits elastoplastic behaviour in the form of a hysteretic restoring force–displacement characteristic

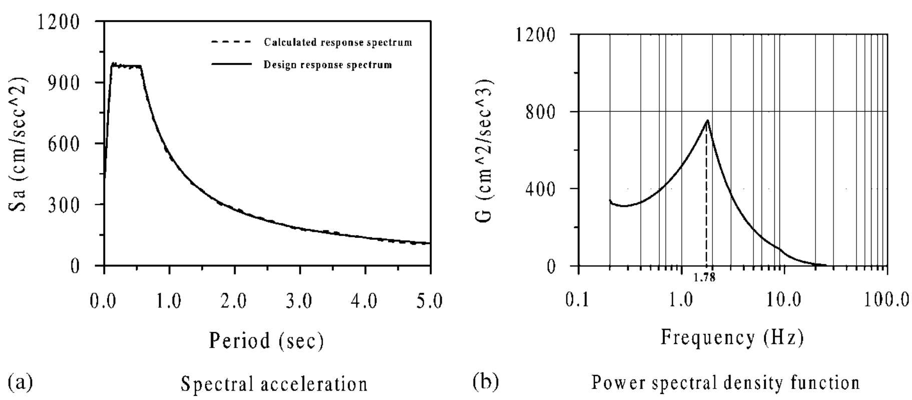


Figure 2. Response spectrum and power spectral density function for dense soils and soft rocks (PGA $= 0.4g$).

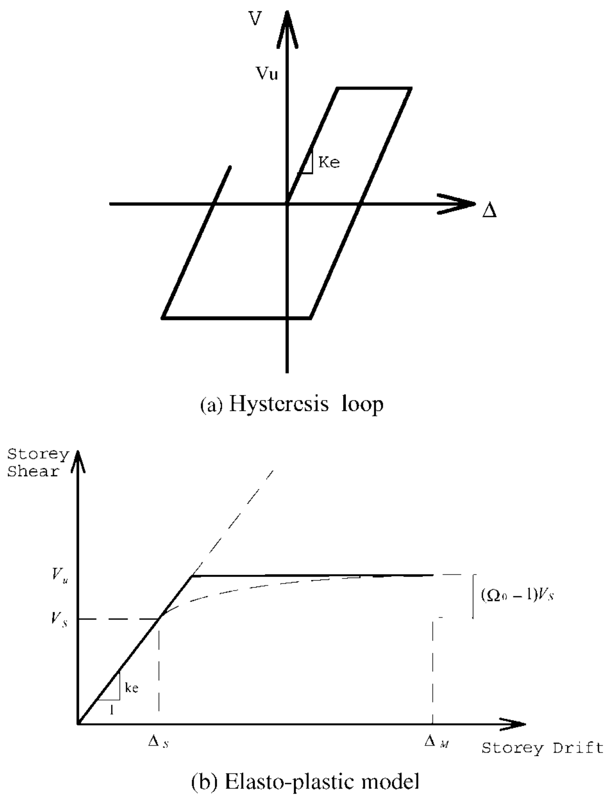


Figure 3. Storey shear vs. storey drift.

(Figure 3), although the elastoplastic behaviour may not fully represent the actual behaviour of the SMRF structures. Torsional effects on structure responses are ignored. For each building, the relation of the fundamental period and the building height, shown in Table I, is determined from formula (30-8) of the UBC'97 for steel moment-resisting frames. For buildings having the same heights and periods, the responses are assumed to be the same. It is noted that this assumption is only valid for those buildings having the same elastoplastic hysteresis behaviours.

In addition, it is assumed that floor elevations are the same for all buildings so that pounding occurs only at those elevations where the masses are lumped. For adjacent buildings having different heights, the pounding location is assumed to occur at the top level of the shorter building, as shown in Figure 1(b). The equation of motion for the idealized non-linear multi-degree-of-freedom system is expressed as

$$\{f_{\mathrm{I}}(t)\} + \{f_{\mathrm{D}}(t)\} + \{f_{\mathrm{S}}(t)\} = \{p(t)\} \tag{2}$$

where $\{f_{\mathrm{I}}(t)\}$, $\{f_{\mathrm{D}}(t)\}$, $\{f_{\mathrm{S}}(t)\}$, and $\{p(t)\}$ are inertial force vector, damping force vector, elastic force vector and equivalent force vector, respectively. In this study, an unconditionally

Table I. Parameter values of buildings investigated in this study.

Storey number of building, n	Building height, H (cm)	Fundamental[(a)] period, T (sec)	Stiffness, Ke_1,[(b)] (kN/cm)	Design base shear, V_{s_1} (kN)	Mean ductility demand, μ_s
4	1280	0.575	4708	2040	4.0
6	1920	0.780	5482	2258	4.1
8	2560	0.967	6288	2427	3.6
10	3200	1.144	7080	2566	5.0
12	3840	1.311	7900	2686	4.5
14	4480	1.472	8723	2791	5.1
16	5120	1.627	9574	3136	4.9
18	5760	1.777	10455	3528	4.8
20	6400	1.923	11368	3920	5.2

Note: 1. (a) Formula (28-3) of the 1994 Uniform Building Code for steel moment-resisting frames.
(b) Elastic stiffness of first storey.
2. The mass of each storey equals 454545 kg.

stable step-by-step method, the Wilson θ method, is used to investigate the dynamic responses of structures.

CALCULATION OF BUILDING SEPARATION DISTANCE

Minimum separation distance required to avoid structural pounding

The emphasis in structural pounding problems is on the "relative displacements" of potential pounding location of adjacent buildings. As shown in Figure 1, if $u_a(t)$ and $u_b(t)$ are the displacement time histories and $Z(t)$ is the relative displacement time history of two adjacent buildings A and B at the potential pounding position, then $Z(t)$ can be expressed as

$$Z(t) = u_b(t) - u_a(t) \tag{3}$$

The minimum separation distance required to avoid pounding may be defined as

$$S_{\text{req'd}} = \sup(Z(t)) \tag{4}$$

where "sup" implies the maximum value of the entire range of the relative displacement time history. The structural pounding may occur once the separation distance of adjacent buildings is less than $S_{\text{req'd}}$.

Minimum code-specified separation of adjacent buildings

As illustrated in Figure 4, the UBC'97 requires that all structures be separated from adjoining structures. Separations shall allow for the maximum inelastic response displacement Δ_M, where

$$\Delta_M = 0.7R\Delta_S \tag{5}$$

in which R is the numerical coefficient representative of the inherent overstrength and global ductility capacity of lateral-force-resisting systems and Δ_S is the design level response

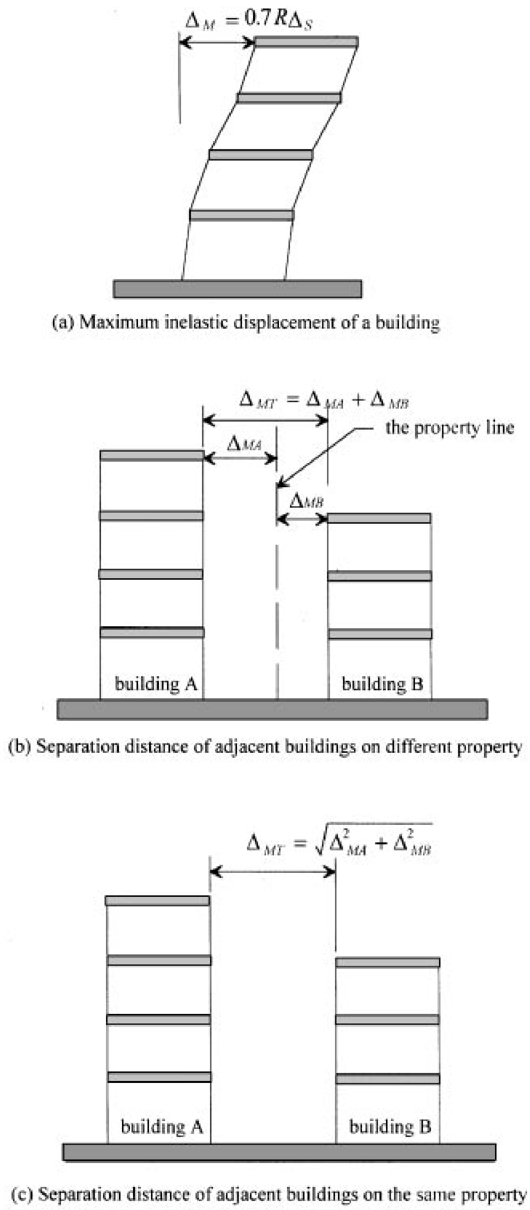


Figure 4. Minimum building separation specified by the UBC'97.

displacement, which is the total drift or total storey drift that occurs when the structure is subjected to the design seismic forces.

When a structure adjoins a property line not common to a public way, that structure shall be set back from the property line by at least the displacement Δ_M of that structure. In other words, adjacent buildings shall be separated by at least Δ_{MT} which can be determined by the ABS (absolute sum) expression

$$\Delta_{MT} = \Delta_{MA} + \Delta_{MB} \tag{6}$$

in which Δ_{MA} and Δ_{MB} are the inelastic displacements of the adjacent buildings A and B, respectively. In addition, adjacent buildings on the same property shall be separated by at least Δ_{MT} which can be determined by the square root of the sum of the squares (SRSS) expression

$$\Delta_{MT} = \sqrt{(\Delta_{MA})^2 + (\Delta_{MB})^2} \tag{7}$$

Note that the use of the ABS and SRSS combination methods, implied by the UBC, provides an upper limit of the required separation distance of adjacent buildings to avoid pounding. These methods generally overestimate the required separation distance. The SRSS method ignores the cross-correlation of the responses of adjacent buildings and provides a conservative estimate for Δ_{MT}. The ABS method considers the entire out-of-phase motion, regardless of the relative magnitudes of the periods of buildings A and B, providing a more conservative estimate for Δ_{MT}.

STUDIED PARAMETERS

Two adjacent buildings, A and B, of different storeys are investigated for the probability of seismic pounding. A total of 36 cases are studied in this research, which include four cases for building A (storey number of building A, $na = 6, 10, 14, 18$) and 9 cases for building B (storey number of building B, $nb = 4, 6, 8, \ldots, 18$, and 20). For each case, statistical analyses are performed on the separation distances computed by Equation (4) for relative displacement responses of adjacent buildings resulting from 1000 artificial earthquakes which are generated compatible with the power spectral density function, shown in Figure 2, and have the same earthquake intensity.

The parameter values of the buildings are given in Table I. In each building, the storey masses and the modal damping ratios are kept the same. The mean ductility ratio which is evaluated by dividing the summation of storey ductility ratio of the building by the storey number is also shown in the table. The structural damping of the Rayleigh type is specified to produce modal damping, 5 per cent of the critical value.

For each building, the storey ultimate shear, V_u, is found by multiplying the design seismic storey shear, V_s, to the overstrength factor, Ω_0 (i.e. $V_u = \Omega_0 V_s$). The design seismic storey shear is the summation of design lateral force, obtained from formula (30-15) of the UBC'97, above the storey under consideration. The elastic stiffness of the first storey, Ke_1, is selected by a trial-and-error method to produce the desired fundamental periods, shown in Table I. The stiffness ratio of the $i+1$th storey to the ith storey, Ke_{i+1}/Ke_i, is equal to 0.95. The relations of the fundamental periods of buildings and building heights, shown in Table I, can be determined from formula (30-8) of the UBC'97 for steel moment-resisting frames. The storey masses are equal to 454545 kg.

Owing to different dynamic characteristics of buildings, the periods of buildings with the same heights may be significantly different. Therefore, two adjacent buildings, A and B, of the same storeys are also investigated for the effect of period distribution of a building on the probability of seismic pounding. A total of 18 cases are studied for this purpose, which include two cases for building A (period of building A, $T_a = 0.78$ and 1.144 sec) and 9 cases for building B (period of building B, $T_b = 0.575$, 0.78, 0.967, 1.144, 1.311, 1.472, 1.627, 1.777 and 1.923 sec).

In this research, the values of R and Ω_0, for steel moment-resisting frames, are equal to 8.5 and 2.8, respectively (Table 16-N of the UBC'97). The seismic zone factor Z, the importance factor I, the seismic coefficients C_a and C_v, and the near source factors N_a and N_v, are taken as 0.4, 1.0, 0.4, 0.56, 1.0, and 1.0, respectively (Tables 16-Q, 16-R, 16-S, and 16-T of the UBC'97).

PROBABILITY DISTRIBUTION OF REQUIRED SEPARATION DISTANCE TO AVOID STRUCTURAL POUNDING

Ruiz and Penzien [18] investigated the probability distribution of the peak values of storey drift of a shear-type building based on 50 sets of earthquake motion. A total of 8 single buildings were studied. The results suggested that the type I extreme value distribution gives close correlations with the actual distribution. However, as for the probability distribution of building separation distance to avoid seismic pounding, the literature survey conducted by the authors revealed that no related publication is found to date.

To investigate the probability distributions of the separation distance of adjacent buildings, the well-known Kolmogorov–Smirnov test that considers the quality of fit between a hypothesized distribution function and an empirical distribution function, is performed on observed separation distances. This test establishes the confidence of the hypothesized probability distribution which is used to simulate the unknown actual distribution. In this study, the hypothesis will be rejected with the level of significance α if the statistic D_n exceeds the critical value ε [19].

The Kolmogorov–Smirnov statistic, D_n, and the critical value, ε, can, respectively, be expressed as

$$D_n = \sup |F_n(S_{\text{req'd}}) - F(S_{\text{req'd}})| \tag{8}$$

and

$$\varepsilon = 1.36/\sqrt{nd} \quad \text{for } \alpha = 0.05 \tag{9}$$

where "sup" implies the maximum value of the entire range of separation distances, F_n represents the empirical distribution function, F is the hypothesized distribution function, and nd denotes the sample size. In this study, the probability distribution of separation distances is still assumed to be type I extreme value distribution and nd equals 1000.

POUNDING PROBABILITY OF ADJACENT BUILDINGS SEPARATED BY MINIMUM CODE-SPECIFIED DISTANCE

The design earthquake ground motion by itself does not determine pounding risk of adjacent buildings; the pounding risk is also affected by the design rules and analysis procedures used in connection with the design ground motion. The overall pounding probability of adjacent buildings during some period of time can be evaluated by combining the results of the seismic hazard analyses and the relations of PGA and the conditional pounding probability of adjacent buildings, which means the pounding probability of adjacent buildings subjected to earthquakes with a specified PGA. It is noted that the emphasis of this study is not on the severity of impacts to which the probability of damage is related but on the chance of structural pounding during earthquake motions.

If the ground motion intensity is characterized by the peak acceleration, a^*, then the seismic pounding risk evaluation proceeds as follows. For structural pounding to occur, two events must take place. Firstly, a ground motion with intensity, a^*, must occur; secondly, this motion must cause pounding. All possible values of a^* must be considered. The probability that pounding will occur during some period of time, P_{p}, may be expressed as follows.

$$P_{\mathrm{p}} = \int_a P_{\mathrm{p}/a^*} Pa^* \mathrm{d}a^* = \int_a P_{\mathrm{p}/a^*} \frac{\mathrm{d}\gamma}{\mathrm{d}a^*} \mathrm{d}a^* \cong \sum_i (P_{\mathrm{p}/a})_i (P_a \, \Delta a)_i \cong \sum_i (P_{\mathrm{p}/a})_i (\Delta\gamma)_i \tag{10}$$

in which P_{p/a^*} expresses the conditional pounding probability of adjacent buildings, which means the pounding probability of adjacent buildings subjected to earthquakes with a specified PGA, a^*; $P_{a^*}\,\mathrm{d}a^*$ or $(\mathrm{d}\gamma/\mathrm{d}a^*)\,\mathrm{d}a^*$ expresses the probability of occurrence of a ground motion with intensity between a^* and a^*+$\mathrm{d}a^*$. γ is the rate at which intensities of shaking are exceeded. The values $a_1, a_2, a_3, \ldots$ provide a suitable discretization of the continuous intensity parameter. For convenience of numerical calculation, the function to be integrated has been evaluated at equal increments Δa. The numerical integration of Equation (10) requires the evaluation of $(\Delta\gamma)_i$ and $(P_{\mathrm{p}/a})_i$ of a ground motion with intensity between a_i and $a_i + \Delta a$. In integration procedure, it is assumed that P_{p/a^*} remains constant between a_i and $a_i + \Delta a$ and can be evaluated from the relation curves of PGA and conditional pounding probability of adjacent buildings, expressed as $(P_{\mathrm{p}/a})_i$. This assumption is valid as long as a short enough Δa is used. Additionally, the value of $(\Delta\gamma)_i$ can be evaluated from the results of the seismic hazard analyses.

Figure 5, which is based on information supplied by Algermissen and Perkins [20, 21] from their study, is a result of the seismic hazard analyses at a given location and indicates the probabilities of not being exceeded in a 50-year interval if the levels of PGA were to be selected. The probability of not being exceeded can be translated into other quantities such as mean recurrence interval and average annual risk. The 90 per cent probability of not being exceeded in a 50-year interval is equivalent to a mean recurrence interval of 475 years or an average annual risk of 0.002 events per year. As shown in Figure 6, there is 90 per cent probability that the PGA will not exceed 0.4g at this location. The value of $(P_a\Delta a)_i$ or $(\Delta\gamma)_i$, which is the occurrence probability of a ground motion with intensity between a_i and $a_i + \Delta a$ in a 50-year interval, can then be evaluated from this figure. The numerical summation process of Equation (10) is depicted graphically in Figure 6.

To investigate the conditional pounding probability of adjacent buildings separated by minimum code-specified separation under earthquakes with different PGA, statistical analyses are performed for the separations of adjacent buildings under 1000 artificial earthquakes. The cumulative distribution function given in Equation (11), called type I asymptotic extreme value

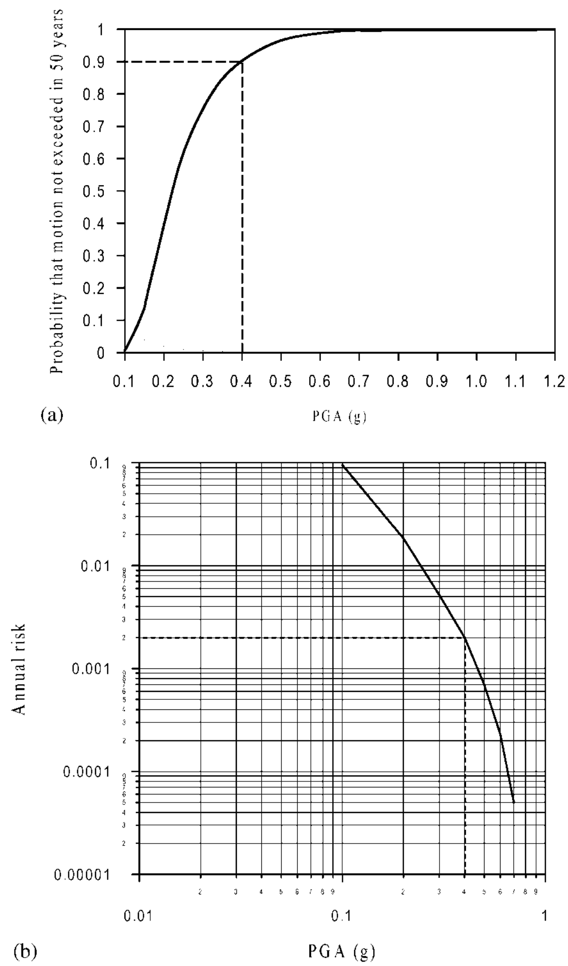


Figure 5. Seismic hazard curve: (a) probabilities of not being exceeded in a 50-year life; (b) annual probability of exceedance.

distribution, is assumed.

$$G(S_{\text{req'd}}) = \exp\{-\exp\{-\alpha_n(S_{\text{req'd}} - u_n)\}\}, \quad -\infty < s < \infty \tag{11}$$

where

$$\alpha_n = \pi/\sqrt{6}\sigma_{S_{\text{req'd}}} \tag{12}$$

and

$$u_n = \bar{S}_{\text{req'd}} - 0.577/\alpha_n \tag{13}$$

in which $\bar{S}_{\text{req'd}}$ and $\sigma_{S_{\text{req'd}}}$ are the mean and the standard deviation of the required separation distances, respectively.

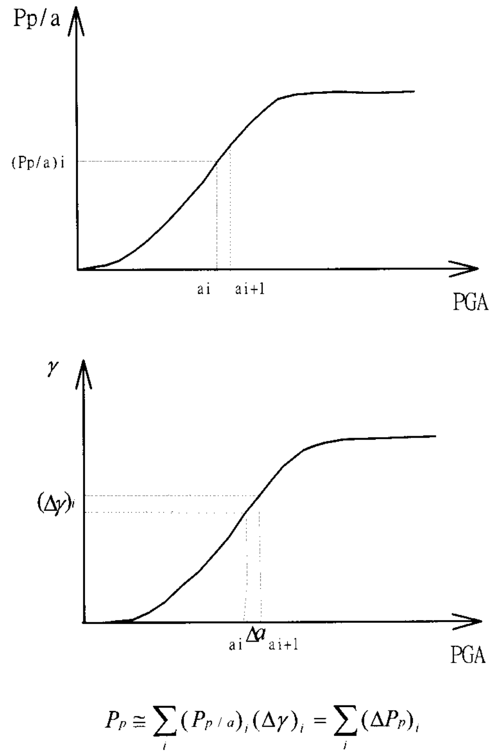


Figure 6. Numerical summation process of overall seismic pounding probability.

The conditional pounding probability of two adjacent buildings can be evaluated once the values of $\bar{S}_{\text{req'd}}$, $\sigma_{S_{\text{req'd}}}$, and Δ_{MT} are determined. In other words, if the $\bar{S}_{\text{req'd}}$, $\sigma_{S_{\text{req'd}}}$, and Δ_{MT} are known, the conditional pounding probability of adjacent buildings, $P_{p/a}$, can be evaluated by Equation (14)

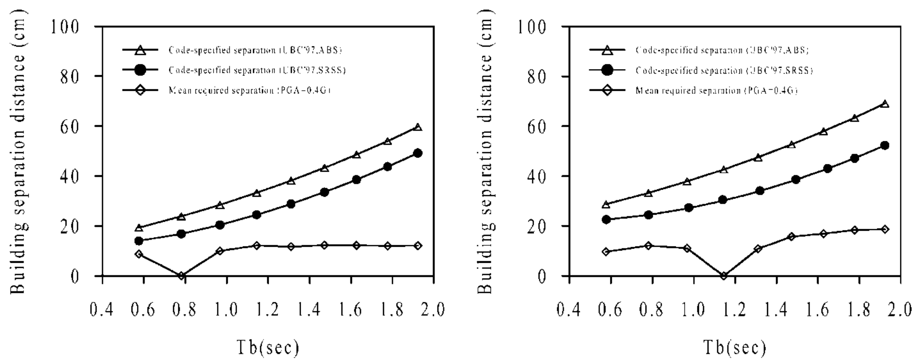
$$\begin{aligned} P_{p/a} &= P[S_{\text{req'd}} > \Delta_{\text{MT}}, \text{ for a specified PGA}] \\ &= 1 - \exp\{-\exp\{-\alpha_n(\Delta_{\text{MT}} - u_n)\}\} \end{aligned} \tag{14}$$

where $S_{\text{req'd}}$ is the required separation distance to avoid pounding, Δ_{MT} is the building separation designed according to the UBC'97 (Equation (6) or (7)), α_n and u_n can be determined from Equations (12) and (13), respectively.

RESULTS AND DISCUSSIONS

Required separation distance of adjacent buildings to avoid pounding

Figures 7(a) and (b) show the comparisons of the separation distances proposed by this study and specified by the UBC'97. The proposed separation distances in these figures are



(a) Ta=0.780 sec. (b) Ta=1.144 sec.

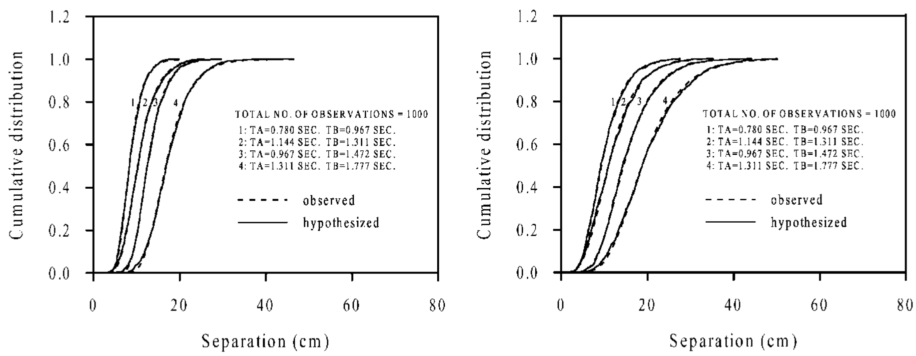
Figure 7. Comparisons of the separation distance proposed by this study and the 1997 Uniform Building Code.

the computed mean values of separation distance required to avoid pounding of the adjacent buildings A and B under earthquake motions of $0.4g$.

As shown in these figures, for a specified period of building A, T_a, the tendency of the calculated mean separation distance relative to the period of building B, T_b, is significantly different from that of the minimum code-required separation distances, especially when the periods of the adjacent buildings become close to each other. For the cases in which the period of building A equals 1.472 or 1.777 sec, similar trends are observed to those shown in Figures 7(a) and 7(b). It is noted that the discrepancy between the calculated mean separation distances and the code-required separation distances mainly results from the fact that the UBC'97 ignores the correlative effect of buildings A and B (Equation (6) and (7)). The combination methods used in the UBC'97 generally overestimate the required separation distance. The SRSS method ignores the correlation of the responses of adjacent buildings and provides a conservative estimate for Δ_{MT}. The ABS method considers the entire out-of-phase motion and provides a more conservative estimate for Δ_{MT}.

Probability distribution of required separation distance to avoid pounding

As shown in Figures 7, the difference between the code-required separation distance and the calculated mean separation distance required to avoid pounding varies with the period of building B for a prescribed period of building A. This observation indicates that the probability of structural pounding of adjacent buildings under major earthquakes may vary with the periods or the period ratios. In order to investigate and demonstrate this observation, the probability distribution of separation distance of adjacent buildings to avoid pounding is assumed to be type I extreme value distribution. It is noted that Ruiz and Penzien [18] had presented that, for shear-type buildings, probability distribution based on the 50 extreme-values of storey drift and shown in the form of type I extreme value distribution shows very good correlations with the actual distribution. However, the literature survey conducted by the authors revealed that no published results on the probability distributions of the building separation distances exist.



(a) PGA=0.3g (b) PGA=0.4g

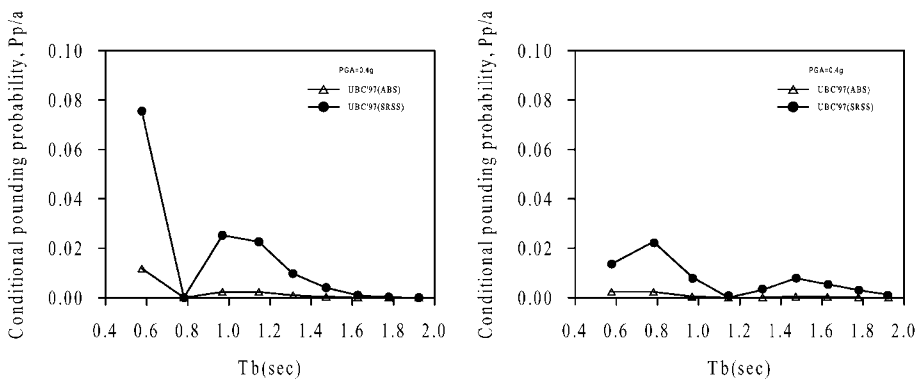
Figure 8. Comparisons of the hypothesized type I distribution function and the simulated distribution function.

Figures 8(a) and (b) show the results of comparisons of the hypothesized type I distribution function and the simulated distribution function for four discrete period ratios and three different earthquake intensities. The simulated distribution plots of the separation distances are constructed from data consisting of 1000 observations. Figure 8 shows that the separation data obtained by the proposed simulation procedures fit almost perfectly with the hypothesized type I distribution. In other words, the simulated distribution functions agree well with the assumed type I distribution functions.

The agreement between the hypothesized type I distribution and the simulated distribution can be further demonstrated by the Kolmogorov–Smirnov statistic, D_n, and the hypothesized probability distribution will be accepted with a level of significance of $\alpha = 0.05$ if the statistic D_n does not exceed the critical value, ε ($\varepsilon = 0.043$ for $nd = 1000$). The results of the Kolmogorov–Smirnov test show that all of the computed D_n values are smaller than 0.043. This observation indicates that the above assumption is satisfactory. Therefore, it would be reasonable to assume that the probability distribution of the required separation distances to avoid structural pounding is a type I extreme value distribution.

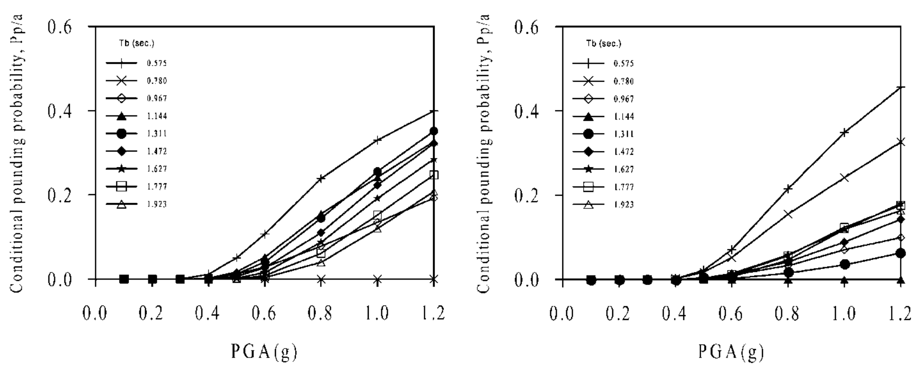
The conditional pounding probability of adjacent buildings

Figure 9 shows the conditional probability of structural pounding of two adjacent buildings separated by a distance determined by the ABS and SRSS methods, according to the UBC'97, with an earthquake intensity of $0.4g$. Four different periods of building A varying from 0.78 to 1.777 sec are assumed for this investigation. For simplicity, only two graphs are shown in the figure and similar results exist for the cases in which the period of building A equals 1.472 or 1.777 sec. As shown in Figure 9, the conditional pounding probabilities of adjacent buildings vary also with T_b. The relations between the conditional pounding probability and PGA for discrete periods of buildings A and B are shown in Figures 10 and 11 for building separations determined by the ABS and SRSS combination methods, respectively. These relation curves are useful in calculating the overall pounding probability of adjacent buildings in a 50-year life.



(a) Ta=0.780 sec. (b) Ta=1.144 sec.

Figure 9. Probability of structural pounding (PGA $= 0.4g$).



(a) Ta=0.780 sec. (b) Ta=1.144 sec.

Figure 10. Conditional pounding probability vs. PGA (combination method: ABS).

The overall pounding probability of adjacent buildings

For all cases studied in this paper, the overall pounding probabilities, P_p, of adjacent buildings separated by minimum code-specified separation during their useful life of 50 years are calculated and depicted in Figure 12(a). Comparisons of the effects of period ratio and combination method adopted in the UBC'97 on the overall pounding probability are made in Figure 12(a) for two adjacent buildings with different heights.

As shown in Figure 12(a), the overall pounding probabilities of adjacent buildings vary with the combination method adopted, the period ratio of an adjacent buildings, and the period of an individual building. In other words, the pounding risks of buildings separated by minimum code-specified separation are not consistent and vary with these factors. Figure 12(a) also shows that the most dangerous case studied is the adjacent buildings whose periods are similar but not equal and simultaneously near the fundamental period of soil (point A of

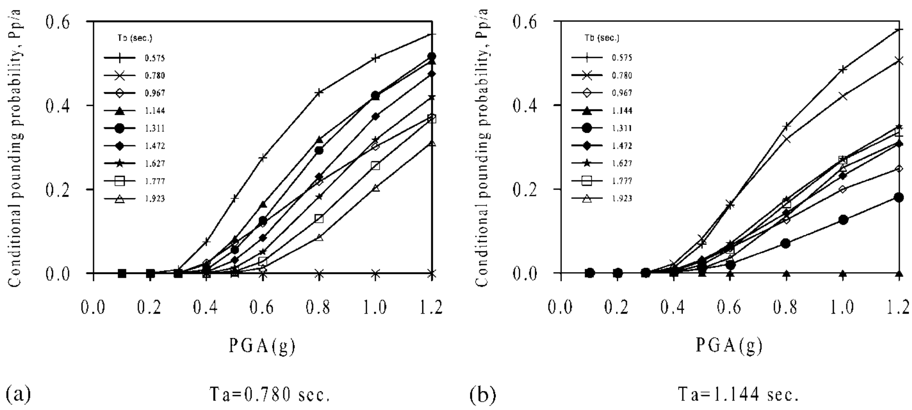


Figure 11. Conditional pounding probability vs. PGA (combination method: SRSS).

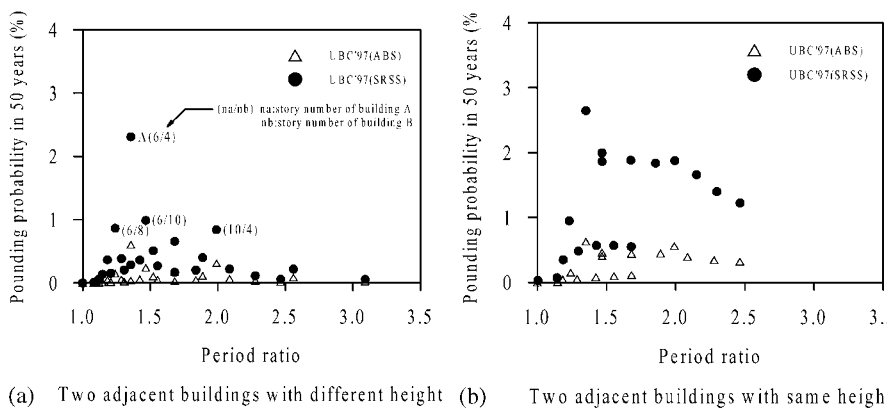


Figure 12. Comparisons of overall pounding probability associated with ABS and SRSS combination methods.

Figure 12(a)). As the periods of two adjacent buildings are well separated or the period ratio of adjacent buildings is far away from 1.0, the pounding probability of buildings is small and decreases rapidly with period ratio. In comparison with the probability (10 per cent) that the design basis ground motion adopted in the UBC'97 will be exceeded during a 50-year period, the maximum pounding probability (2.7 per cent) of adjacent buildings studied seems to be lower. This is the reason why the methods used in the UBC'97 generally overestimate the required separation distance and provide a quite conservative estimate for Δ_{MT}.

Note that due to the differences of the dynamic characteristics (such as: mass and/or stiffness) of the buildings, the periods of the adjacent buildings having the same height are generally not equal. To investigate the effects of period distribution of a building on the pounding probability of adjacent buildings having the same height, a total of 18 cases are studied, which include two cases of T_{a} (0.78 and 1.144 sec) and nine cases of T_{b} (0.575, 0.78, 0.967, 1.144, 1.311, 1.472, 1.627, 1.777, and 1.923 sec). These two cases of T_{a} (0.78

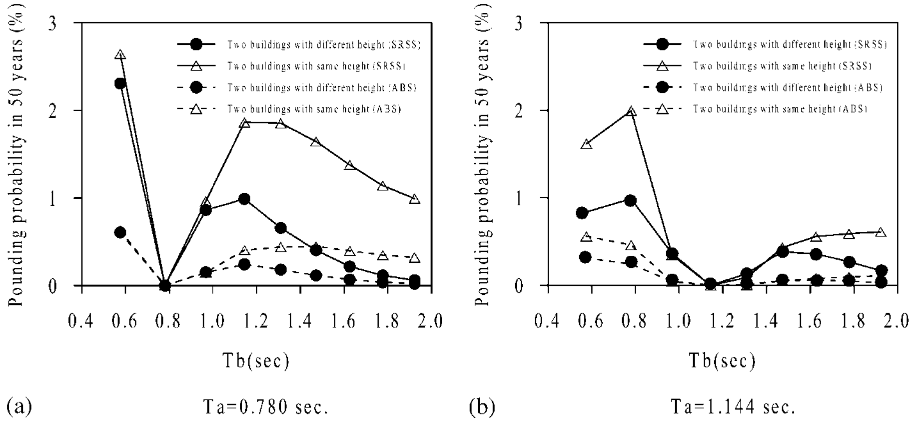


Figure 13. Comparisons of seismic pounding probability of adjacent buildings having different heights and the same height.

and 1.144 sec) express the periods of a 6-storeyed building A and a 10-storeyed building A, respectively.

The effects of period distribution of building B on the pounding probability of adjacent buildings having the same height are shown in Figures 12(b) and 13. As shown in Figure 12(b), the overall pounding probabilities of adjacent buildings vary also with the combination method adopted, the period ratio of adjacent buildings, and the period of an individual building. Comparing Figure 12(b) with Figure 12(a), for two adjacent buildings with the given period ratio, the pounding probability of adjacent buildings having the same height is significantly greater than that of adjacent buildings having different heights when the period ratio of two adjacent buildings is larger. This observation can be further illustrated by the results of Figure 13.

Figure 13(a) illustrates the case of two adjacent 6-storeyed buildings having the same height with $T_a = 0.78$ sec. As shown in Figure 13(a), the pounding probabilities of adjacent buildings having the same height are significantly greater than those of adjacent buildings having different heights when T_a and T_b are well separated. In practice, the most severe and catastrophic cases of pounding have been observed in adjacent buildings with different heights [22, 23]. The pounding occurred at the unsupported part of buildings (e.g., midheight level of the column) resulting in more severe damage than at the supported part of buildings (eg., floor levels) [24]. Note that the pounding of adjacent buildings having the same height generally occurs at the top floor level of both buildings. During a field survey, the surveyors might especially focus their attention on the most severe and catastrophic cases of pounding and pay less attention to the cases of minor or local pounding damage. Thus, the cases in which the pounding of adjacent buildings having the same height generally occurred at the top floor level of both buildings might be ignored. It is noted that the emphasis of this study is not on the degree of pounding damage but on the chance of pounding during earthquake motions. Thus, the intensity of collisions is not considered as a factor that affects the pounding probability studied (see the definition of pounding probability in Equation (14)). However, to detect the effect of period distribution of buildings on the pounding probability, the cases of adjacent buildings having the same height and significantly different periods are also investigated in this study. In addition, the pounding probabilities of adjacent buildings are similar for the case of adjacent buildings having the same height and the case of adjacent buildings having different heights when T_a and T_b become close to each other. Figure 13(b) illustrates the case of two adjacent 10-storeyed buildings having the same height with $T_a = 1.144$ sec. Similar trends are observed to those shown in Figure 13(a) even though the building heights considered in Figure 13(a) and Figure 13(b) are quite different.

CONCLUSIONS

The emphasis of this study is on the use of statistical and numerical simulation approach to investigate the seismic pounding probability of adjacent buildings separated by a minimum code-specified separation distance and the probability distribution of required separation distance of adjacent buildings to avoid seismic pounding.

Some major findings of this study are summarized as follows:

(1) The probability distribution of the required separation distance of adjacent buildings to avoid pounding under earthquake motions with a specified PGA, obtained by the proposed simulation procedures, fits well with type I extreme value distribution.
(2) Results of this study reveal that the pounding risk of adjacent buildings is significantly affected by the natural period of an individual building and the period ratio of adjacent buildings.
(3) The methods used in the UBC'97 provide poor estimates of the required building separation due to improper treatment of the vibration phase of adjacent buildings.
(4) The pounding risks of buildings separated by minimum code-specified separation distance are not consistent for all cases studied in this research.
(5) The pounding risk of adjacent buildings increases as the periods of buildings approach the period of the site soil.

For future study, it is noted that adjacent buildings may be constructed with different materials and exhibit different hysteretic behaviours. To better simulate the actual pounding probability of adjacent buildings of different materials, the use of different hysteretic loops for each building will be necessary.

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