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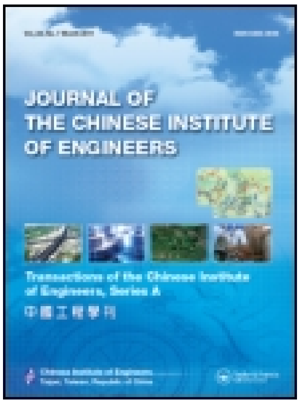

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A study on seismic pounding probability of buildings in Taipei metropolitan area

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A STUDY ON SEISMIC POUNDING PROBABILITY OF BUILDINGS IN TAIPEI METROPOLITAN AREA

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Key Words: seismic pounding probability, building separation distance, Taipei metropolitan area.

ABSTRACT

This study investigates the seismic pounding probability of buildings in the Taipei metropolitan area. Detailed procedures of the analytical method are presented. The results indicate that the building separation specified in the Seismic Provisions of the 1997 Taiwan Building Code (TBC'97) generally provides a relatively conservative estimate compared to that specified in the 1994 Uniform Building Code (UBC'94) for the required distance to avoid pounding. This observation is demonstrated by comparing both the separation distance and/or the pounding probability of adjacent buildings based on the TBC'97 with those based on the UBC'94. The comparison results also reveal that the building separation distance specified by the TBC'97 is 1.6 times that specified by the UBC'94 for the same building and site soil condition. If a reduction coefficient of 0.375 is adopted instead of the 0.6 specified in the TBC'97 to consider the effect of vibration phase difference of adjacent buildings, the critical pounding risk of the TBC'97 and the UBC'94 will be similar.

I. INTRODUCTION

The theory of structural pounding risk analysis may be considered as a branch of applied probability theory. The main issue of this theory is to define an event called "structural pounding" and to set up a "probability space" that contains that event. This modeling part of structural pounding risk analysis is based on statistical information about the uncertainty of the relevant parameters or knowledge about the inherent stochastic nature of the applied earthquake loads. Additionally, the analytical processes should be able to, by some mathematical algorithm, calculate the probability of structural pounding. The result may be needed for comparison with standardized critical values fixed by the adopted building code.

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Fig. 1 Buildings without proper separation distance (Keelung Road, Taipei)


Fig. 2 Collapse example of structural pounding in Dong-Shi

For buildings in the Taipei metropolitan area, the seismic pounding of adjacent buildings may pose a potentially serious problem since the past Taiwan Building Code (TBC) did not provide definite guidelines on building separation and maximum land use is often required due to high population density and economic considerations. As shown in Fig. 1, there are many buildings which are already built in contact with or extremely close to one another in this area. It is noted that out-of-phase vibrations may be induced when adjacent buildings are subjected to earthquake loading and pounding may occur if the separation distance is inadequate.

Pounding damage was observed in past earthquakes such as Thessaloniki, Greece (1978), Central Greece (1981), Guerrero-Michoacan, Mexico (1985), Loma Prieta, Santa Cruz (1989), etc. Especially for the 1985 Mexico earthquake, it shocked the world and attracted more concerns to structural pounding problems of buildings. A surveyed result of the 1985 Mexico earthquake revealed that over 40% of the collapsed or severely damaged buildings were as a result of structural pounding events, and for at least 15% of them, pounding was the main cause for collapse (Rosenblueth and Meli, 1986). A clear review of the reported pounding damage was given by Anagnostopoulos (1995). In 1999, the Chi-Chi earthquake in central Taiwan, unfortunately, brought towns and villages near the epicenter to destruction. Not surprisingly, structural pounding events were also observed after the earthquake. As shown in Figs. 2 to 4, many structural failure examples resulted from seismic pounding due to inadequate building separation distance were observed by the writers in Dong-Shi, Feng-Yuan, Pu-Li, Da-Li, etc.


Fig. 3 Major damage example of structural pounding in Pu-Li

In the past, there were many valuable studies regarding the pounding behavior of buildings under the action of earthquakes. Most of the investigations emphasized the deterministic aspect of the problem.

Fig. 4 Minor damage example of structural pounding in Dong-Shi

Based on a literature survey conducted by the authors, there are no published results found on the study of the probability of seismic pounding of adjacent buildings, although the concept and the philosophy of probability-based design have been accepted for many years. Despite significant advances in structural engineering design in recent years, uncertainty induced by structural loads, however, gives rise to risk. The framers of building codes frequently address the questions: “What is the probability of structural failure during its useful life?”. Therefore, the need to investigate the level of seismic pounding risk of buildings is quite apparent in future code calibrations.

To gain an insight into the pounding risk of buildings in the Taipei metropolitan area and to evaluate the validity of the pounding related provisions of the Taiwan Building Code, this study investigates the pounding probability of buildings designed according to the TBC’97. Comparisons of the pounding related provisions of TBC’97 and UBC’94 are also made. It is noted that the need to investigate the pounding risk of buildings is essential to future code calibrations.

II. LITERATURE REVIEW

Valuable insights on structural pounding behavior and formulas for evaluating the minimum separation distance based on linear or equivalent linear procedures have been proposed. Miller and Fatemi (1983) investigated the pounding problem of adjacent buildings subjected to hamonic motions by vibroimpact concept. Anagnostopoulos (1988) analyzed the effect of pounding for buildings under strong ground motions by simplified single-degree-of-freedom (SDOF) model. Anagnostopoulos and Spiliopoulos (1992) investigated the response to mutual pounding between adjacent buildings in city blocks in several strong earthquakes. In the study, the buildings were idealized as lumped-mass, shear beam type, multi-degree-of-freedom (MDOF) systems. Westermo (1989) applied links to adjacent buildings to reduce the pounding effect. Maison and Kasai (1990) modeled buildings as multiple-degree-of-freedom systems and analyzed the response to structural pounding of different types of idealizations. Papadrakakis *et al.* (1991) 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.* (1996).

In evaluation of building separation, Jeng *et al.* (1992) estimated the minimum separation distance required to avoid pounding of adjacent buildings by the spectral difference (SPD) method. Kasai *et al.* (1996) 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 (1997) proposed a formula for evaluating separation distances of two buildings, based on the procedure of equivalent linearization and the assumptions that the minimum separation distance $S_{req'd}$ is controlled by the first-mode type of responses and the mode shape of responses is linear. Lin (1997) proposed a theoretical solution based on random vibration theory to predict the statistics of separation distance of adjacent buildings, assuming linear elastic responses. Hao and Zhang (1999) investigated earthquake ground motion spatial variation effects on relative linear elastic response of adjacent building structures.

In evaluation of the pounding risk of buildings, Lin and Weng (2001a) proposed a spectral approach to investigate the seismic pounding probability of adjacent buildings based on random vibration theory and total probability theory, assuming linear elastic structure responses. Recently, Lin and Weng (2001b) investigated the probability distribution of the required separation distance of buildings with steel moment-resisting frame (SMRF), which exhibit elasto-plastic behavior in the form of a hysteretic restoring force-displacement characteristic, by the Kolmogorov-Smirnov test that considers the quality of fit between a hypothesized distribution function and an empirical distribution function, based on data obtained by the Monte Carlo simulation method. The results indicated that the separation data fit almost perfectly with the type I extreme value distribution.

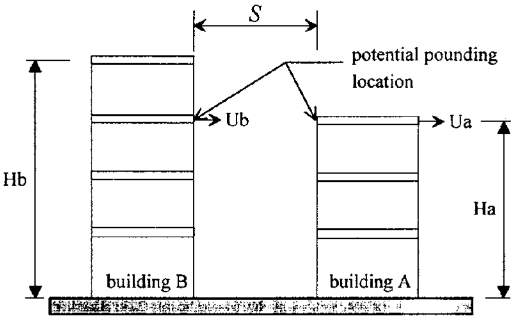
III. BUILDING SEPARATION

1. Required Separation Distance to Avoid Structural Pounding

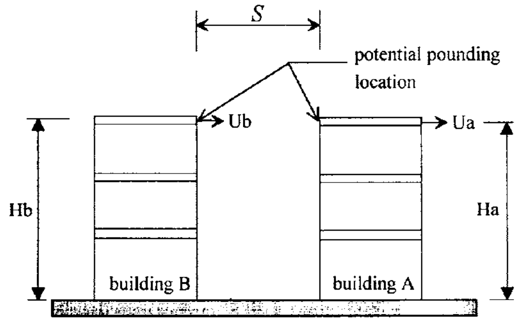
The emphasis in structural pounding problems is on the “relative displacement” of potential pounding location of adjacent buildings. As shown in Fig. 5, if $u_a(t)$ and $u_b(t)$ are the displacement time histories of adjacent buildings A and B at the potential pounding position, then the “maximum” relative displacement of potential pounding location of adjacent buildings or the required separation distance to avoid structural pounding can be expressed as

$$S_{req'd}=sup(u_b(t)-u_a(t)) \qquad (1)$$

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 $S_{req'd}$.



(a) Adjacent buildings having different height



(b) Adjacent buildings having same height

Fig. 5 Potential pounding location: (a)Adjacent building having different height; (b)Adjacent building having same height

2. Code-specified Separation Distance

Since the 1985 Mexico major earthquake brought Mexico city to destruction, seismic pounding provisions have been introduced into almost all of the major building codes worldwide such as: the Uniform Building Code, Mexico’s Federal District Code, and National Building Code of Canada, etc. There are some differences in details among these codes. However, the design philosophy and bases for the provisions are similar. Calibrations of the related provisions are still processing to date. Especially, the seismic pounding provisions in the 1997 Uniform Building Code (UBC’97), one of the most advanced seismic codes worldwide, has important modifications with respect to previous versions.

(i) Taiwan Building Code

Calibrations of the seismic provisions of the Taiwan Building Code (TBC) have been made over three years since 1997. This version is up to date and has great modifications to the seismic provisions for the design of structures with respect to previous versions. The seismic pounding provisions in the new version require that all structures shall be separated from adjoining structures to prevent pounding and building separations shall allow for $0.6*1.4*\alpha_y*R_a$ times the displacement Δ_e due to design seismic forces, where 1.4 is the overstrength factor, α_y is the first yielding amplification factor, and R_a is the allowable system ductility factor. As a reduction factor, the coefficient of 0.6 implies two special considerations in the provision of building separation. First, the required separation distance to prevent pounding largely depends on the vibration phase difference between adjacent buildings. Second, the probability that the peak displacements of two adjacent buildings occur simultaneously is small. In other words, the building separation distance specified in the TBC’97 is taken as 60% of the absolute sum of maximum inelastic displacements of two adjacent buildings, as illustrated in Fig. 6.

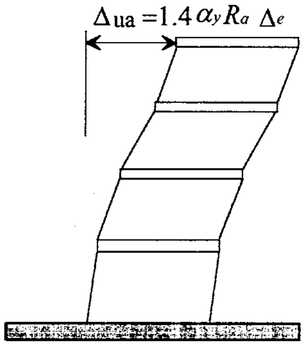
If the story drift ratios in each of the adjacent buildings are within the maximum value, the minimum code-specified separation distance of adjacent buildings A and B can be expressed by

$$S_{code}=0.6(\Delta_{ua,A}+\Delta_{ua,B}) \qquad (2)$$

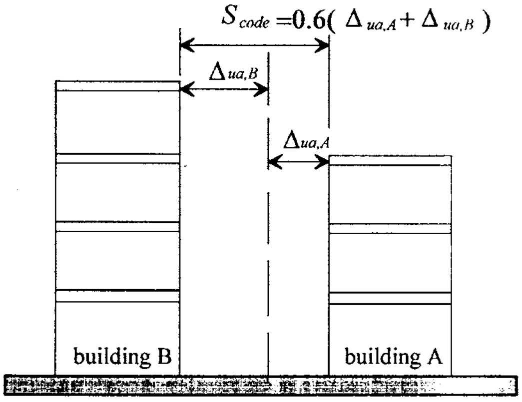
where $\Delta_{ua,A}=1.4*\alpha_y*R_{a,A}*\Delta_{e,A}$

$$\text{and } \Delta_{ua,B}=1.4*\alpha_y*R_{a,B}*\Delta_{e,B} \qquad (3)$$

in which $\Delta_{ua,A}$ and $\Delta_{ua,B}$ are, respectively, the allowable plastic displacement of buildings A and B;



(a) Allowable inelastic displacement of a building



(b) Separation distance of adjacent buildings

Fig. 6 Minimum building separation specified by the TBC'97

$\Delta_{e,A}$ and $\Delta_{e,B}$ are, respectively, the elastic displacements of buildings *A* and *B* due to design seismic forces.

(ii) Uniform Building Code

The UBC'94 requires that all structures shall be separated from adjoining structures, and separations shall allow for $3(R_w/8)$ times the displacement due to seismic forces, where R_w is the system performance factor. In addition, it is also required that the story drift shall not exceed $0.04/R_w$ or 0.005 times the story height for structures having a fundamental period of less than 0.7 seconds and the story drift shall not exceed $0.03/R_w$ or 0.004 times the story height for structures having a fundamental period of 0.7 seconds or greater.

If the story drift ratios in each of the adjacent buildings are within the maximum values mentioned above, the minimum code-specified separation distance of adjacent buildings *A* and *B* can be expressed by

$$S_{code} = (3R_{w,a}/8)\sum_{i=1}^{na}(\theta_{ai} * h_{ai}) + (3R_{w,b}/8)\sum_{i=1}^{nb}(\theta_{bi} * h_{bi}) \tag{4}$$

where θ_{ai}, h_{ai}, na, and $R_{w,a}$ are the i^{th} story drift ratio, the i^{th} story height, the story number, and the system performance factor of building *A*, respectively; θ_{bi}, h_{bi}, nb, and $R_{w,b}$ are the i^{th} story drift ratio, the i^{th} story height, the story number, and the system performance factor of building *B*, respectively. Note that the use of the ABS (absolute sum) method is implied by the UBC'94. The ABS method provides an upper limit of the required separation distance of adjacent buildings *A* and *B* to avoid pounding. The method considers the entire out-of-phase motion between adjacent buildings, regardless of the relative magnitudes of the periods of buildings *A* and *B*, and provides an extremely conservative estimate for required separation distance.

3. Comparison of the Pounding Related Provisions Between the Taiwan Building Code and the Uniform Building Code

For two buildings designed, respectively, according to the TBC'97 and the UBC'94, if both buildings have the same building conditions (including structural system, dynamic characteristics, occupancy requirement) and site soil conditions (including site soil profile and intensity of design basis ground motion), and if the structural systems of both buildings are the SMRF systems and structural periods are greater than 0.465 seconds, the design seismic force ratio and the property line setback ratio of the TBC'97 to the UBC'94 are determined as follow:

(i) If the reduction coefficient of earthquake force $Fu \leq 2.5$, the design seismic force ratio

$$\frac{V_{TBC}}{V_{UBC}} = \frac{\dfrac{ZIC_T W}{1.4\alpha_y F_u}}{\dfrac{ZIC_u W}{R_W}} = \frac{R_W}{1.4\alpha_y F_u} = \frac{12}{1.4 * 1.4 * 2.9} = 2.11 \tag{5}$$

Then, the property line setback ratio

$$\frac{\Delta_{TBC}}{\Delta_{UBC}} = \frac{(0.6)(1.4)\alpha_y R_a \Delta_{e,TBC}}{\frac{3}{8} R_W \Delta_{e,UBC}} = \frac{(0.6)(1.4)\alpha_y R_a}{\frac{3}{8} R_W}\left(\frac{V_{TBC}/K}{V_{UBC}/K}\right)$$

$$= \frac{0.6 * 1.4 * 1.4 * 2.9}{\frac{3}{8} * 12}(2.11) = 1.6 \tag{6}$$

(ii)If the reduction coefficient of earthquake force $Fu > 2.5$, the design seismic force ratio

$$\frac{V_{TBC}}{V_{UBC}} = \frac{\dfrac{ZIF_u\left(\dfrac{C_T}{F_u}\right)_m W}{3.5\alpha_y}}{\dfrac{ZIC_u W}{R_W}} = \frac{R_W}{3.5\alpha_y} = \frac{12}{3.5 * 1.4} = 2.45 \tag{7}$$

Then, the property line setback ratio

$$\frac{\Delta_{TBC}}{\Delta_{UBC}} = \frac{(0.6)(1.4)\alpha_y R_a^* \Delta_{e,TBC}}{\frac{3}{8} R_W \Delta_{e,UBC}} = \frac{(0.6)(1.4)\alpha_y R_a^*}{\frac{3}{8} R_W} \left(\frac{V_{TBC}/K}{V_{UBC}/K}\right)$$

$$= \frac{0.6 * 1.4 * 1.4 * 2.5}{\frac{3}{8} * 12}(2.45) = 1.6 \qquad (8)$$

Note that, as shown above, the property line setback designed according to the TBC'97 is 1.6 times that designed according to the UBC'94.

IV. POUNDING PROBABILITY OF ADJACENT BUILDINGS

The overall pounding probability of adjacent buildings, P_p, during a period of time can be evaluated by total probability theory. In other words, the overall pounding probability of adjacent buildings during a period of time can be evaluated by combining the results of the seismic hazard analyses and the relations of PGA (Peak Ground Acceleration) and the pounding probability of adjacent buildings.

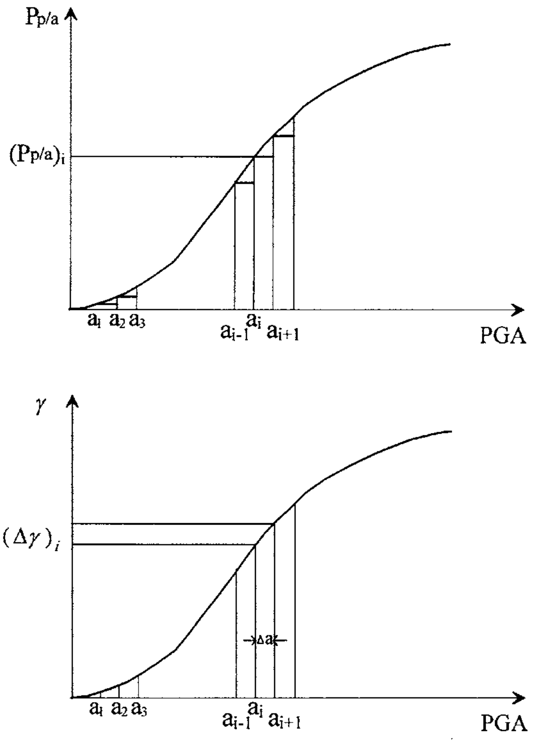
If the ground motion intensity is characterized by the peak acceleration, a^*, then the seismic pounding risk evaluation proceeds as follows. For structural pounding to occur, two events must happen. First, a ground motion with intensity, a^*, must occur; secondly, this motion must cause pounding. All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

$$P_p = \int_a P_{p/a^*} P_{a^*} da^* = \int_a P_{p/a^*} \frac{d\gamma}{da^*} da^*$$

$$\cong \sum_i (P_{p/a})_i (P_a \Delta a)_i$$

$$\cong \sum_i (P_{p/a})_i (\Delta\gamma)_i \qquad (9)$$

in which P_{p/a^*} expresses the pounding probability of adjacent buildings subjected to earthquakes with a specified PGA, a^*; $P_{a^*}da^*$ or $\frac{d\gamma}{da^*}da^*$ expresses the probability of occurrence of a ground motion with intensity between a^* and a^*+da^*. The numerical summation process of Eq. (9) is depicted graphically in Fig. 7. The values a_1, a_2, a_3,...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 Eq. (9) requires the evaluation of $(\Delta\gamma)_i$ and $(P_{p/a})_i$ 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 pounding probability of adjacent buildings, expressed as $(P_{p/a})_i$. This assumption is available so 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.



$$P_p \cong \sum_i (P_{p/a})_i (\Delta\gamma)_i = \sum_i (\Delta P_p)_i$$

Fig. 7 Numerical summation process of overall pounding probability

As shown in Fig. 8, the solid-line curve, which are respectively based on information supplied by Tan *et al.* (1985) is a result of seismic hazard analyses in the Taipei basin. The curve shown in Fig. 8 indicates the probabilities of not being exceeded in a 50 year interval if the levels of PGA were to be selected. A probability of not being exceeded can be translated into other quantities such as mean recurrence interval. A 90 percent probability of not being exceeded in a 50 year interval is equivalent to a mean recurrence interval of 475 years. As shown in Fig. 8, there is 90 percent probability that the PGA will not exceed 0.23g in the Taipei basin. The value of $(P_p\Delta a)_i$ or $(\Delta\gamma)_i$, which is the occurance 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.

Note that Ruiz and Penzien (1969) showed that, for shear type buildings, a probability distribution based on the 50 extreme-values of story drift and

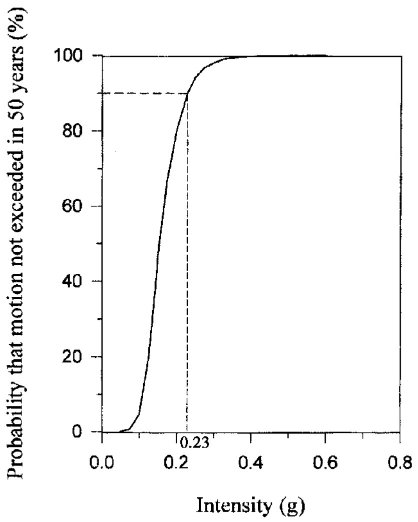


Fig. 8 Seismic hazard curve for a site in the Taipei metropolitan area

shown in the form of type I extreme value distribution shows a very good correlation 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. Recently, to investigate the probability distribution of the required separation distance to avoid structural pounding, 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 by Lin and Weng (2001b). The test establishes the confidence of the hypothesized probability distribution that is used to simulate the unknown actual distribution. In the study, the simulated distribution plots of the separation distances are constructed from data consisting of 1000 observations. The results show that the separation data obtained by the Monte Carlo simulation procedures fit almost perfectly with the hypothesized type I distribution. In other words, the probability distribution of the building separation distances can be assumed to be the type I extreme value distribution. Thus, the probability distribution of the random variable $S_{req'd}$, demonstrated by Lin and Weng (2001b), can be given by the form

$$G(S_{req'd})=\exp\{-\exp\{-\alpha_n(S_{req'd}-u_n)\}\} \tag{10}$$

where $$\alpha_n=\frac{\pi}{\sqrt{6}\sigma_{S_{req'd}}} \tag{11}$$

and $$u_n=\overline{S}_{req'd}-0.577/\alpha_n \tag{12}$$

in which $\overline{S}_{req'd}$ and $\sigma_{S_{req'd}}$ are the mean and the standard deviation of random variable $S_{req'd}$, respectively. Hence, the pounding probability of two adjacent buildings separated by a minimum code-specified separation and subjected to earthquakes with a "specified" peak ground acceleration (called the "conditional" pounding probability of adjacent buildings) can be evaluated, if the $\overline{S}_{req'd}$, $\sigma_{S_{req'd}}$, and S_{code} are determined. In other words, if the $\overline{S}_{req'd}$, $\sigma_{S_{req'd}}$, and S_{code} are known, the conditional pounding probability of adjacent buildings, $P_{p/a}$, can be evaluated by Eq. (13).

$$P_{p/a}=1-\exp\{-\exp\{-\alpha_n(S_{code}-u_n)\}\} \tag{13}$$

where α_n and u_n can be determined from Eqs. (11) and (12), respectively. In this study, the values of $\overline{S}_{req'd}$ and $\sigma_{S_{req'd}}$ are determined by the Monte Carlo technique.

To investigate the conditional pounding probability of adjacent buildings separated by minimum code-specified separation under earthquakes with different PGA, statistical analyses are performed in this study for $\overline{S}_{req'd}$ and $\sigma_{S_{req'd}}$ of adjacent buildings under 1000 artificial earthquakes.

V. DETERMINATION OF POUNDING RISK OF BUILDINGS

The seismic pounding risk analysis is to express, in quantitative terms, the probability of structural pounding of adjacent buildings within a specified period of time. The analytical procedure to discover the seismic pounding probability of two adjacent buildings during a period of time is briefly summarized in a step-by-step format as follows:

1. Generate a set of artificial earthquake motions with a "specified" peak ground acceleration (PGA) for dynamic analyses of two adjacent building structures.
2. Calculate the mean value, $\overline{S}_{req'd}$, and standard deviation, $\sigma_{S_{req'd}}$, of the maximum relative displacement between the two adjacent buildings at the top level of the shorter building subjected to the earthquakes generated from step 1.
3. Calculate the code-specified separation distance, S_{code}, according to the related pounding provisions of the building code.
4. Calculate the "conditional" pounding probability, $P_{p/a}$, of the adjacent buildings with the results of step 2 and 3.
5. Repeat step 1-4 with different PGA's until the relations between pounding probability of adjacent buildings and PGA are constructed.
6. Calculate the "overall" pounding probability of adjacent buildings from Eq. (9) by combining the

Table 1 Parameter values used in numerical examples

Degree of Freedom, n	Fundamental Period, T (sec)	Stiffness, k (kN/m)	Yielding Shear of 1st Story (kN)	Mass, m (kg)	Damping Ratio (%)
4	0.575	470840	3741	454545.5	5
6	0.780	548183	5612		
8	0.967	628801	6863		
10	1.144	707999	8196		
12	1.311	789888	9836		
14	1.472	872340	11475		
16	1.627	957420	13114		
18	1.777	1045528	13698		
20	1.923	1136785	14063		

results of the seismic hazard analyses and the relations of the pounding probability and PGA constructed in step 5.

VI. KEY ASSUMPTIONS AND STUDY PARAMETERS

1. Earthquake Motions

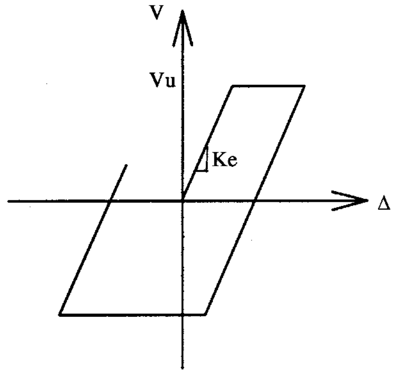
For dynamic analysis of structures and comparison of the pounding risks of buildings designed according to the TBC'97, the design response spectrum of the Taipei basin is selected. To simulate the transient character of real earthquakes, the stationary earthquake motions generated from the power spectral density function associated with the design response spectrum of the Taipei basin are multiplied by a trapezoidal intensity envelope function, expressed by

$$I(t)=\begin{cases} t/0.15t_d & 0\le t\le 0.15t_d \\ 1.0 & 0.15t_d\le t\le 0.75t_d \\ t_d-t/0.25t_d & 0.75t_d\le t\le t_d \end{cases} \tag{14}$$

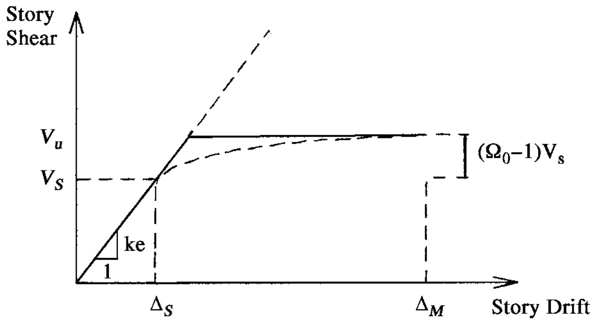
where t_d is the time duration and is taken as 30 seconds in this study.

2. Characteristics and Dynamic Behavior of Building Structures

It is assumed that the dynamic response of a building can well be simulated by using the lumped-mass structural system. The structural system of the buildings investigated in this study is steel moment-resisting frame (SMRF). For simplicity of numerical simulation, the structure is modeled as a multi-degree-of-freedom shear type model which exhibits elasto-plastic behavior in the form of a hysteretic restoring force-displacement characteristic (Fig. 9), although the elasto-plastic behavior may not fully represent the actual behavior 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 1, is determined from formula (2.9) of the TBC'97 for steel moment-resisting frames. The yielding story shear or the ultimate story shear and the initial stiffness of

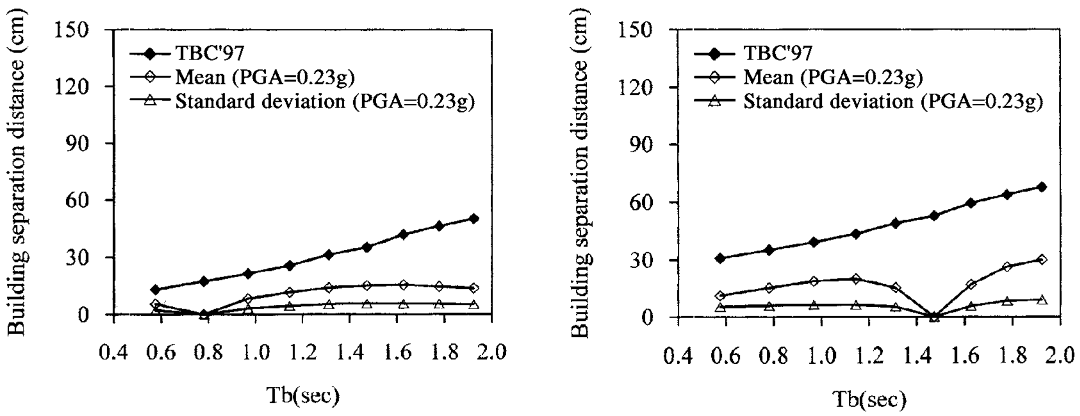


(a) Hysteresis loop



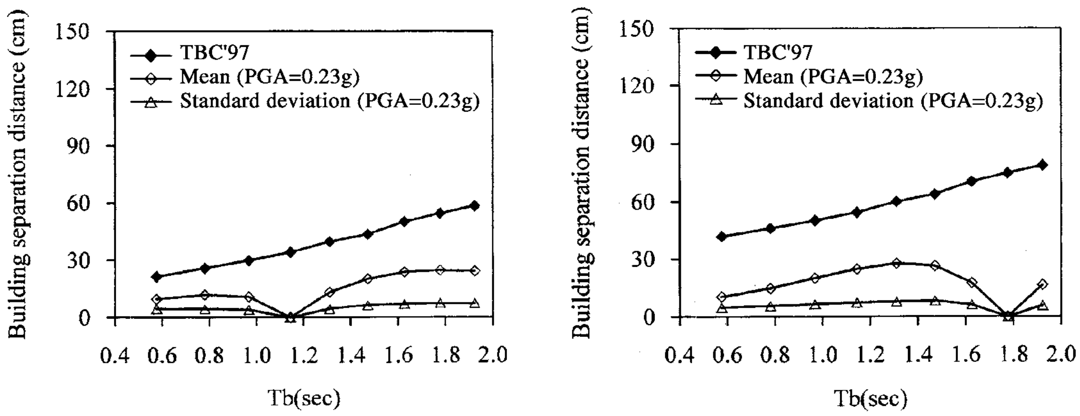
(b) Elasto-plastic model

Fig. 9 Story shear vs. story drift: (a) Hysteresis loop; (b) Elasto-plastic model



(a) Ta=0.780 sec.

(c) Ta=1.472 sec.



(b) Ta=1.144 sec.

(d) Ta=1.777 sec.

Fig. 10 Building separation distance vs. period of building B for discrete period of building A: (a) Ta=0.78sec.; (b) Ta=1.144sec.; (c) Ta=1.472 sec.; (d) Ta=1.777sec.

first story of buildings in elasto-plastic hysteretic analysis is shown in Table 1. For buildings having the same heights, the responses are assumed to be the same. It is noted that this assumption is only valid for these buildings having the same period and elasto-plastic hysteresis behaviour.

In addition, it is assumed that floor elevations are the same for all buildings so that pounding occurs only at these 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 Fig. 5(a); for adjacent buildings having the same heights, the pounding location is assumed to occur at the roof level of both buildings, as shown in Fig. 5(b).

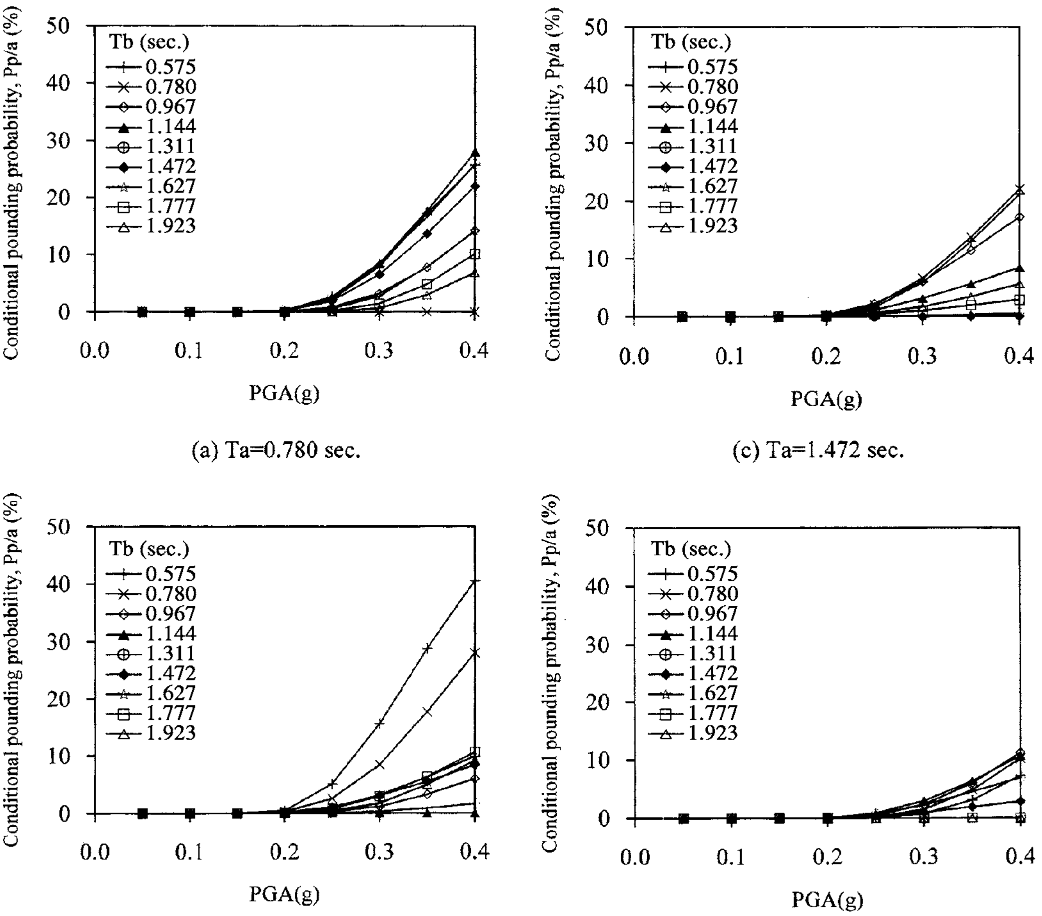
3. Study Cases of Adjacent Buildings

A total of 36 cases of adjacent buildings are investigated, which include 4 cases for building *A* (story number of building *A*, *na*= 6, 10, 14, 18) and 9 cases for building B (story number of building *B*, *nb*= 4, 6, 8, 10, 12, 14, 16, 18, 20). The parameter values of buildings are given in Table 1.

VII. RESULTS AND DISCUSSIONS

1. Building Separation Distance

Comparisons of the building separation distances specified by the TBC'97 and obtained by the Monte Carlo simulation method with PGA of 0.23g vs. period of building *B* for discrete period of building *A* are made and shown in Fig. 10. Figure 10 shows that the TBC's method provides a conservative estimate for the distance. Especially for the cases that the fundamental periods of buildings *A* and *B* are closed, the TBC's methods overestimate the building separation distance due to neglect of the cross correlation terms or improper treatment of the vibration phase difference of adjacent buildings. Note that, as the periods of buildings *A* and *B* are closed, the cross



(a) Ta=0.780 sec.

(c) Ta=1.472 sec.

(b) Ta=1.144 sec.

(d) Ta=1.777 sec.

Fig. 11 Conditional pounding probability of buildings separated according to the TBC'97 vs. PGA: (a)Ta=0.780sec.; (b)Ta=1.144sec.; (c) Ta=1.472sec.; (d) Ta=1.777sec.

correlation terms of the relative displacement response of adjacent buildings are significant.

2. The Conditional Pounding Probability of Adjacent Buildings

Figure 11 shows the relations of PGA and conditional pounding probability of adjacent buildings separated by a distance determined by the TBC's method. Four different periods of building *A* varying from 0.78 to 1.777 seconds are assumed for this investigation. These relation curves are useful in calculating the overall pounding probability of adjacent buildings in a period of time. As shown in Fig. 11, the conditional pounding probabilities of adjacent buildings vary also with period of building B. By comparing Fig. 11 with Fig. 10, the pounding probability of adjacent buildings is significantly dependent on the periods of buildings *A* and *B*. This observation indicates that the TBC's method seems not to provide an uniform risk for all studied cases.

3. The Overall Pounding Probability of Adjacent Buildings

For all cases studied in this paper, the overall pounding probabilities of adjacent buildings designed according to the TBC'97 during their useful life of 50 years are calculated and depicted in Fig. 12 to investigate the effect of period ratio of adjacent buildings on the overall pounding probability. As shown in Fig. 12, the overall pounding probabilities of adjacent buildings vary significantly with the period ratio of adjacent buildings and the period of individual building. In other words, the pounding risks of buildings are not consistent and vary with these factors.

Figure 12 also shows that all of the cases considered gain a low seismic pounding probability. For the most dangerous case studied, the pounding probability obtained from the TBC's method is 1.2 percent. Not surprisingly, the pounding probability is small for the cases that the periods of adjacent buildings are extremely closed and well separated.

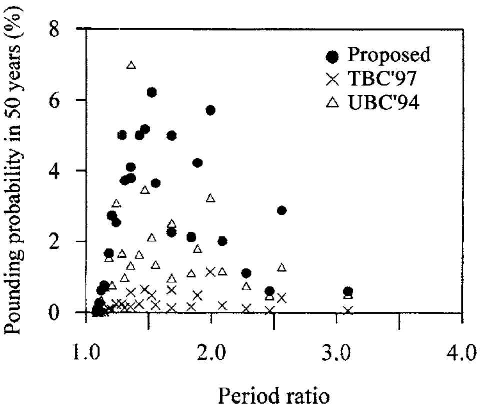


Fig. 12 Comparisons of the pounding probability of buildings separated according to the recommended and code-specified distance

For comparison, the overall pounding probability of buildings designed according to the UBC'94 is also shown in this figure. Similar trends are observed to those obtained from the TBC's method. For the most critical case, the pounding probability of adjacent buildings based on the seismic provisions of the UBC'94 is 7 percent (Lin and Weng, 2000). Compared to the pounding probabilities based on the UBC, the pounding probabilities based on the TBC seems to be lower. In other words, the building separation distance specified by the TBC'97 generally provides a relatively conservative estimate compared to that specified by the UBC'94 for the required separation distance due to a conservative estimate for the property line setback as a result of high design seismic force. This conclusion can be further illustrated, on one hand, by comparing the building separation distance specified by the TBC'97 with that by the UBC'94, as shown in Section 3.3, and, on the other hand, by comparing the pounding probability of buildings designed according to the TBC'97 with that of buildings designed according to the UBC'94, as shown in Fig. 12.

The comparison results in Section 3.3 indicate that the building separation distance specified by the TBC'97 is 1.6 times that specified by the UBC'94 for the same building conditions and site and soil conditions. If a reduction coefficient of 0.375 (0.6/1.6=0.375) is used instead of 0.6 in Eq. (2), the peak pounding probability of the TBC'97 is similar to that of the UBC'94 (Fig. 12). From an efficiency point of view of land use, a reduction coefficient of 0.375 is better than 0.6.

In addition, the concept and the philosophy of probability-based design have been adopted by modern building codes for many years. One of the critical objectives of design codes is to control the "maximum risk" to a socially acceptable level. Modern seismic codes of practice have adopted the concept that certain structural malperformance or damage can be tolerated during earthquakes, provided that structures are adequately designed so that satisfactory performance can be achieved in a somewhat regulated manner. Moreover, the structural design according to the adopted code is more economical, if the various probabilities of structural malperformance or damage can be "similar".

It is noted that the probability, implicated in the seismic provisions of the adopted building codes, that the recommended intensity of earthquake motions at a given location will be exceeded during a 50-year period is estimated to be about 10 percent. However, for the most critical case investigated, the pounding probability of adjacent buildings is 1.2 percent based on the TBC'97 and 7 percent based on the UBC'94. Comparing the pounding probabilities based on the seismic provisions of the TBC'97 and the UBC'94 with the probability that the recommended intensity of earthquake motions will be exceeded during a 50-year period, the conclusion that, from the viewpoint of economy, the pounding related provision of the UBC'94 is more satisfactory than that of the TBC'97 may be made.

VIII. CONCLUSIONS

This study investigates the seismic pounding probability of buildings in the Taipei metropolitan area. The buildings are separated according to the related seismic provisions of Taiwan Building Code (1997). Some major findings of this study are summarized as follows:

1. The pounding probability of adjacent buildings is found to be significantly affected by the natural period of individual buildings and the period ratio of the adjacent buildings.
2. It is noted that there is no specific consideration of the effect of period ratio on the pounding risk of adjacent buildings in the related seismic provisions of the building code in Taiwan.
3. Due to the lack of proper treatment of the vibration phases of adjacent buildings, it is found that the method used in the current Taiwan Building Code (TBC'97) provides poor estimates for the required building separation distance and produces a non-uniform risk for all the cases investigated in this study.
4. The building separation distance specified by the TBC'97 generally provides a relatively conservative estimate compared to that specified by the UBC'94 for the required separation distance to avoid pounding due to a higher estimate for the setback of the building property line. It is noted that the building separation distance specified by the

TBC'97 is 1.6 times that specified by the UBC'94 for the same building and site soil conditions, including structural system, importance factor I, seismic zone factor Z, site response spectrum coefficient C, and seismic hazard curve.

5. It is noted that the probability of exceeding the design basis ground motion specified in the UBC'94 during a 50-year period is 10%. However, for the most critical case investigated by the writers, the pounding probabilities of the adjacent buildings are 7% and 1.2% based on the seismic provisions of the UBC'94 and the TBC'97, respectively.
6. From the pounding risk point of view, the results also indicate that if a reduction coefficient of 0.375 (0.6/1.6=0.375) is used instead of 0.6 specified in the current Taiwan Building Code, the critical pounding risk of the TBC'97 and the UBC'94 will be similar.

It is noted that a mathematical model in the form of cantilever beam is approximate. However, in order to establish a mathematical model, this study adopts the commonly used lumped-mass-cantilever beam model in structural dynamic analysis. The primary objective of the model is to illustrate the physical behavior and pounding probability of adjacent buildings subjected to earthquakes. The writers fully acknowledge that a real structure is much more complex than the simplified model, and the use of the calculated results proposed in this study is subjected to errors resulting from the simplification of the analytical model.

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臺北都會區建築物之地震碰撞機率研究

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摘　要

本研究調查台北都會區建築物之地震碰撞機率，並推導求取碰撞機率之解析方法。研究結果顯示，從碰撞機率的觀點而言，相較於1994年美國UBC規範之規定，1997年台灣建築技術規則耐震設計規範有關建築物分隔距離之規定較爲保守。此結論係基於本文的理想假設條件下，藉由比較台灣及美國建築規範設計之建築物分隔距離及比較相應於台灣及美國建築規範設計之建築物的碰撞機率獲得證實。對於具有相同建築條件及工址土壤條件之建築物而言，台灣建築技術規則耐震設計規範設計之建築物分隔距離爲美國UBC規範設計之建築物分隔距離的1.6倍。研究結果亦顯示，如果用以考慮相鄰建築物間振動相位差之折減因子採用0.375替代現行台灣建築技術規則耐震設計規範的0.6，則依此二規範設計分隔距離之建築物將具有類似的臨界碰撞機率。

關鍵詞：地震碰撞機率，建築物分隔距離，台北都會區。