

Short Paper

EVALUATION OF SEISMIC POUNDING RISK OF BUILDINGS IN TAIWAN

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ABSTRACT

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. Based on the developed approach, the seismic pounding probability of buildings designed according to the 1997 Taiwan Building Code (TBC) is investigated. The effects of site soil profile type on pounding probability of buildings are investigated. Comparisons of the pounding related provisions in the Taiwan Building Code and those in the Uniform Building Code (UBC) are made.

The results reveal that if a reduction coefficient of 0.375 is adopted, instead of the 0.6 specified in the TBC, to consider the effect of vibration phase difference of adjacent buildings, the critical pounding risk of the TBC and that of the UBC will be similar.

Key Words: seismic pounding, building separation, dynamic analysis, risk analysis.

I. INTRODUCTION

Taiwan, located on the Circum-Pacific seismic belt, has very high seismicity. However, adjacent buildings with small or no separation are very common in Taiwan. There exist many buildings, which were already built, in contact with, or extremely close to, one another since the TBC, in the past, did not provide definite guidelines on building separation and a maximum land use is often required due to high population density and economic considerations.

The 1982 TBC requires all new constructions to have a seismic separation between adjacent buildings to avoid pounding. The seismic pounding provisions in the 1997 TBC has important modifications with respect to previous versions. Based on a literature survey conducted by the author, there exist no published results investigating the pounding probability of buildings in Taiwan or demonstrating the validity of the pounding related provisions of TBC, although the concept and the philosophy of probability-based

design have been accepted for many years. Therefore, the need to investigate the pounding risk of buildings and to demonstrate the validity of the pounding related provisions is essential to future code calibrations.

Based on the developed procedure from Lin and Weng (2001), this study investigates the pounding probability of buildings designed according to the 1997 TBC, to gain an insight into the validity of the pounding related provisions. Comparisons of the pounding related provisions in the TBC and those in the UBC are also made. The combination method implied in the formula used to evaluate the separation distance of adjacent buildings to avoid seismic pounding in the present TBC is the absolute sum (ABS) method with a reduction factor, which is used to consider the effect of vibration phase difference between adjacent buildings. The validity of this factor in the TBC is also demonstrated.

II. CODE REQUIREMENTS

The TBC is generally one edition behind the latest available UBC. Many buildings in Taiwan have been designed following requirements for moment resisting frame (MRF) systems identical to those of

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the 1994 UBC. The 1994 UBC 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. Note that the use of the ABS method is implied by the 1994 UBC.

The calibrations of the seismic provisions of the TBC have been made over six years since 1997. This version incorporates great modifications to the seismic provisions for the design of building structures with respect to previous versions. The seismic pounding provisions in the 1997 TBC 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 is taken as 60% of the absolute sum of maximum inelastic displacements of two adjacent buildings. So, the minimum code-specified separation distance of adjacent buildings A and B can be expressed by

$$S_{code} = 0.6(\Delta_{ua, A} + \Delta_{ua, B}) \quad (1)$$

where

$$\begin{aligned} \Delta_{ua, A} &= 1.4 * \alpha_y * R_{a, A} * \Delta_{e, A} \text{ and} \\ \Delta_{ua, B} &= 1.4 * \alpha_y * R_{a, B} * \Delta_{e, B} \end{aligned} \quad (2)$$

in which $\Delta_{ua, A}$ and $\Delta_{ua, B}$ are, respectively, the allowable plastic displacement of buildings A and B; $\Delta_{e, A}$ and $\Delta_{e, B}$ are, respectively, the elastic displacements of buildings A and B due to design seismic forces.

III. SEISMIC POUNDING RISK ANALYSIS

1. Estimation of Pounding Probability

The overall pounding probability of buildings, P_p , may be expressed as follows

$$\begin{aligned} P_p &= \int_a P_{p/a} * P_a * da^* = \int_a P_{p/a} * \frac{d\gamma}{da^*} da^* \\ &\cong \sum_i (P_{p/a})_i (P_a \Delta a)_i \\ &\cong \sum_i (P_{p/a})_i (\Delta \gamma)_i \end{aligned} \quad (3)$$

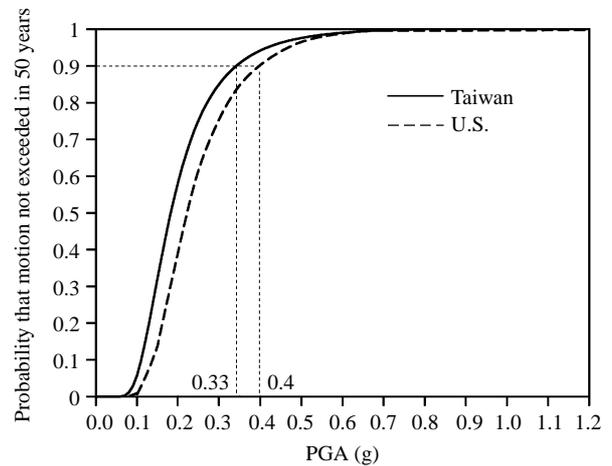


Fig. 1 Seismic hazard curves for a site in the central Taiwan and the west of U.S

in which P_{p/a^*} , called the “conditional” pounding probability, 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 integration of Eq. (3) 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 the 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 $(P_{p/a})_i$. Additionally, the value of $(\Delta \gamma)_i$ can be evaluated from the seismic hazard curve.

In Fig. 1, the dashed-line curve is a result of seismic hazard analyses in the west of the U.S. and the solid-line curve is obtained from the correction of the dashed-line curve. The curves shown in Fig. 1 indicate the probabilities of not being exceeded in a 50 year interval if those 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. 1, there is 90 percent probability that the PGA will not exceed 0.33g in Taichung city. 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.

2. Conditional Pounding Probability

For shear type buildings, the probability distribution of the required separation distance, $S_{req'd}$, of

adjacent buildings to avoid pounding under earthquake motions with a specified PGA fit well with the type I extreme value distribution (Lin and Weng, 2001). In other words, the probability distribution of the random variable $S_{req'd}$ can be given by the form

$$G(S_{req'd}) = \exp\{-\exp\{-\alpha_n(S_{req'd} - u_n)\}\} \quad (4)$$

where

$$\alpha_n = \frac{\pi}{\sqrt{6}\sigma_{S_{req'd}}} \quad (5)$$

and

$$u_n = \bar{S}_{req'd} - 0.577/\alpha_n \quad (6)$$

in which $\bar{S}_{req'd}$ and $\sigma_{S_{req'd}}$ are the mean and the standard deviation of random variable $S_{req'd}$, respectively. If the $\bar{S}_{req'd}$, $\sigma_{S_{req'd}}$ and S_{code} are known, the conditional pounding probability of adjacent buildings, $P_{p/a}$, can be evaluated by Eq. (7).

$$P_{p/a} = 1 - \exp\{-\exp\{-\alpha_n(S_{code} - u_n)\}\} \quad (7)$$

In this study, $\bar{S}_{req'd}$ and $\sigma_{S_{req'd}}$ are determined by the Monte Carlo technique.

3. Analytical Procedure

The analytical procedure to estimate the seismic pounding probability of buildings during a period of time is summarized in a step-by-step format as follows.

1. Generate a set of artificial earthquake motions with a "specified" PGA.
2. Calculate $\bar{S}_{req'd}$ and $\sigma_{S_{req'd}}$ of adjacent buildings subjected to the earthquakes generated from step 1 and calculate S_{code} , according to the building code.
3. Calculate $P_{p/a}$ of the adjacent buildings with the results of step 2.
4. Repeat steps 1~3 with different PGA's until the relations between pounding probability of adjacent buildings and PGA are constructed.
5. Calculate P_p of adjacent buildings from Eq. (3) by combining the results of the seismic hazard analyses and the results of step 4.

IV. KEY ASSUMPTIONS AND STUDY CASES

There are three soil profile types including soil type 1(rock and stiff soils), soil type 2(deep cohesionless or stiff clay soils), and soil type 3(soft to medium clays and sands) to be considered in this study. For dynamic analysis of structures, the design response spectra of the 1997 TBC are selected. To investigate

the conditional pounding probabilities of adjacent buildings, given earthquakes of different PGA, statistical analyses are performed for $\bar{S}_{req'd}$ and $\sigma_{S_{req'd}}$ using 1000 artificial earthquakes. To simulate the transient character of real earthquakes, the artificial stationary earthquake motions generated from the power spectral density function associated with the specified design response spectrum are multiplied by a trapezoidal intensity envelope function, expressed by

$$I(t) = \begin{cases} \frac{t}{0.15t_d} & 0 \leq t \leq 0.15t_d \\ 1.0 & 0.15t_d \leq t \leq 0.75t_d \\ \frac{(t_d - t)}{0.25t_d} & 0.75t_d \leq t \leq t_d \end{cases} \quad (8)$$

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

The structural systems of the buildings are assumed to be SMRF systems. The structures are modeled as multi-degree-of-freedom shear type models which exhibit elasto-plastic behavior in the form of a hysteretic restoring force-displacement characteristic. Torsional effects on structure responses are ignored. For each building, the relation of the fundamental period and the building height is determined from formula (2.9) of the 1997 TBC for SMRF systems. For adjacent buildings having different heights, the pounding location is assumed to occur at the top level of the shorter building; for adjacent buildings having the same height, the pounding location is assumed to occur at the roof level of both buildings.

A total of 36 cases of adjacent buildings A and B are investigated, which include 4 cases for building A (number of stories building A, $n_a = 6, 10, 14, 18$) and 9 cases for building B (number of stories building B, $n_b = 4, 6, 8, 10, 12, 14, 16, 18, 20$). The values of studied parameters are shown in Table 1.

V. RESULTS AND DISCUSSIONS

Comparisons of building separations specified by the TBC and those by the UBC are made and shown in Fig. 2. The comparison results reveal that the building separation specified by the TBC is approximately 1.6 times that specified by the UBC for the same building conditions and site soil conditions. For cases where the fundamental periods of buildings A and B are closed, the cross correlation terms of the relative displacement response of adjacent buildings are significant. Thus, both the TBC method and the UBC method overestimate the building separation distance due to neglect of the cross correlation terms or due to improper treatment of the vibration phase difference of adjacent buildings.

Table 1 Parameter values used in numerical examples

Degree of freedom, n	Building height, H (m)	Fundamental period, T (sec)	Stiffness of first story, k_1 (kN/m)	Mass, m (kg)	Damping ratio (%)
4	12.8	0.575	470840	454545.5	2
6	19.2	0.780	548183		
8	25.6	0.967	628801		
10	32.0	1.144	707999		
12	38.4	1.311	789888		
14	44.8	1.472	872340		
16	51.2	1.627	957420		
18	57.6	1.777	1045528		
20	64.0	1.923	1136785		

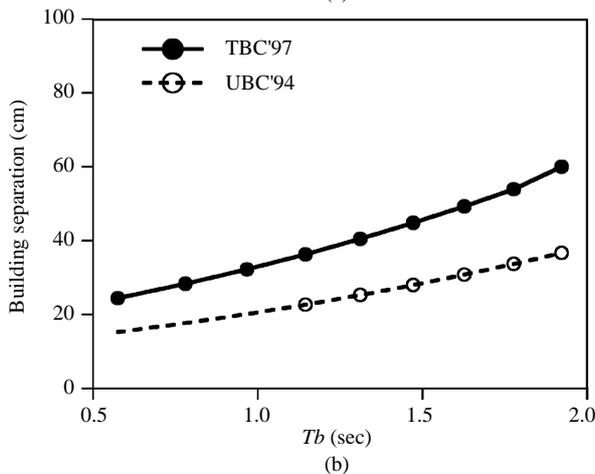
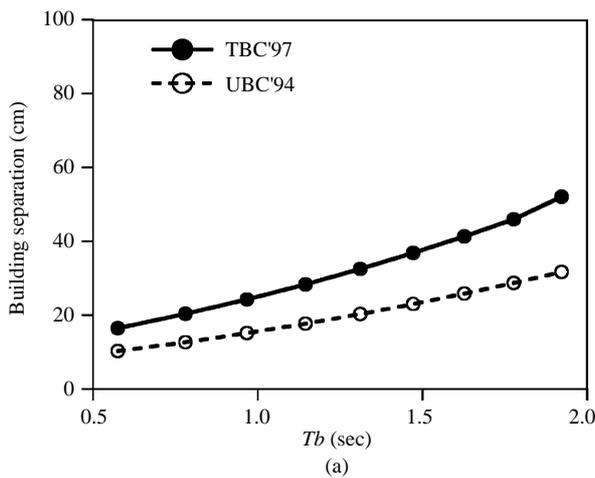


Fig. 2 Comparisons of building separations specified by the 1997 TBC and by the 1994 UBC (type 2 soil, PGA = 0.4g): (a) $T_a = 0.780$ sec.; (b) $T_a = 1.144$ sec

For all cases studied in this paper, the overall pounding probabilities of adjacent buildings designed according to the 1997 TBC during their useful life of 50 years are calculated and depicted in Fig. 3 to investigate the effect of period ratio of adjacent buildings on the overall pounding probability. As shown in

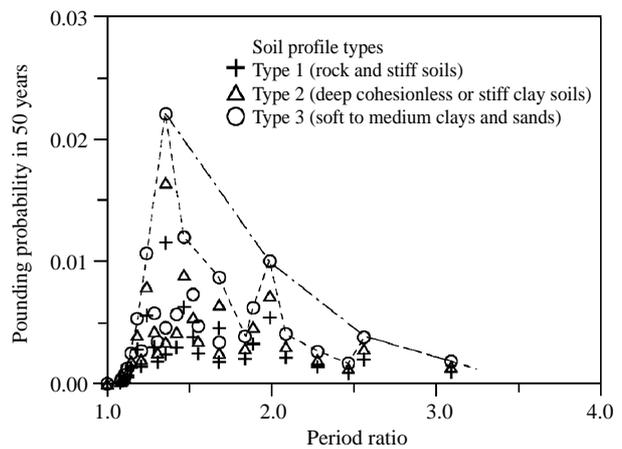


Fig. 3 Pounding probability vs. period ratio of adjacent buildings in Taiwan for different soil profile types

Fig. 3, the overall pounding probabilities of adjacent buildings vary significantly with the period ratio of adjacent buildings and the period of an individual building. In other words, the pounding risks of buildings are not consistent and vary with these factors. Fig. 3 also shows that all of the cases considered gain a low seismic pounding probability. For the most dangerous case studied, the pounding probabilities of buildings located on soil profiles of Type-1, Type-2, and Type-3, and separated by the TBC method, are approximately 1.15, 1.64, and 2.20 percent, respectively. Not surprisingly, the pounding probability is small for cases where the periods of adjacent buildings are extremely close and well separated.

Figures 4(a) to 4(c) show the results of pounding probability vs. period ratio of adjacent buildings designed according to the 1997 TBC on soil profiles of Type-1, Type-2, and Type-3, respectively. For comparison, based on the dashed-line curve in Fig. 1, the overall pounding probabilities of buildings designed according to the 1994 UBC on Type-2 soil are shown also in Fig. 4(b). For the most critical case in

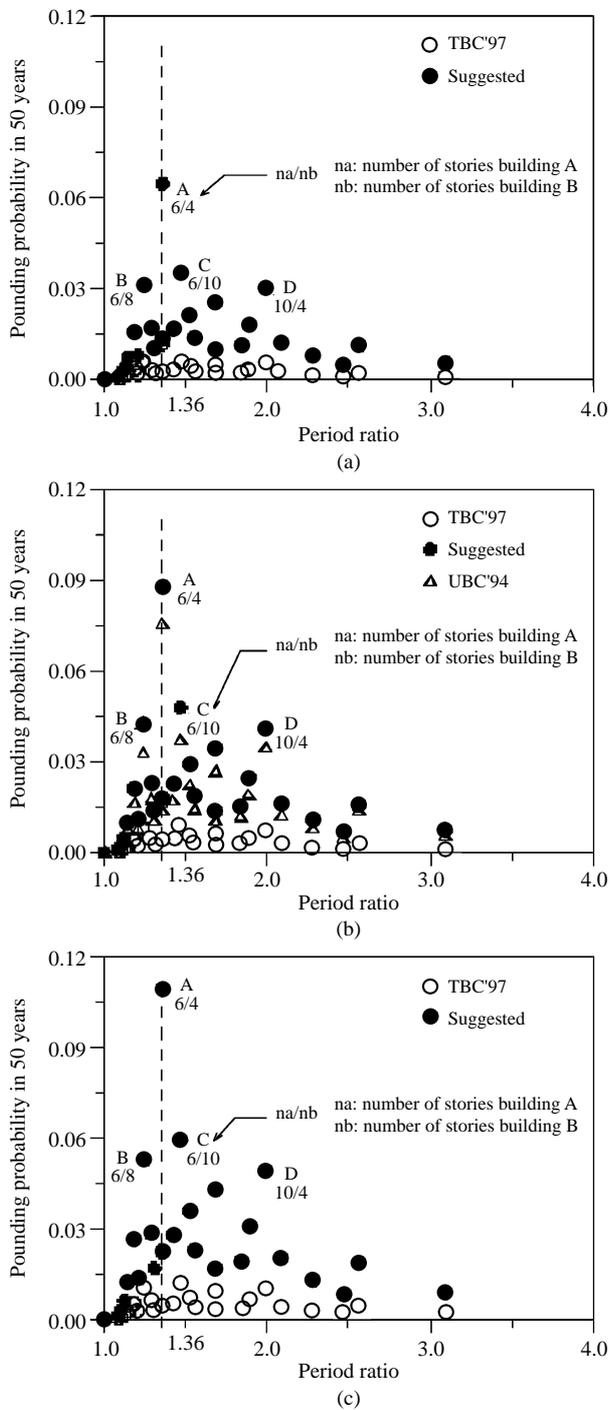


Fig. 4 Pounding probabilities of adjacent buildings separated by suggested building separation on: (a) Type-1 soil, (b) Type-2 soil, and (c) Type-3 soil

Fig. 4(b), the pounding probability of adjacent buildings based on the seismic provisions of the UBC is approximately 7.5 percent. Compared to the pounding probabilities based on the UBC, the pounding probabilities based on the TBC seem to be lower.

As shown in Fig. 2, the building separation

specified by the TBC is 1.6 times that specified by the UBC for the same building conditions and site soil conditions. If a reduction coefficient of 0.375 ($0.6/1.6 = 0.375$) is used instead of 0.6 in Eq. (1), the peak pounding probability of the TBC is similar to that of the UBC (Fig. 4(b)). From an efficient land use point of view, a reduction coefficient of 0.375 is better than 0.6. Figs. 4(a) to 4(c) show the results with a reduction coefficient of 0.375. Modern seismic codes of practice have adopted the concept that certain structural mal-performance 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 mal-performance or damage can be “similar”.

It is noted that the probability, implicated in the seismic provisions of the TBC, 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 2.20 percent. Comparing the pounding probabilities based on the seismic provisions of the TBC 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, a reduction coefficient of 0.375 is used instead of 0.6 in Eq. (1) is more satisfactory may be made.

VI. CONCLUSIONS

Some major findings of this study are summarized as follows:

- (1) For the most dangerous case studied, the pounding probabilities of buildings located on soil profiles of Type-1, Type-2, and Type-3, and separated by the TBC method, are approximately 1.15, 1.64, and 2.20 percent, respectively.
- (2) It is noted that the probability of exceeding the design basis ground motion specified in the building code during a 50-year period is 10 percent. However, for the most critical case investigated, the pounding probability of the adjacent buildings is 2.20 percent based on the seismic provisions of the 1997 TBC. From an efficient land use point of view, the pounding related provisions in the current TBC are not satisfactory.
- (3) From the pounding risk point of view, the results indicate that if a reduction coefficient of 0.375 is used instead of the 0.6 specified in the current TBC, the critical pounding risk of the 1997 TBC and that of the 1994 UBC will be similar.

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