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Probabilistic evaluation of separation distance between two adjacent structures

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Abstract. Structural pounding is commonly observed phenomenon during major ground motion, which can cause both structural and architectural damages. To reduce the amount of damage from pounding, the best and effective way is to increase the separation distance. Generally, existing design procedures for determining the separation distance between adjacent buildings subjected to structural pounding are based on approximations of the buildings' peak relative displacement. These procedures are based on unknown safety levels. The aim of this research is to estimate probabilistic separation distance between adjacent structures by considering the variability in the system and uncertainties in the earthquakes characteristics through comprehensive numerical simulations. A large number of models were generated using a robust Monte-Carlo simulation. In total, 6.54 million time-history analyses were performed over the adopted models using an ensemble of 25 ground motions as seismic input within OpenSees software. The results show that a gap size of 50%, 70% and 100% of the considered design code for the structural periods in the range of 0.1-0.5 s, leads to have the probability of pounding about 41.5%, 18% and 5.8%, respectively. Finally, based on the results, two equations are developed for probabilistic determination of needed structural separation distance.

Keywords: structural pounding; separation distance; probabilistic analysis; Monte-Carlo simulation; time-history analyses

1. Introduction

In heavily populated regions and Mega cities, structures are usually constructed in close proximity to one another because of restricted availability of space. Because of insufficient separation distance and out of phase vibration, earthquake ground motion can induce pounding in these adjacent structures. Pounding may cause both structural and architectural damage and can lead to partial or complete collapse of the structure. Rosenblueth and Meli (1985) revealed that in the Mexico City earthquake of September 19, 1985 about 40% of the damaged structures experienced some level of pounding, 15% of them lead to structural collapse. This phenomenon has been extensively studied during the last two decades or so. For example, even modern structures were damaged by seismic pounding when separation distances were in-filled with solid architectural flashings (Cole *et al*. 2011, Takewaki *et al*. 2011).

In order to reduce the risk of seismic pounding between new buildings, modern seismic design codes (BCJ 1997, TPC 1997, Eurocode 8 2005, IBC 2009, Standard No. 2800 2015) propose a minimum separation distance between adjacent buildings which appears to be insufficient, as confirmed by many researchers (Kasai *et al*. 1996, Penzien 1997, Mucciarelli *et al*. 2003, Anagnostopoulos and Karamaneas 2008, and others).

Iranian Code of Practice for Seismic Resistant Design of Buildings (Standard No. 2800) (2015), roughly accepts minimum separation gap equal to 1% of building height; so edge of each building should be adjusted at least 0.5% of buildings height from its property line. According to this code, the needed separation distance is determined for the earthquake intensity having a return period of 475 years, corresponding to a probability of exceedance of 10% in 50 years. This site-specific seismic intensity is usually defined using a uniform hazard response spectrum, whose spectral ordinates are characterized by a target return period. International Building Code (IBC) (2009), specifies that separation gap between adjacent buildings with same property line shall be equal to or greater than the Square Root of the Sum of the Squares (SRSS) of adjacent buildings. However, generally existing procedures to specify a minimum separation distance needed to avoid seismic pounding are based on the use of approximate response combination rules present many limits and shortcomings and are characterized by unknown safety levels which strongly depend on the natural periods of the adjacent buildings (Lin 1997, Lopez-Garcia and Soong 2009a, 2009b, Tubaldi and Barbato 2011, Tubaldi *et al*. 2012, Barbato and Tubaldi 2013, Raheem 2014, Chase *et al*. 2014, Tubaldi *et al*. 2016). Therefore, despite of the building codes provisions risk of building pounding is still high because existing and old buildings may not meet new building code requirements.

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Various analytical models have been developed to define the structural response of adjacent structures during an earthquake. Anagnostopoulos (1988) presented a comprehensive study on pounding of adjacent buildings modeled as SDOF nonlinear systems. Penzien (1997) conducted a study to predict the minimum separation gap to avoid pounding during strong earthquakes for linear and nonlinear buildings. He found that there are possibilities of exceedance of the relative displacement than the values defined in the codes (SRSS and ABS) which would result in higher probabilities of building pounding. Hao and Shen (2001) concluded that SRSS provides up to 20% of underestimation for relative displacements of adjacent structures for out of phase vibration because SRSS cannot consider the difference of responses adequately. Muthukumar and DesRoches (2006) evaluated pounding of adjacent buildings modeled as elastic and inelastic SDOF systems using different pounding models. Jankowski (2006) proposed the notion of the impact force response spectrum for elastic and inelastic adjacent structures.

Despite the extensive researches carried out on the seismic collision of buildings during the last two decades, which have been mainly reported earlier, the findings of many works have been refuted by other pertinent studies. On the other hand, only a relatively small number of studies can be found in which the simultaneous probabilistic effects of pounding are accounted for. Barbato and Tubaldi (2013) used a probabilistic approach to find the appropriate required distance between adjacent structures. They studied linear and nonlinear structures and found that certain building codes underestimate the clear distance. Efraimiadou *et al*. (2013) evaluated the effect of adjacency configuration and type of the ground motion on pounding by evaluating two adjacent 5-story and two adjacent 8-story buildings at nine different cases of adjacency. They concluded that the code-based clear distance was not enough to suppress the negative effects of pounding in this case. Review of the literature as mentioned clearly confirms that state of knowledge about probabilistic evaluation of pounding is still at its early situation.

This study proposes a probabilistic estimation for evaluating the probability of pounding between nonlinear SDOF systems by considering the variability in the systems and uncertain properties in the earthquakes characteristics through comprehensive numerical simulations. This methodology overcomes the aforementioned limitations of the current approaches by proposing two probabilistic formulas to evaluate the clear separation distance that corresponds to the probability of pounding. Thus, it allows the designer to rationally choose a required separation distance that corresponds to desirable probability of pounding for different period of structures. In the models, the adjacent structures were developed with bilinear elastic-plastic (BLEP) load-displacement relationship. A comprehensive parametric study that covers a wide range of structural systems was carried out via adopted Monte-Carlo simulation (Fishman 1995). For this purpose, 6.54 million nonlinear dynamic time history analyses on various systems are conducted. The inelastic time-history responses of the models were evaluated by means of the seismic analysis OpenSees (McKenna *et al*. 2000) software and MATLAB (2015b) programming tool.

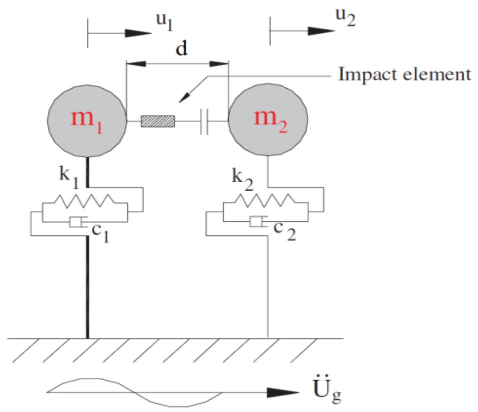


Fig. 1 Model idealization of adjacent structures

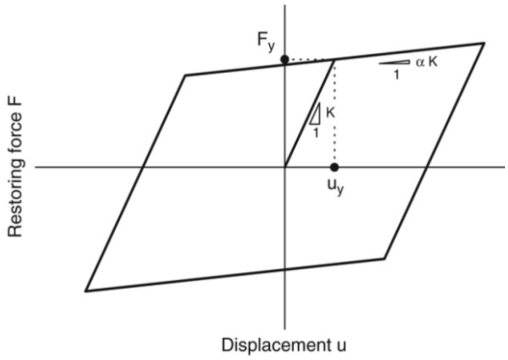


Fig. 2 BLEP model used to represent the nonlinear force-deflection behavior of the structures

2. Specifications of adopted dynamic model

The idealized mathematical models used in this study for two equivalent nonlinear single degree of freedom (SDOF) structures, situated at a gap distance, d, is shown in Fig. 1. This model can be interpreted as an equivalent representation of the fundamental mode of vibration of a multi-storey structure. To numerically model the pounding phenomenon, a nonlinear spring in conjunction with a nonlinear dashpot element is used to estimate the induced pounding displacements at the floor levels. The SDOF structural representation is characterized by (i) structural mass participating in the fundamental mode of vibration, m_1 and m_2 (ii) structural lateral stiffness, k_1 and k_2 (iii) 5% equivalent viscous structural damping, ξ.

As shown in Fig. 2, BLEP model was used to represent the nonlinear force-deflection behavior of the structures. In this model, the linear branch of the structural stiffness was considered equal to k and the yield strength was defined assuming a displacement ductility of 6 at 2% drift. This ductility limit was considered to ensure that the structural part of all generated models responds in the nonlinear range. However, it does not mean all models reach this ductility level. The procedure defining F_y was based on Newmark's so-called Equal Displacement Rule. In addition, the post-yielding stiffness factor, α, for hardening modulus

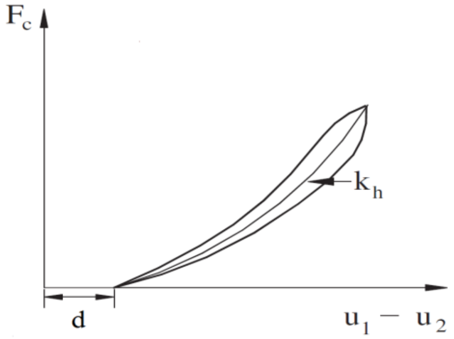


Fig. 3 Contact force-displacement relationship for Hertz-damp model

was considered equal to 0.05 (5% of the linear branch) to cover structural nonlinearity. The parameters F_y and u_y are the yielding force and displacement, respectively. Moreover, u_1 and u_2 are the peak displacement response of the adjacent structures 1 and 2 at the potential pounding location, respectively.

2.1 Nonlinear pounding model

Since pounding between adjacent structures is a complex phenomenon, in order to accurately simulate impact, an appropriate impact force model should be adopted. The nonlinear hertz-damp model (Jankowski 2005) which uses the general trend of the nonlinear Hertz law of contact together with an incorporated hysteretic damping function is utilized to capture impacting force. According to the nonlinear hertz-damp model, the contact force between two adjacent buildings can be expressed as

$$F_c = 0 \qquad if: u_1 - u_2 - d \le 0 \tag{1}$$

$$F_c = k_h (u_1 - u_2 - d)^n + c_h (\dot{u}_1 - \dot{u}_2) \quad if: u_1 - u_2 - d > 0 \tag{2}$$

where k_h and c_h are the spring and dashpot constants of the element, respectively. In these equations, $u_1 – u_2 – d$ is the relative penetration and $\dot{u}_1 - \dot{u}_2$ is the penetration velocity. The value of k_h depends on the material properties of the pounding structure and the geometry of the contact area. The c_h is proposed so that the expected hysteresis loop during impact matches the one shown in Fig. 3. Hertz factor, n, is typically introduced as 1.5. Fig. 3 shows the contact force-displacement relationship for Hertz-damp model. If a nonzero pounding force in the models was observed, it found that at least one structural pounding occurred.

3. Probabilistic analysis

Significant uncertainties in ground motion characteristics and model parameters lead to a wide range of responses of the system. The approach adopted in this study was to systematically compute the seismic response for a wide range of adjacent structures models when subjected to various earthquakes with different ground motion characteristics. A robust Monte-Carlo simulation was applied to develop models through random selection procedure as outlined below:

Table 1 The clear distances based on periods of adjacent structures for T=0.1-0.5 s

Periods of structures (s)									
T_1(s)	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
T_2(s)	Separation distances (m)								
0.10	0.013	0.018	0.024	0.030	0.036	0.043	0.049	0.057	0.064
0.15	0.018	0.024	0.030	0.036	0.043	0.049	0.057	0.064	0.069
0.20	0.024	0.030	0.036	0.043	0.049	0.057	0.064	0.069	0.075
0.25	0.030	0.036	0.043	0.049	0.057	0.064	0.069	0.075	0.080
0.30	0.036	0.043	0.049	0.057	0.064	0.069	0.075	0.080	0.087
0.35	0.043	0.049	0.057	0.064	0.069	0.075	0.080	0.087	0.093
0.40	0.049	0.057	0.064	0.069	0.075	0.080	0.087	0.093	0.100
0.45	0.057	0.064	0.069	0.075	0.080	0.087	0.093	0.100	0.108
0.50	0.064	0.069	0.075	0.080	0.087	0.093	0.100	0.108	0.115

Table 2 The clear distances based on periods of adjacent structures for T=0.5-1 s

Periods of structures (s)											
T_1(s)	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
T_2(s)	Separation distances (m)										
0.50	0.115	0.123	0.131	0.139	0.147	0.156	0.164	0.173	0.182	0.191	0.201
0.55	0.123	0.131	0.139	0.147	0.156	0.164	0.173	0.182	0.191	0.201	0.210
0.60	0.131	0.139	0.147	0.156	0.164	0.173	0.182	0.191	0.201	0.210	0.219
0.65	0.139	0.147	0.156	0.164	0.173	0.182	0.191	0.201	0.210	0.219	0.227
0.70	0.147	0.156	0.164	0.173	0.182	0.191	0.201	0.210	0.219	0.227	0.235
0.75	0.156	0.164	0.173	0.182	0.191	0.201	0.210	0.219	0.227	0.235	0.244
0.80	0.164	0.173	0.182	0.191	0.201	0.210	0.219	0.227	0.235	0.244	0.253
0.85	0.173	0.182	0.191	0.201	0.210	0.219	0.227	0.235	0.244	0.253	0.261
0.90	0.182	0.191	0.201	0.210	0.219	0.227	0.235	0.244	0.253	0.261	0.271
0.95	0.191	0.201	0.210	0.219	0.227	0.235	0.244	0.253	0.261	0.271	0.281
1.00	0.201	0.210	0.219	0.227	0.235	0.244	0.253	0.261	0.271	0.281	0.290

1. Two groups of models were defined including 9 different periods varying from 0.1-0.5 s for first group as well as 11 different periods varying from 0.5-1 s for the second group, with a period increment of 0.05 s. Both periods set were chosen to represent structures about 3-30m high and to satisfy the period-height relationship stipulated in the Standard No. 2800 (2015). For each of these two groups, four primary separation distances were considered. Therefore, eight sub-groups were evaluated. Moreover, these separation distances are obtained based on the structural heights which are calculated by Eq. (3) and based on the periods of adjacent structures. As various periods for structures are considered, more separation distances are evaluated. Actually, as shown in Table 1 and 2, 38 different separation distances are considered in this study.
2. For first and second groups, 26244 and 39204 models constrained to conform to the adopted periods and to produce structural pounding models were randomly generated, respectively. A relatively large number of 26244

and 39204 models were chosen in order to provide high level of accuracy in analyses results. Moreover, four relative separation distances were considered. Each model was subjected to 25 different earthquake ground motions. Thus, the total number of time history analyses comes up to 6.54 million analyses. Then, all models were analyzed using nonlinear Opensees software.

3.1 Structural parameters and uncertainties

In order to conduct a parametric study, a number of parameters are defined that describe various aspects of the structural system. Most of the structural parameters were considered as uncertain parameters. The following parameters are deemed to best describe this system, which for each of them, a realistic range was defined first, and then many distributed values were assigned to that range:

The variation range of 175-375 m/s, to a depth of 30 m, was chosen for V_s (Soil shear wave velocity) to represent soils type *C* based on Standard No. 2800 classification. Soil mass density, ρ, is modeled as a lognormal random variable with a mean of 1800 and a CoV of 6.8%. Note that mean and CoV are computed in a way that ρ lies between 1600 kg/m^3 and 2000 kg/m^3 with 90% confidence level. Randomly varying structural parameters include: (i) total height of the structure, h_{str}, (ii) radius of the cylindrical foundation, *r*, and (iii) structural mass, m_{str}. Then based on these randomly generated parameters, the values for the structural stiffness, k_{str}, and structural damping, c_{str}, were obtained. To obtain adequate structural pounding models, the selection of the mentioned structural parameters was limited by commonly accepted relationship for structures. The first parameter to be calculated was h_{str}. For each group of models with a specified *T* (Eight groups with *T*=0.1-0.5s and *T*=0.5-1s), a range of variation for h_{str} was defined based on (i) a typical period-height relationship adopted in Standard No. 2800 (2015) that can be presented as Eq. (3)

$$0.05(h_{str})^{0.75} \le T \le 0.08(h_{str})^{0.75} \tag{3}$$

and (ii) the considered limitation on the height of the structure of 3-30 m. It was assumed that h_{str} is uniformly distributed (equally likely to occur) in the mentioned range. After defining h_{str} at each range of *T* for all models, the structure aspect ratio, h_{str}/r, was used to obtain the foundation radius, *r*. It was assumed that the ratio, h_{str}/r, for ordinary structures is in the range between 1 and 3. For each predefined value of h_{str}, a random value was picked for *r* satisfying the above-mentioned limitations. To consider a adequate structural mass, m_{str}, for the defined structural parameters, the relative mass index $\overline{m}$ defined as follows

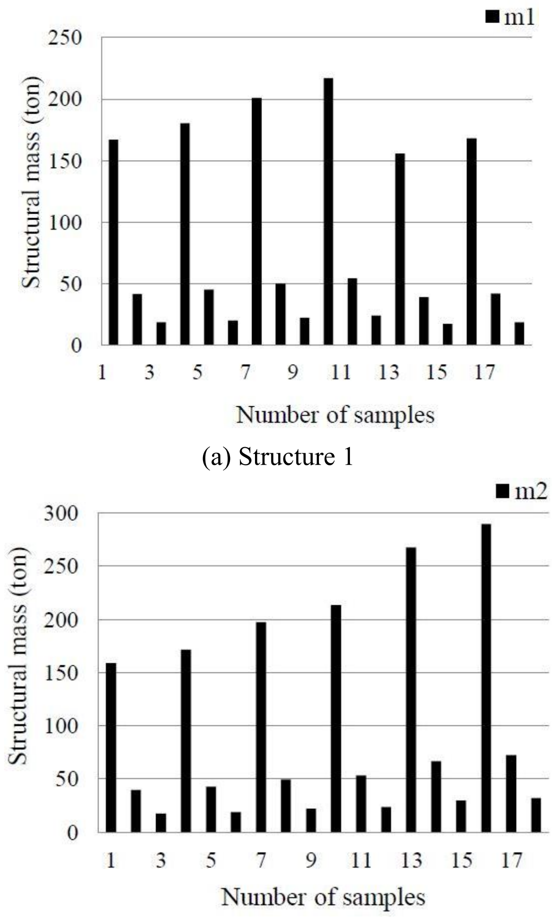
$$\overline{m} = \frac{m_{str}}{\rho r^2 h_{str}} \tag{4}$$

where $\overline{m}$ is effective mass of the structure, and is modeled as a lognormal random variable with a mean of 0.6 and a CoV of 20%, based on Khosravikia's work (2016). To achieve its probability distribution, $\overline{m}$ was derived in terms of more basic physical variables that define the mass, geometry and material properties of the foundation and the structure. Thereafter, a probability distribution was assigned to these basic variables based on their typical range in engineering practice. Finally, the probability distribution of $\overline{m}$ was obtained by carrying out a sampling analysis. For ordinary structures, it varies between 0.4-0.8 (Khosravikia *et al*. 2017, Khosravikia *et al*. 2018). Thus, knowing previously defined values for h_{str}, *r*, and ρ and considering a lognormal distribution for $\overline{m}$ within the defined range, the value for the structural mass, m_{str}, was defined. For example, Fig. 4 illustrates the distribution of structural mass obtained for *T*=0.1-0.5s. The x-axis shows the number of samples which considered for structural masses. Because of space limitation, the structural masses are presented only for the adjacent structures with the periods in the range of 0.1-0.5 s. Following this estimation of m_{str}, the initial structural stiffness, $(k_{str})_i$, was calculated directly based on Eq. (5)

$$(k_{str})_i = \frac{4\pi^2}{T^2} m_{str} \tag{5}$$

To obtain the structural damping coefficient, c_{str}, a constant 5% equivalent viscous structural damping was employed, and c_{str} was defined as

$$0.05(h_{str})^{0.75} \le T \le 0.08(h_{str})^{0.75} \tag{6}$$



(a) Structure 1

(b) Structure 2

Fig. 4 Distribution of structural mass for two adjacent structures

It can be found from Eqs. (5)-(6) that the distributions of $(k_{str})_i$ and c_{str} will be similar to that of m_{str}.

4. Minimum separation distance between structures

Seismic codes specify minimum separation distances between adjacent buildings, to avoid pounding, which is equal to the relative displacement demand of the two potentially colliding structural systems. For instance, the Standard No. 2800 (2015) and many seismic design codes (e.g., International Building Code IBC 2009), specify that for buildings with different properties, minimum separation distances can be obtained based on Eqs. (7)-(8)

$$d = u_1 + u_2 \tag{7}$$

$$d = \sqrt{u_1^2 + u_2^2} \tag{8}$$

where d is the separation distance, u_1 and u_2 are the peak displacement response of the adjacent structures 1 and 2 at the potential pounding location, respectively (i.e., at the top of the shorter structures). These parameters are shown in Fig. 1. Eqs. (7) and (8) subsequently are referred to as the ABS and SRSS rule, respectively. Previous studies (Jeng *et al.* 1992, Kasai *et al*. 1996) have shown that the ABS rule gives poor estimates of d, especially when the natural periods of the adjacent structures are close to each other. The same studies have also shown that, as the periods of the adjacent structures become closer to each other, results given by the SRSS rule evolve from reasonably accurate (not always conservative) to very conservative as well (but not as conservative as those given by the ABS rule). It should be noted that there are some more methods to obtain the separation distance (such as Spectral Difference Method presented by Jeng *et al.* (1992)) which for brevity are not considered in this paper. Due to the intrinsic random nature of earthquakes, none of the abovementioned rules gives the separation distance required to avoid pounding. Rather, there is always a finite probability that, during a given period, the relative displacement response exceeds the separation distance indicated by any of the rules mentioned above. Therefore, it is important to define the separation distance based on probabilistic conditions, as considered in this paper.

4.1 Considered clear distances

In this study, for the purpose of probabilistic evaluation of minimum gap between two structures, different periods were considered for structures 1 and 2. The peak of relative response of the structures gives the minimum separation distance between them. Standard No. 2800 (2015) requires

Table 3 Strong ground motion records used as input to considered structures

EQ	Earthquake name	Year	Station name	M	PGA (g)	R_{rup} (km)	V_s (m/sec)	Soil type
EQ1	Morgan Hill	1984	Gilroy Array #4	6.2	0.35	11.5	221.78	C
EQ2	Superstition Hills	1987	Poe Road (temp)	6.5	0.47	11.1	316.64	C
EQ3	Loma Prieta	1989	Capitola	6.9	0.51	15.2	288.62	C
EQ4		1989	Gilroy Array #4	6.9	0.42	14.3	221.78	C
EQ5		1989	Gilroy Array #7	6.9	0.44	22.6	333.85	C
EQ6	Landers	1992	Coolwater	7.3	0.42	19.7	352.98	C
EQ7	Northridge	1994	Canoga Park- Topanga Can	6.7	0.39	14.7	267.49	C
EQ8		1994	Glendale-Las Palmas	6.7	0.37	22.2	371.07	C
EQ9		1994	LA - Centinela St	6.7	0.48	28.3	321.91	C
EQ10		1994	LA - Saturn St	6.7	0.47	27.0	308.71	C
EQ11		1994	Pacific Palisades-Sunset	6.7	0.46	24.0	191.06	C
EQ12		1994	Santa Monica City Hall	6.7	0.88	26.4	336.2	C
EQ13		1994	Tarzana-Cedar Hill A	6.7	0.99	15.6	257.21	C
EQ14	Kobe, Japan	1995	Kakogawa	6.9	0.32	22.5	312	C
EQ15	Kocaeli, Turkey	1999	Duzce"	7.5	0.36	15.3	281.86	C
EQ16	Cape Mendocino	1992	Fortuna Fire Station	7.0	0.33	20.4	355.18	C
EQ17	Chuetsu-oki, Japan	2007	Kawanishi Izumozaki, NS	6.8	0.36	11.7	338.32	C
EQ18		2007	Tamati Yone Izumozaki, NS	6.8	0.63	11.4	338.32	C
EQ19		2007	Kashiwazaki NPP, Unit 1	6.8	0.90	10.9	329	C
EQ20		2007	Tamati Yone Izumozaki, EW	6.8	0.50	11.4	338.32	C
EQ21		2007	Kashiwazaki NPP Unit 1: ground surface, EW	6.8	0.91	11.7	338.32	C
EQ22	El Mayor-Cucapah, Mexico	2010	El Centro Differential Array, 360	7.2	0.55	23.4	202.26	C
EQ23		2010	El Centro Differential Array, 90	7.2	0.51	23.4	202.26	C
EQ24	Iwate, Japan	2008	Misato, Miyagi Kitaura- A, NS	6.9	0.40	38.0	278.35	C
EQ25		2008	Misato, Miyagi Kitaura- A, EW	6.9	0.35	38.0	278.35	C

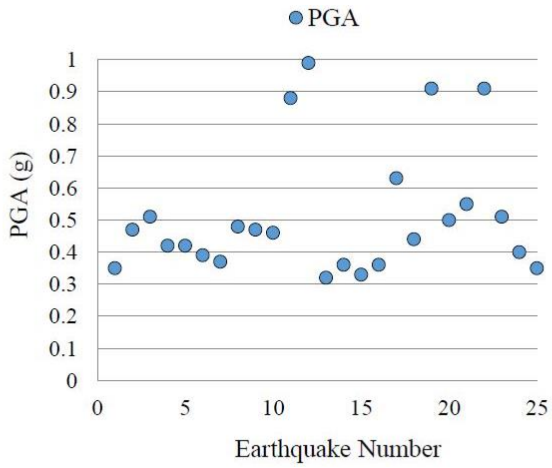


Fig. 5 PGA distribution of the selected records

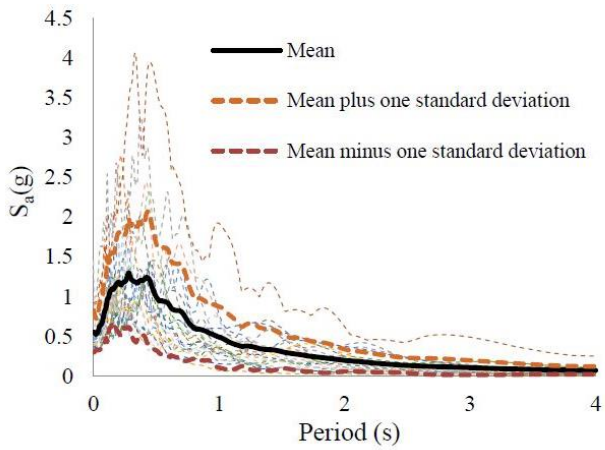


Fig. 6 Normalized 5%-damped elastic acceleration response spectra of the selected re cords

that the following equation to be considered for calculation of d

$$d = 0.005(h_1 + h_2) \tag{9}$$

in which h_1 and h_2 are the structures height over the base. Four cases are considered in this study regarding the clear distance as being 50%, 70%, 100% and 110% of the Standard No. 2800's prescribed values (Eq. (9)). In this paper, the ratio of considered clear distances to separation distances defined by Standard No. 2800, d, is called the gap ratio. Therefore, the gap ratios as 0.5, 0.7, 1 and 1.1 are evaluated. Since for fewer distances pounding obviously occurs, they are not discussed here. Tables 1-2 show the values of 38 different clear distances used in this study, based on the above description. A large number of 38 clear distances is considered to cover the probable uncertainties.

5. Selection of input ground motions

To comprehensively account for the record-to-record variability in the ground motion, all adopted models were subjected to a large number of earthquake ground motions with different characteristics. The records are obtained from the strong motion database of the Pacific Earthquake Engineering Research Center (Chiou *et al*. 2008).

The criteria of the soil being type C, the earthquake magnitude being 6-7.5, and source-to-site distance (closest distance to fault rupture) being 10-30 km, an ensemble of 25 ground motions from 11 different earthquakes is selected, as listed in Table 3. All selected records are taken from the PEER (The Pacific Earthquake Engineering Research) Strong Motion Database. These records have peak ground acceleration (PGA) within the range of 0.3-1.0g, assuming that nonlinear behavior of the structures would be induced from earthquakes of such intensity. The outcome of the adopted scheme was to have 16 records with 0.3≤PGA≤0.5 g, 5 records with 0.5≤PGA≤0.7 g and 4 records with 0.7≤PGA≤1.0 g (Fig. 5). Normalized 5%-damped elastic acceleration response spectra, S_a, of these records together with median spectrum of them are shown in Fig. 6. In this figure, comparing mean and mean plus-minus deviation clearly shows the huge amount of uncertainty in the ground motion

6. Evaluation of probability of structural pounding

To quantify the pounding effects on the response of the structures, the probability of at least one impact based on 38 different clear separation distances for different structural periods is shown in Tables 4-5. Each number of pounding in these tables is calculated out of 26244 and 39204 models. Moreover, Table 6 lists the total probability of pounding based on different clear separation distances for adjacent structures. It can be seen from Tables 4-5 that the responses of the adjacent structures are very sensitive to the gap size and structural period's values. As the gap size increases up to the code's prescribed value, the probability of pounding decreases. Even a gap size of 1.1 of the design code leads to have the probability for pounding about 4.49% and 1.03% for the structural periods in the range of 0.1-0.5 s and 0.5-0.1 s, respectively. Moreover, it is observed that for the same relative distance, in comparison with shorter structures, the probability of pounding decreases for taller structures with higher periods. It means that the code prescribed values for separation distances are more conservative for taller structures. Furthermore, ground motion characteristics may affect on the probability of structural pounding. Generally, records with high PGA are more effective on structural pounding. However some exceptions have been observed.

6.1 Curve fitting and proposed equations

Curve fitting is one of the most powerful and most widely used analysis tools to find the best curves corresponding to numerical data. It is the process of constructing a curve, or mathematical function that has the best fit to a series of data points, possibly subject to constraints. It examines the relationship between one or more predictors (independent variables) and a response variable (dependent variable), with the goal of defining a "best fit" model of the relationship. Fig. 7 shows the

Table 4 Probability of at least one impact based on different clear separation distances for adjacent structures with T=0.1-0.5 s

Record	Pounding	Clear separation distance			
		0.5d	0.7d	d	1.1d
EQ1	Number of pounding	3240	0	0	0
	Probability of pounding	12.35%	0%	0%	0%
EQ2	Number of pounding	11016	4212	0	0
	Probability of pounding	41.98%	16.05%	0%	0%
EQ3	Number of pounding	17172	9396	648	0
	Probability of pounding	65.43%	35.80%	2.47%	0%
EQ4	Number of pounding	10692	5184	0	0
	Probability of pounding	40.74%	19.75%	0%	0%
EQ5	Number of pounding	14256	5184	324	0
	Probability of pounding	54.32%	19.75%	1.23%	0%
EQ6	Number of pounding	10368	0	0	0
	Probability of pounding	39.51%	0%	0%	0%
EQ7	Number of pounding	1620	0	0	0
	Probability of pounding	6.17%	0%	0%	0%
EQ8	Number of pounding	729	0	0	0
	Probability of pounding	2.78%	0%	0%	0%
EQ9	Number of pounding	10044	2592	0	0
	Probability of pounding	38.27%	17.28%	0%	0%
EQ10	Number of pounding	10692	2592	0	0
	Probability of pounding	40.74%	9.88%	0%	0%
EQ11	Number of pounding	15552	5184	0	0
	Probability of pounding	59.26%	19.75%	0%	0%
EQ12	Number of pounding	21708	17820	13932	11988
	Probability of pounding	82.71%	67.90%	53.09%	45.68%
EQ13	Number of pounding	7128	0	0	0
	Probability of pounding	27.16%	0%	0%	0%
EQ14	Number of pounding	12312	3888	0	0
	Probability of pounding	46.91%	14.81%	0%	0%
EQ15	Number of pounding	11016	4536	0	0
	Probability of pounding	41.98%	41.98%	0%	0%
EQ16	Number of pounding	4860	0	0	0
	Probability of pounding	18.52%	0.00%	0.00%	0.00%
EQ17	Number of pounding	17172	9072	1620	324
	Probability of pounding	65.43%	34.57%	6.17%	1.23%
EQ18	Number of pounding	11988	648	0	0
	Probability of pounding	45.68%	2.47%	0%	0%
EQ19	Number of pounding	18468	11664	4860	3888
	Probability of pounding	70.37%	44.11%	18.52%	14.81%
EQ20	Number of pounding	16200	10672	648	
	Probability of pounding	61.73%	40.70%	2.47%	0%
EQ21	Number of pounding	14904	7128	0	0
	Probability of pounding	56.79%	27.16%	0%	0%
EQ22	Number of pounding	20736	19440	15876	13287
	Probability of pounding	79.01%	74.07%	60.49%	50.62%
EQ23	Number of pounding	9396	1296	0	0
	Probability of pounding	35.80%	4.94%	0%	0%
EQ24	Number of pounding	972	0	0	0
	Probability of pounding	3.70%	0%	0%	0%
EQ25	Number of pounding	0	0	0	0
	Probability of pounding	0%	0%	0%	0%

variation of probability of pounding versus the gap ratio (Defined in section 4.1) and corresponding fitted curves for two ranges of periods based on numerical data. These curves show the general trend for the increase of pounding

Table 5 Probability of at least one impact based on different clear separation distances for adjacent structures with T=0.5-1.0 s

Record	Pounding	Clear separation distance			
		0.5d	0.7d	d	1.1d
EQ1	Number of pounding	0	0	0	0
	Probability of pounding	0%	0%	0%	0%
EQ2	Number of pounding	4658	0	0	0
	Probability of pounding	11.88%	0%	0%	0%
EQ3	Number of pounding	12809	776	0	0
	Probability of pounding	32.67%	2%	0%	0%
EQ4	Number of pounding	0	0	0	0
	Probability of pounding	0%	0%	0%	0%
EQ5	Number of pounding	12421	3882	0	0
	Probability of pounding	31.68%	9.90%	0%	0%
EQ6	Number of pounding	0	0	0	0
	Probability of pounding	0%	0%	0%	0%
EQ7	Number of pounding	0	0	0	0
	Probability of pounding	0%	0%	0%	0%
EQ8	Number of pounding	0	0	0	0
	Probability of pounding	0%	0%	0%	0%
EQ9	Number of pounding	2717	0	0	0
	Probability of pounding	6.93%	0%	0%	0%
EQ10	Number of pounding	0	0	0	0
	Probability of pounding	0%	0%	0%	0%
EQ11	Number of pounding	0	0	0	0
	Probability of pounding	0%	0%	0%	0%
EQ12	Number of pounding	22513	13974	776	0
	Probability of pounding	57.42%	35.64%	2.47%	0%
EQ13	Number of pounding	0	0	0	0
	Probability of pounding	0%	0%	0%	0%
EQ14	Number of pounding	10868	0	0	0
	Probability of pounding	27.72%	0%	0%	0%
EQ15	Number of pounding	2329	0	0	0
	Probability of pounding	5.94%	0%	0%	0%
EQ16	Number of pounding	15914	1164	0	0
	Probability of pounding	40.59%	2.97%	0%	0%
EQ17	Number of pounding	10092	6211	0	0
	Probability of pounding	25.74%	15.84%	0%	0%
EQ18	Number of pounding	8928	388	0	0
	Probability of pounding	22.77%	1.23%	0%	0%
EQ19	Number of pounding	19796	9127	11644	3493
	Probability of pounding	50.49%	27.16%	29.70%	11.11%
EQ20	Number of pounding	11645	0	0	0
	Probability of pounding	29.70%	0%	0%	0%
EQ21	Number of pounding	4658	0	0	0
	Probability of pounding	11.88%	0.00%	0%	0%
EQ22	Number of pounding	15915	12033	6987	6599
	Probability of pounding	40.59%	30.69%	17.82%	16.83%
EQ23	Number of pounding	12421	1941	0	0
	Probability of pounding	31.68%	4.95%	0%	0%
EQ24	Number of pounding	2620	0	0	0
	Probability of pounding	3.70%	0%	0%	0%
EQ25	Number of pounding	0	0	0	0
	Probability of pounding	0%	0%	0%	0%

against variation of separation distances. It is seems that exponential and power distributions are the closest distributions that could fit the considered data obtained for structures with the periods in the range of 0.1-0.5 s and 0.5-1 s, respectively. This means

that exponential and power distribution fit are the best fits to the numerical data of this study. As shown, by a reduction in the separation distance, the probability of pounding increases following mentioned distributions. The fitted curves, which model the numerical data, can be state

Table 6 Total probability of pounding based on different clear separation distances for adjacent structures

Total probability of pounding (T=0.1-0.5 s)				
	0.5d	0.7d	d	1.1d
Number of pounding	272241	120508	37908	29487
Number of models	656100	656100	656100	656100
Probability of pounding	41.49%	18.37%	5.78%	4.49%
Total probability of pounding (T=0.5-1.0 s)				
	0.5d	0.7d	d	1.1d
Number of pounding	62208	18362	7200	3744
Number of models	656100	656100	656100	656100
Probability of pounding	17.11%	5.05%	1.98%	1.03%

by formulas (10)-(11)

$$PP = 263e^{-3.756x} \tag{10}$$

$$PP = 1.632x^{-3.365} \tag{11}$$

which PP and X are the probability of pounding of adjacent structures and relative gap, respectively. The R-squares for formulas (10) and (11) are obtained as 0.99 and 0.98, respectively. These results are shown in Fig. 7. It is found that good matches for developed curves are observed. Moreover, in Fig. 7, it can be concluded that this variation becomes noticeable as the gap decreases. Furthermore, the correlation between proposed formulas and the curves obtained based on numerical data is very good. It is proposed to use these formulas to evaluate the probability of pounding for adjacent structures based on clear separation distances.

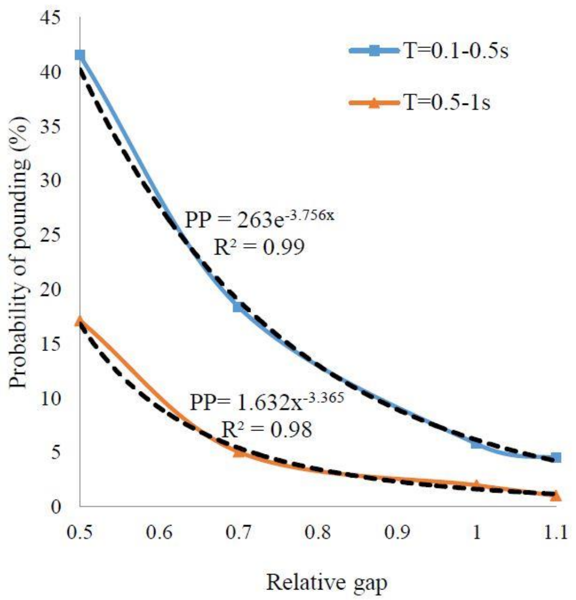


Fig. 7 Variation of probability of pounding versus relative gap and corresponding fitted curves

7. Conclusions

In the present study, pounding of adjacent structures of equal height modeled as SDOF systems with bilinear elasto-plastic force-deformation relationship is studied. To evaluate the probability of pounding of adjacent structures, the value of the gap distance between them, d, is varied between 0.5 and 1.1 of the Standard No. 2800 (2015) and the peak response of both structures is determined for each separation distance (Distancing at 50%, 70%, 100% and 110% of the clear distance required by the sample seismic code). The separation distance is taken randomly based on structural height and periods. The effects of pounding on the seismic response of structures have been investigated using a robust Monte-Carlo simulation. A large number of models with varying structural properties were used to systematically examine the response of adjacent structures when subjected to 25 earthquake ground motions with different earthquake characteristics. Based on the statistical analysis of the results from 6.54 million analyses, the following conclusions can be made:

1. Pounding of adjacent buildings is seen to occur once or more (see Tables 6-7) for adjacent structures with separation gap even based on Standard No. 2800 (2015). For example, for structures with the period in the range of 0.1-0.5 s, the probability of pounding is about 4.49% for 110% of the clear distance required by the mentioned code. Therefore, the application of the seismic code procedure results in separation distances that correspond to inconsistent and potentially non-conservative values.
2. The probability of pounding is very sensitive to variations in the separation distance, i.e., small variations in the separation distance can result in large variations in the probability of pounding. As the gap size increases up to about the code's prescribed value, the probability of pounding decreases. A gap size of 50% of the design code leads to have the probability for pounding about 41.5% and 17.1% for the structural periods in the range of 0.1-0.5 s and 0.5-0.1 s, respectively. A gap size of 70% of the design code leads to have the probability for pounding about 18% and 5% for the structural periods in the range of 0.1-0.5s and 0.5-0.1s, respectively. A gap size of 100% of the design code leads to have the probability for pounding about 5.8% and 2% for the structural periods in the range of 0.1-0.5 s and 0.5-0.1 s, respectively. A gap size of 1.1 of the design code leads to have the probability for pounding about 4.49% and 1.03% for the structural periods in the range of 0.1-0.5 s and 0.5-0.1 s, respectively.
3. It is observed that higher probability of pounding is found for structures with shorter periods compared to those with longer periods. It is rational, because based on Eq. (3), shorter periods lead to have shorter structural heights and smaller separation distances which increase the probability of pounding. Moreover, based on different characteristics of selected records, they cause different vibration patterns in adjacent structures. Therefore, different pounding probabilities are found for different ground motions.
4. The results show that with the same relative distance, the probability of pounding for shorter structures is

more significant than taller structures. It means that the code prescribed values for separation distances are more conservative for taller structures.

5. The proposed methodology can be used to develop current seismic code provisions that aim to mitigate the pounding probability and to calibrate appropriate safety factors for use with simpler methods of estimating the critical separation distance between adjacent buildings. It can also be directly used for reliability-based design of the separation distance between adjacent buildings.

6. Two formulas are developed base on the data obtained from a large number of numerical models. It is seemed that exponential and power distributions are the closest distributions that could fit the considered data resulted for structures with the periods in the range of 0.1-0.5 s and 0.5-1.0 s, respectively. Based on these formulas, especially for areas with high-seismicity rate, the required separation distances could be obtained by probabilistic procedure. These formulas can be used for structures periods in the range of 0.1-0.5 s and 0.5-1.0 s.

7. In this study, evaluation the probability of pounding and of separation distance is carried out only for equal height structures.

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