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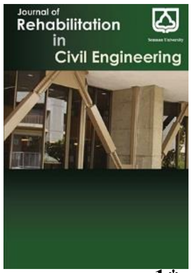

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Stochastic Analysis of Adjacent Structures Subjected to Structural Pounding under Earthquake Excitation

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ABSTRACT

Seismic pounding occurs as a result of lateral vibration and insufficient separation distance between two adjacent structures during earthquake excitation. This research aims to evaluate the stochastic behavior of adjacent structures with equal heights under earthquake-induced pounding. For this purpose, many stochastic analyses through comprehensive numerical simulations are carried out. About 4.65 million time-history analyses were carried out over the considered models within OpenSees software framework. Various separation distances effects are also studied. The response of considered structures is obtained by means of Hertzdamp contact element. The models have been excited using 25 earthquake records with different peak ground accelerations. The probability of collision between neighboring structures has been evaluated. An efficient combination of analytical and simulation techniques is used for the calculation of the separation distance under the assumptions of non-linear elasto-plastic behavior for the structures. The results obtained through Monte Carlo simulations show that use of the current provision's rule may significantly overestimate or underestimate the required separation distance, depending on the natural vibration periods of adjacent buildings. Moreover, based on the results, a formula is developed for stochastic assessment of required separation distance.

1. Introduction

The seismic pounding between two adjacent structures during strong ground motions has been receiving considerable attention in recent decades. This phenomenon occurs due to insufficient separation distance and out of phase vibration under earthquake ground motions. Pounding leads to additional forces and develops damages to structure at the point of collision. In the 1985 Mexico City [1] and 1989 Loma Prieta [2] earthquakes,

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due to pounding, a large number of seismic damage was observed. Because of the aforesaid reasons, the pounding phenomenon is an issue that should be considered in the structural design. Davis carried out a numerical study on a pounding system including damped single-degree-of-freedom (SDOF) structure and a rigid barrier [3]. He modeled the pounding of adjacent buildings by an impact oscillator subjected to harmonic excitation. Spectra of impact velocity were presented for a range of model parameters. Pantelides and Ma [4] evaluated the coupling behavior of damped SDOF elastic and inelastic structures with one-sided pounding under earthquake excitation using a Hertz contact element. They evaluated the effects of separation distance and inelastic structural behavior on the magnitude of the pounding force. It was observed that an increase in the damping energy absorption capacity of the pounding structure results in the reduction of the pounding forces. Hao et al. [5] and Hao and Gong [6] evaluated the behavior of the two adjacent structures subjected to seismic pounding due to spatially varying earthquakes. Jankowski [7] proposed a notion pounding force response spectrum for two elastic and inelastic adjacent structures. Furthermore, there have been some studies that investigated seismic pounding between adjacent structures of specific design considering differing heights and structural layout as effective parameter [8-10]. Similar works have considered this issue for base isolated structures with and without added devices [11-13]. Many researches have also developed and presented measures for mitigating and preventing pounding damages [14–16]. Alam and Kim [17] evaluated the effects of the spatially varying ground motion on the behavior of adjacent structures considering soil–structure interaction. Kharazian and Lopez-Almansa [18] investigated the seismic pounding between some buildings with aligned slabs. Moustafa and Mahmoud [19] evaluated the seismic pounding in adjacent buildings using input energy, damage indices and dissipated energy. Naderpour et al. [20], in order to simulate impact, used an unreal element between the two mentioned points, which is mathematically described as a spring and dashpot. They suggested a new equation of motion to calculate the IDR and investigated the accuracy of equation. Naderpour et al. [21] studied on preventing collisions between structures during seismic excitation based on gap size. Artificial neural networks were utilized to estimate the required distance between structures. They modeled some MDOF models equivalently and estimated optimum gap size between buildings and finally suggested a new equation for separation distance.

Naderpour et al. [22] studied the case of pounding between two adjacent buildings by the application of single degree-of-freedom structural models. The results of the study indicate that the impact force time history is much dependent on the earthquake excitation analyzed. Moreover, the peak impact forces during collision depend substantially on such parameters as gap size, coefficient of restitution, impact velocity, and stiffness of impact spring element.

In many cases pounding in bridges have also been investigated [23-26]. Sheikh et al. [27] performed an analytical study on the use of magnetorheological (MR) dampers in decreasing the pounding influence of base-isolated multi-span RC highway bridges. Moreover, in some cases risk of pounding have been studied. Tubaldi et al. [28] presented a procedure to find the seismic pounding risk between adjacent linear structures with deterministic and uncertain properties. Barbato and Tubaldi [29] developed a probabilistic method to obtain the required separation distance between adjacent structures.

This study presents a more complete stochastic assessment of pounding based on the key factors identified in prior works. Namely, the gap between structures and structural period. Also, the variability in the systems and uncertain properties in the earthquakes characteristics are considered. Its aim is to evaluate the probability of impact and propose a formula for stochastic calculation of separation distance between non-linear adjacent structures for periods in the range of 1-1.5 s, which can extended for other periods. A comprehensive parametric study that covers a wide range of structural systems was performed via Monte-Carlo simulation. For this purpose, a total of 4.65 million non-linear dynamic time history analyses on various systems are carried out by means of the seismic analysis OpenSees [30] software framework and MATLAB [31] programming tool. This methodology allows the designer to choose a separation distance that ensures consistent probability levels for different types of structures with the period in the range of 1-1.5 s which is considered in this study.

2. Structures and Pounding Models

2.1. Development of the Analytical Models

In this study, idealized mathematical models for adjacent SDOF structures situated at separation distance of d are evaluated (Fig. 1). It is worth noting that the left and right structures are entitled as the structure 1 and 2, respectively. Based on the Fig. 1, x1 and x2 are the displacements of the structures, k1 and k2 are structural stiffness, m1 and m2 are the structural mass, c1 and c2 are the damping coefficients, and d is the separation gap based on Iranian Code of Practice for Seismic Resistant Design of Buildings (Standard No. 2800 [32]). To model the pounding phenomenon between two adjacent structures, the Hertzdamp [33-34] element is used which appears to be an adequate contact model, as it can model energy loss. The Hertzdamp element becomes active when the corresponding nodes come into contact. According to the nonlinear Hertzdamp model, the pounding force between adjacent structures can be written as Eq. (1):

$$F_c = \begin{cases} k_h \delta^{3/2} + c_h \dot{\delta} & \delta > 0 \\ 0 & \delta < 0 \end{cases} \qquad (1)$$

where δ is the relative displacement of the adjacent structures, $\dot{\delta}$ presents the relative deformation velocity of the colliding masses during the collision process, k_h expresses the Hertzdamp model impact spring stiffness, and c_h is the damping coefficient, and can be calculated by Eq. (2):

$$c_h = \xi \delta^{3/2} \qquad (2)$$

Additionally, the relationship between damping constant, ξ, nonlinear stiffness, k_h, coefficient of restitution e, and the relative initial velocity of structure impact δ can be obtained as:

$$\xi = \frac{3k_h(1-e^2)}{4\dot{\delta}} \qquad (3)$$

which e represents the coefficient of restitution which considered as 0.65.

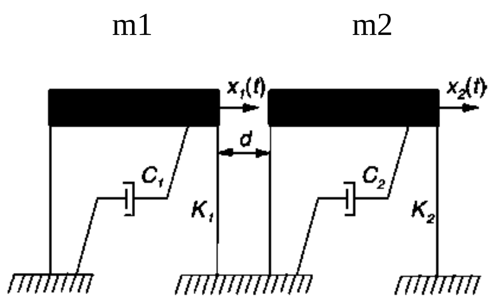


Fig. 1. Model of two interacting structures

The nonlinear dynamic equation of motion which includes pounding force during collisions can be expressed as Eq. (4):

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}\begin{bmatrix} \ddot{x}_1(t) \\ \ddot{x}_2(t) \end{bmatrix}+\begin{bmatrix} c_1 & 0 \\ 0 & c_2 \end{bmatrix}\begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \end{bmatrix}+\begin{bmatrix} k_1 & 0 \\ 0 & k_2 \end{bmatrix}\begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix}+\begin{bmatrix} F(t) \\ -F(t) \end{bmatrix}=-\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}\begin{bmatrix} \ddot{x}_{g1}(t) \\ \ddot{x}_{g2}(t) \end{bmatrix} \quad (4)$$

where $\ddot{x}_1$, $\ddot{x}_2$ and $\dot{x}_1$, $\dot{x}_2$ represent the accelerations and velocities of the structure 1 and 2, respectively; $F(t)$ expresses the value of pounding force; and $\ddot{x}_g$ is the earthquake acceleration.

As shown in Fig. 2, a bilinear elasto-plastic model with kinematic hardening describes the relationship between the inelastic restoring force and the displacement of the equivalent SDOF systems is used. In this model, the linear branch was considered equal to k and the yield strength was defined assuming a displacement ductility of 6 at 2% drift. The post-yielding stiffness factor, α, for hardening modulus was considered equal to 0.05. 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, respectively.

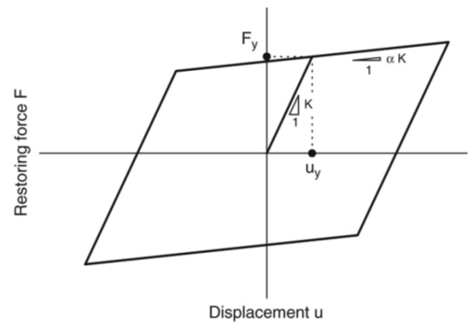


Fig. 2. Bilinear elasto-plastic representing structural nonlinear response.

2.2. Separation Distance Between Structures

In the present study, for all models, different periods were assigned to structure 1 and 2 which result in various displacements. The peak displacement of the structures gives the minimum separation distance between them. Standard No. 2800 [32] requires that the Eq. (5) to be used for calculation of the separation distance:

$$d = 0.005(h_1 + h_2) \quad (5)$$

where h_1 and h_2 are the structures height over the base for structural system 1 and 2, respectively. In Eq. (5), the separation is obtained by combining the quantities u_1 and u_2 according to the well known ABS. It should be noted that there are some more methods to obtain the separation distance (such as SRSS and Spectral Difference) 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.

Overall, six cases are considered in this study regarding the clear distance as being 10%, 20%, 30%, 50%, 70% and 100% of the code's prescribed value (Eq. (5)). In this paper, the ratio of considered separation distances to separation distances defined by Standard No. 2800, d , is called the gap ratio. Therefore, the gap ratios including 0.1, 0.2, 0.3, 0.5, 0.7 and 1 are used. Since for fewer distances pounding obviously occurs, they are not discussed here. Table 1 shows the values of 21 different separation distances used in this study, based on the above description. A noticeable number of 21 separation distances is considered to cover the probable uncertainties.

3. Analysis Methodology for Stochastic Assessment of Structures

The procedure used in this study was to systematically compute the seismic response for a wide range of adjacent structures models when subjected to various earthquakes. Significant uncertainties in model parameters and earthquake characteristics result in a noticeable range of responses of the structures. A robust Monte-Carlo simulation was applied to analyze models through random selection procedure.

For each of two adjacent structures, 11 fundamental structural periods (T) in the range of 1-1.5 s, with a period increment of 0.05 s, are considered. This period set was chosen to represent structures about 30-50 m high and to satisfy the period-height relationship stipulated in the Standard No. 2800 [32]. Moreover, for every earthquake records, six separation distances were considered. For each separation distance, 30976 models constrained to conform to the adopted periods and to produce realistic structural pounding models were randomly generated. A relatively large number of 30976 models were chosen in order to provide high level of accuracy of the Monte-Carlo simulation. Each model was subjected to 25 different earthquake ground motions. Then, all 4.65 million models were analyzed using OpenSees software.

3.1. Structural Parameters and Uncertainties

For parametric study, some parameters are defined to describe various aspects of the structural system. Most of the structural parameters were defined as uncertain parameters. The uncertainty in the properties of the elements in the introduced discrete model is described by random variables. The following parameters are assumed 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.

To represent soils class C based on Standard No. 2800 [32] classification, the variation range of 175-375m/s, to a depth of 30m, was chosen for V_s (Soil shear wave velocity). Soil mass density, ρ, is modeled as a lognormal random variable with a mean of 1800 and a CoV (coefficient of variation) of 6.8%. Mean and CoV are obtained in a way that ρ lies between 1600 kg/m3 and 2000 kg/m3 with 90% confidence level. Effective height of the structure, h_{eff}, radius of the cylindrical foundation, r, and structural mass, m_{str}, were some randomly generated structural parameters. Using these randomly generated parameters, the values for the structural stiffness, k_{str}, and structural damping coefficient, c_{str}, were calculated. To evaluate realistic structural pounding models, the selection of the mentioned structural parameters was constrained by commonly accepted relationship for structures. The first parameter to be calculated was h_{eff}. For each model with a specified T (1-1.5 s), a range of variation for h_{eff} was obtained based on a typical period-height relationship adopted in Standard No. 2800 [32] which can be presented as Eq. (6) and the considered limitation on the height of the structure of 30-50 m.

$$0.05(h_{eff})^{0.75} \le T \le 0.08(h_{eff})^{0.75} \quad (6)$$

It was assumed that h_{eff} is uniformly distributed (equally likely to occur) in the mentioned range. After defining h_{eff} at each range of T, for all models, the structure aspect ratio, h_{eff}/r, was used to achieve the foundation radius, r. It was assumed that the ratio takes on the constant values of 1, 2, and 3 to represent a range of conventional buildings. The uncertainty in quantifying h_{eff}/r is considered negligible compared with that of other variables.

For each predefined value of h_{eff}, a random value was calculated for r satisfying the above-mentioned limitations. To obtain a realistic structural mass, m_{str}, for the defined structural parameters, the relative mass index $\overline{m}$ calculated as Eq. (7):

$$\overline{m} = \frac{m_{str}}{\rho r^2 h_{eff}} \quad (7)$$

where $\overline{m}$ is the structure to soil mass ratio index, and is modeled as a lognormal random variable with a mean of 0.6 and a CoV of 20%. To obtain its probability distribution, $\overline{m}$ was derived in terms of more basic physical variables that define the mass, geometry and material properties of the structures and foundations. Then, a probability distribution was assigned to these variables based on their typical range in engineering practice. Finally, the probability distribution of $\overline{m}$ was calculated by performing a sampling analysis. For ordinary structures, it varies between 0.4-0.8. Thus, knowing previously defined values for h_{eff}, r, and ρ and considering a lognormal distribution for $\overline{m}$ within the defined range, the value for the structural mass, m_{str}, was obtained. Fig. 3 shows the distribution of structural mass obtained for T=1-1.5s. Following this calculation of m_{str}, the initial structural stiffness, $(k_{str})_i$, was obtained based on Eq. (8):

$$(k_{str})_i = \frac{4\pi^2}{T^2} m_{str} \quad (8)$$

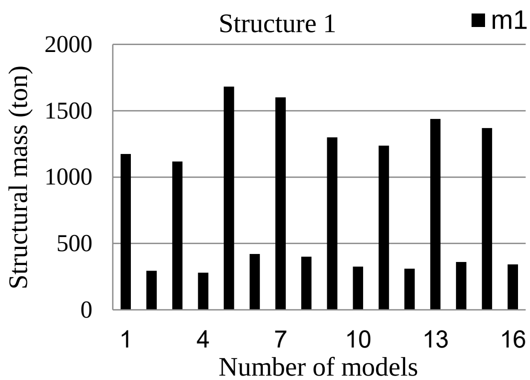
To calculate the structural damping coefficient, c_{str}, a constant 5% equivalent viscous structural damping was employed, and c_{str} was defined as:

$$c_{str} = 2(0.05)\sqrt{(k_{str})_i m_{str}} \quad (9)$$

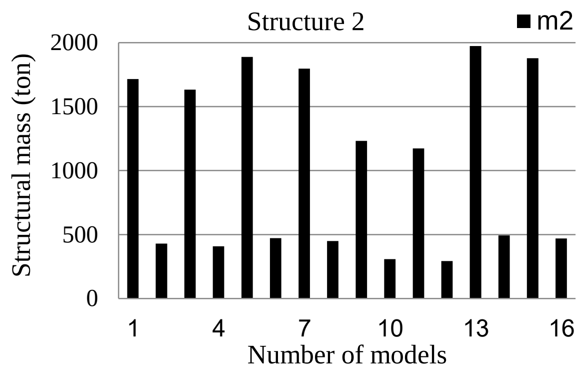
It can be resulted from Eqs. (8) and (9) that the distributions of $(k_{str})_i$ and c_{str} will be similar to that of m_{str}.

4. Input Earthquake Records

A set of 25 earthquake records have been used as input to the different models to evaluate the response of the adjacent structures, as listed in Table 1. For consistency, the following important conditions were considered in the selection of the earthquake records: soil class C, magnitude (M) in the range of 6–7.5, peak ground acceleration (PGA) in the range of 0.3-1g, source distance (Rrup) 11–38 km, and strong motion duration more than 10 s. The PEER (The Pacific Earthquake Engineering Research) strong ground motion database was used with the previously mentioned limitations. It is assumed that both adjacent structures experience the same excitation at the same time. Fig. 4 shows the 5%-damped elastic pseudo-acceleration spectra, S_a, of these records together with the mean spectra. This figure clearly shows the huge amount of uncertainties in the selected earthquake records.



(a) Structure 1



(b) structure 2

Fig. 3. Distribution of structural mass for two adjacent structures.

Table 1. Strong ground motion records used as input to adjacent buildings.

Record ID	Event	Year	Station	M	PGA (g)	R (km)	Vs (m/sec)	Soil Class
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	Tamati Yone Izumozaki, 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	6.9	0.40	38.0	278.35	C
EQ25		2008	Misato, Miyagi Kitaura	6.9	0.35	38.0	278.35	C

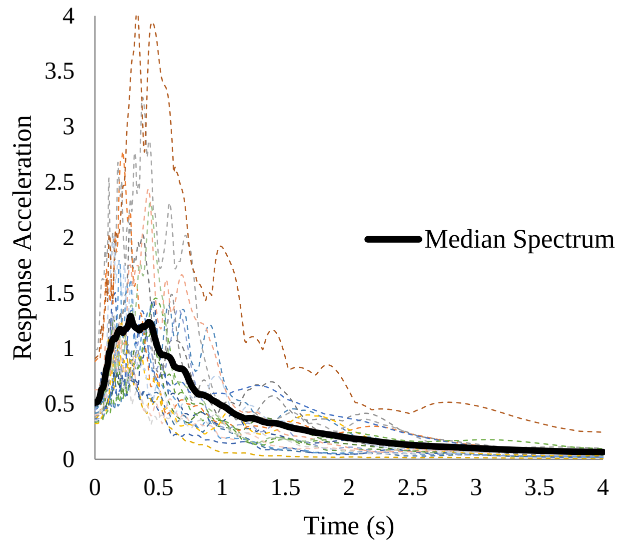


Fig. 4. Normalized elastic acceleration response spectra (5% elastic damping) of the selected earthquake ground motions.

5. Probability Assessment of Structural Pounding

Tables 2 lists the probability of at least one impact based on 21 different separation distances for various structural periods is shown. Each number of pounding in this table is obtained out of 30976 analyses. Moreover, Table 3 lists the total probability of pounding based on various separation distances for adjacent structures. It can be seen that the response of the adjacent structures are sensitive

to the gap size and structural period's values. The probability of pounding noticeably decreases as the gap size increases.

Table 2. Probability of at least one impact based on various separation distances for adjacent structures with T=1-1.5.

Record ID	Evaluation of pounding	Relative separation distance					
		0.1d	0.2d	0.3d	0.5d	0.7d	d
EQ1	Number of pounding	20736	8704	0	0	0	0
	Probability of pounding	66.94%	28.10%	0%	0%	0%	0%
EQ2	Number of pounding	26624	21504	11776	0	0	0
	Probability of pounding	85.95%	69.42%	38.02%	0%	0%	0%
EQ3	Number of pounding	27904	23552	20224	8192	4352	0
	Probability of pounding	90.10%	76.03%	65.28%	26.45%	14.05%	0%
EQ4	Number of pounding	26832	21248	15872	256	0	0
	Probability of pounding	86.62%	68.59%	51.25%	0.80%	0%	0%
EQ5	Number of pounding	26980	21760	17152	5888	0	0
	Probability of pounding	87.10%	70.25%	55.37%	19.01%	0.00%	0%
EQ6	Number of pounding	0	0	0	0	0	0
	Probability of pounding	0%	0%	0%	0%	0%	0%
EQ7	Number of pounding	0	0	0	0	0	0
	Probability of pounding	0%	0%	0%	0%	0%	0%
EQ8	Number of pounding	16640	0	0	0	0	0
	Probability of pounding	53.72%	0%	0%	0%	0%	0%

EQ9	Number of pounding	21248	5120	512	0	0	0
	Probability of pounding	68.59%	16.50%	1.65%	0%	0%	0%
EQ10	Number of pounding	19712	0	0	0	0	0
	Probability of pounding	63.64%	0%	0%	0%	0%	0%
EQ11	Number of pounding	23808	18176	7680	0	0	0
	Probability of pounding	76.86%	58.68%	24.79%	0%	0%	0.00%
EQ12	Number of pounding	25856	18688	13568	2304	0	0
	Probability of pounding	83.47%	60.33%	43.80%	7.44%	0.00%	0.00%
EQ13	Number of pounding	25088	19200	13056	1280	0	0.00%
	Probability of pounding	80.99%	61.98%	42.15%	4.13%	0.00%	0.00%
EQ14	Number of pounding	24320	17664	11264	5888	768	0
	Probability of pounding	78.51%	57.02%	36.36%	19.01%	3.70%	0%
EQ15	Number of pounding	19712	9216	768	0	0	0
	Probability of pounding	63.64%	29.76%	2.48%	0%	0%	0%
EQ16	Number of pounding	24128	17408	7936	0	0	0
	Probability of pounding	77.89%	56.20%	25.62%	0%	0%	0%
EQ17	Number of pounding	22784	14336	2304	0	0	0
	Probability of pounding	73.55%	46.28%	7.44%	0%	0%	0%
EQ18	Number of pounding	23780	16384	8960	0	0	0
	Probability of pounding	76.77%	52.89%	28.93%	0%	0%	0%
EQ19	Number of pounding	27684	24064	19968	11008	3228	0
	Probability of pounding	89.37%	77.69%	64.46%	35.54%	10.42%	0.00%
EQ20	Number of pounding	22016	7936	1280	0	0	0
	Probability of pounding	71.07%	25.62%	4.13%	0%	0%	0%
EQ21	Number of pounding	23040	12288	3072	0	0	0
	Probability of pounding	74.38%	39.67%	9.92%	0%	0%	0%
EQ22	Number of pounding	27136	22784	19456	9728	512	0
	Probability of pounding	87%60	73.55%	62.81%	31.40%	1.65%	0.00%
EQ23	Number of pounding	26880	21504	16384	2816	0	0
	Probability of pounding	86.78%	69.42%	52.89%	9.09%	0%	0%
EQ24	Number of pounding	22528	12800	0	0	0	0
	Probability of pounding	72.73%	41.32%	0%	0%	0%	0%
EQ25	Number of pounding	25088	18432	4352	0	0	0
	Probability of pounding	80.99%	59.50%	14.05%	0%	0%	0%

Table 3. Total probability of pounding based on various separation distances for adjacent structures with T=1-1.5 s.

Total probability of pounding (T=1-1.5s)						
Separation distance	0.1d	0.2d	0.3d	0.5d	0.7d	d
Number of pounding	550524	352768	195584	47360	8860	0
Number of models	774400	774400	774400	774400	774400	774400
Probability of pounding	71.09%	45.56%	25.26%	6.12%	1.14%	0%

6. New Formula for Stochastic Assessment of Separation Distance

Curve fitting is one of the most powerful and most widely used analysis tools to obtain the best curves corresponding to numerical data. Fig. 5 shows the variation of probability of pounding versus the gap ratio (Based on previous sections) and corresponding fitted curve based on numerical data. It shows the trend for the increase of pounding against variation of separation distances. It is seems that polynomial distributions are the closest distributions that could fit the data obtained for structures with considered periods. This means that polynomial distribution is the best fit to the numerical data of this study. The fitted curve can be represented by Eq. (10):

$$PP = -213.7x^3 + 510.3x^2 - 403.4x + 106.8 \quad (9)$$

which PP and x are the probability of pounding and relative gap between adjacent structures, respectively. The variation of probability increases as the gap decreases. Moreover, a desirable correlation between proposed formula and the curve obtained based on numerical data is obtained. It is proposed to use this formula to estimate the probability of pounding for adjacent structures based on separation distances for the structural periods in the range of 1-1.5 s.

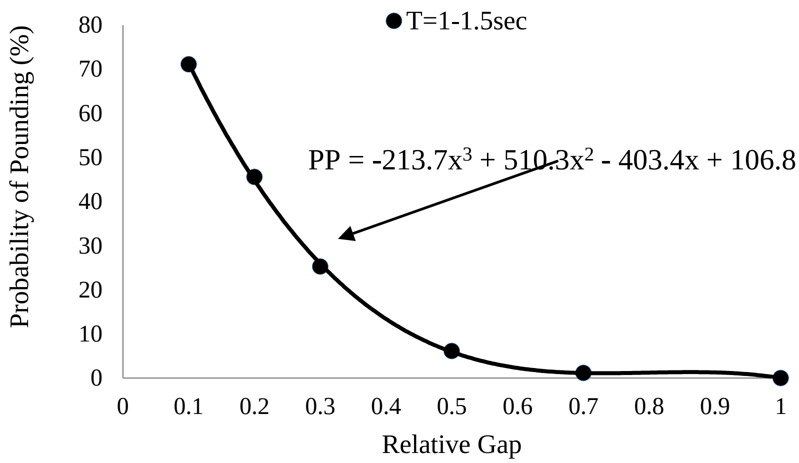


Fig. 10. Variation of probability of pounding for adjacent structures versus relative gap and corresponding fitted curve.

7. Conclusion

In this study, pounding of adjacent structures of equal height modelled as SDOF systems is studied. To estimate the probability of pounding of adjacent structures, the value of the separation distance between them, d , is varied between 0.1 and 1.0 of the Standard No. 2800 [32]. The separation distance is taken randomly based on structural height and periods. The range of natural periods considered is essentially the same range of possible natural periods of actual building structures prone to seismic pounding. The response of the adjacent structures was evaluated through Monte Carlo simulations. A large number of models (About 4.65 million) with varying structural properties were developed to systematically evaluate the response of adjacent structures when subjected to 25 ground motions with various earthquake characteristics. The analysis of the results can be summarized as follows:

1. It is concluded that pounding of adjacent structures is seen to occur once or more for adjacent structures with separation gap even near the gap defined in Standard No. 2800 [32]. In general, the probability of pounding increases as T1 becomes more different from T2. Thus, the application of the seismic codes leads to separation distance that corresponds to inconsistent and potentially non-conservative values.
2. The probability of pounding is sensitive to variations in the separation distance, i.e., small variations in the separation distance

lead to large variations in the probability of pounding. The probability of pounding decreases as the gap size increases up to about the code-based value. A gap size of 10%, 20%, 30%, 50%, 70% and 100% of the design code leads to have the probability for pounding about 71.1%, 45.6%, 25.3%, 6.1%, 1.1% and 0%, for the structural periods in the range of 1-0.5 s, respectively.

3. Based on the data obtained from a large number of numerical models, a formula is developed. It is seemed that polynomial distribution is the closest distribution that could fit the data resulted for structures with the period in the range of 1-1.5 s. The probabilistic determination of needed structural separation distance could be accounted Based on this formula.
4. Further studies can be conducted to extend the model used to more realistic cases, such as adding degrees of freedom, using other periods and developing new formulas.

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