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A new equation based on PGA to provide sufficient separation distance between two irregular buildings in plan

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Abstract. Past earthquakes experience shows that serious damage or collapse of buildings have dramatically accrued when sufficient separation distance has not been provided between two adjacent structures. The majority of past studies related to the pounding topic indicate that obtaining the gap size between two buildings is able to prevent collision and impact hazards during seismic excitations. Considering minimization of building collisions, some relationships have been suggested to determine the separation distance between adjacent buildings. Commonly, peak lateral displacement, fundamental period and natural damping as well as structural height of two adjacent buildings are numerically considered to determine the critical distance. Hence, the aim of present study is to focus on all mentioned parameters and also utilizing the main characteristic of earthquake record i.e. PGA to examine the lateral displacement of irregular structures close to each other and also estimate the sufficient separation distance between them. Increasing and decreasing the separation distance is inherently caused economical problems due to the land ownership from a legal perspective and pounding hazard as well. Therefore, a new equation is proposed to determine the optimum critical distance. The accuracy of the proposed formula is validated by different models and various earthquake records.

Keywords: Pounding; critical distance; fundamental period; damping; peak displacement

1. Introduction

Collision between adjacent structures is usually observed when the relative displacements exceed the limitation of gap size. Because of that, adjacent buildings contact with each other due to insufficient separation distance. In order to provide a safe gap size for preventing collision during seismic excitations, the majority of building codes have directly considered a minimum critical distance based on peak lateral displacement or structural height of adjacent buildings (IBC 2003, NBC 2003 and Iranian Code of Practice for Seismic Resistant Design of Buildings 2017). On the other hand, some researchers have numerically suggested a minimum gap size between structures based on structural period and natural damping. Anagnostopolos (1998), Lopez-Garcia and Soong (2009), Hao and shen (2001) and Valles and Rainhorm (1997) have experimentally evaluated the effectiveness of required separation distance to avoid impact between structures during lateral loading. In these studies, the effects of vibration frequencies, torsional stiffness and eccentricities of adjacent structures on relative displacements of structures have been investigated. In the following up studies, Kasai and Maison (1997), Penzien (1997), Jeng and Tzeng (2000), Naderpour *et al*. (2017) and Khatami *et al*. (2019) have logically demonstrated pounding hazards. Using dynamic models and focusing on linear and nonlinear behavior of buildings during the earthquake, they have suggested numerically some equations to determine the required separation distance between adjacent structures. Karayannis and Naoum (2018) have numerically explored the effectiveness of seismic pounding between multistory structures using an 8-story RC building and a shorter adjacent model. They have considered that two buildings, which are located close to each other, are able to undergo torsional movement due to asymmetric seismic interaction with and without irregularities. Dogrul (2005), Garcia (2004), Filiatrault *et al*. (1995), Jankowski and Mahmoud (2015), Komodromos *et al*. (2007), Komodromos (2008) and Polycarpou *et al*. (2013) have suggested different methods to reduce the lateral displacement and control pounding hazard using rubber bumpers, base isolation systems and different link elements. Falborski *et al*. (2012), Pratesi *et al*. (2014) and Yang *et al*. (2003) have also carried out some studies regarding separation distance to mitigate pounding hazard.

Accordingly, the aim of current study is to evaluate the importance of separation distance to avoid collision during seismic excitations. Due to different suggested equations by researchers and building codes for critical distance, it is a need to consider all used parameters as well as earthquake characteristics to calculate the separation distance between adjacent structures. Owing to economy strategy and the

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Table 1 Some suggested separation distance by seismic codes

Country	Separation distance
Canada	Sum of their individual lateral displacement, calculated by elastic analyses
Australia	More than 1% of the structural height
Turkey	3 cm for 6 m height and 1 cm should be added for every 3 m height
Peru	3+0.004×(h-500) cm
Egypt	2 times the sum of the individual displacement or 0.004 times its height

land ownership from a legal perspective, optimum gap size is of great importance.

2. Available equations

The lack of sufficient distance between two adjacent buildings causes collision during the seismic excitation, which, due to the different behavior of the buildings, sometimes leads to extensive damage. According to the many seismic codes and considering the relationships related to the pounding, desired critical distance is numerically determined based on peak lateral displacement of each building. Relying on recommended gap size by seismic codes, three different equations are presented. These equations that depend significantly on relative displacement, including the absolute sum method (ABS) and square-root-of-sum-of-squares (SRSS) method suggested by Eurocode 8 (2005), and also height of adjacent buildings recommended by Iranian Code of Practice for Seismic Resistant Design of Buildings-Standard No. 2800 (2017), are listed as below

$$S_{(ABS)} = x_i + x_j \tag{1}$$

$$S_{(SRSS)} = \sqrt{x_i^2 + x_j^2} \tag{2}$$

$$S_{(St-2800)} = \overline{\omega}.H_{\max} \tag{3}$$

Where S is minimum gap size between structures and x_i and x_j are peak lateral displacements of buildings i and j, respectively. H denotes the height of taller building and $\overline{w}$ is considered to be 0.01. Other suggested separation distances by some major seismic codes are reported in Table 1.

Moreover, researchers have widely represented some equations to calculate optimum gap size, considering nonlinear behavior of buildings and economy considerations. In order to determine critical distance, Eq. (2) is generally considered and developed to provide safety gap size while reflecting natural behavior of buildings during earthquake. Kasai and Maison (1997) were the first researcher, who have believed that the value of gap size can be decreased by a decreasing factor, μ, and depends directly on structural period. The equations that are generally used are expressed as below

$$S = \sqrt{x_i^2 + x_j^2 - 2.\mu.x_i.x_j} \tag{4}$$

and

$$\mu = \frac{8\sqrt{\zeta_i.\zeta_j}.(\zeta_i + \zeta_j.(\frac{T_i}{T_j})).(\frac{T_i}{T_j})^{1.5}}{(1-(\frac{T_i}{T_j})^2)^2 + 4.\zeta_i.\zeta_j.(1-(\frac{T_i}{T_j})^2).(\frac{T_i}{T_j}) + 4.(\zeta_i^2 + \zeta_j^2).(\frac{T_i}{T_j})^2} \tag{5}$$

Where ζ_i and ζ_j are the natural damping of building i and building j, respectively. T_i and T_j denote period of adjacent buildings assuming linear behavior.

Later, Naderpour *et al*. (2017) had suggested a relationship based on structural period and linear behavior of buildings which can be described as

$$\mu = \left(\frac{T_j}{T_i}\right) - 10.5.(T_j - T_i) \tag{6}$$

Furthermore, Penzien (1997) presented parametrically the natural period of buildings based on their nonlinear response during earthquake. He suggested a new formula for nonlinear period and used Eq. (5) to calculate decreasing factor which is expressed as

$$T_n = T_l.\sqrt{\frac{\sigma}{\eta + \kappa.(\sigma - \eta)}} \tag{7}$$

T_n and T_l are nonlinear and linear period of each building. σ and K are the ductility and ratio of final stiffness of buildings, respectively. η is experimentally recommended to be 0.65.

In addition, based on nonlinear period of buildings during seismic excitation, Jeng and Tzeng (2000) considered the ductility of building for nonlinear period which can be explained as

$$T_n = T_l(1 + 0.18.(\sigma - 1)) \tag{8}$$

Finally, Khatami *et al*. (2019) proposed an equation which is demonstrated as

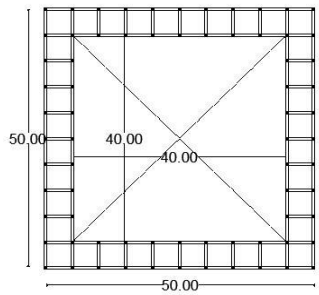
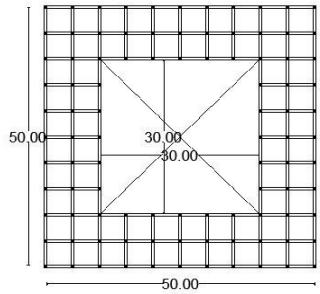
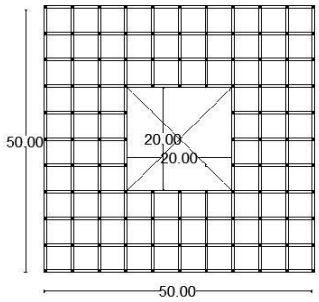
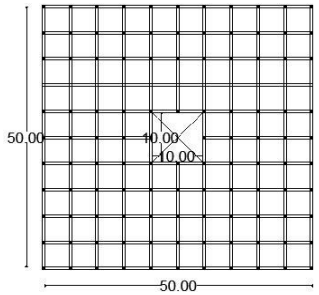
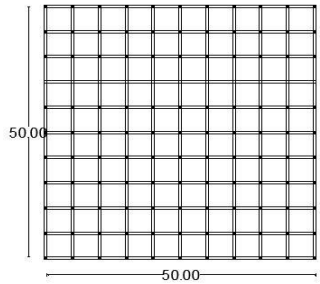
$$T_n = T_l.(1 + \Phi) \rightarrow \Phi = \Omega.(\sigma^{0.385} - 1) \tag{9}$$

Where Φ is an increased factor and is calculated by Ω, which is recommended to be $0.94 \leq \Omega \geq 0.98$.

3. Seperation distance

For the purposes of this study, two MDOF adjacent regular and irregular buildings based on dynamic models are numerically assumed to be separated by a distance from each other. The shape of stories is considered to be square and also assumed to be irregular in plan. The height of each story is 3 m with 9 frames. The dimensions of the first story

Table 2 The plan of models in different story

Model	One-Story	Two-Story	Three-Story	Four-Story	Five-Story
	Story No. 1	Story No.2	Story No.3	Story No.4	Story No.5
		Story No. 1	Story No.2	Story No.3	Story No.4
			Story No. 1	Story No.2	Story No.3
				Story No. 1	Story No.2
					Story No. 1

plan are 50 m in both directions (X and Y). In order to provide irregularity in plan, a square void is considered in center of plan, which is 40×40 m in highest story (roof) and is decreased to 30×30, 20×20 and 10×10 m in lower stories (Table 2). In 5-story model, the story stiffness of first story is considered to be 1.67×106 N/m, story mass and superstructures damping ratio are assumed to be 4000 kg and 5%, respectively. The above values for the highest story are 0.67×106 N/m and 1638 kg, respectively.

Models are typically considered to be one to five stories, located close to each other and separated by a distance based on Eq. (3). The dynamic characteristics of selected

Table 3 The properties of dynamic models

Irregular models					Fundamental eigenperiod (s)	Height (m)	Mass (kg)	Stiffness (N/m)	Damping
5-Story	4-Story	3-Story	2-Story	1-Story	0.2197	3	1638	$0.67*10^6$	2457
					0.4826	6	2048	$0.85*10^6$	3072
					0.5931	9	2560	$1.06*10^6$	3840
					0.7064	12	3200	$1.33*10^6$	4800
					0.9512	15	4000	$1.67*10^6$	6000

Table 4 The properties of selected earthquake records

Earthquake	Date	Magnitude	Station	Component	PGA (cm/s^2)
El Centro	1940	6.9	El Centro	NS	307
Parkfield	1966	6.2	CGS	NS	462
Loma Prieta	1989	6.9	Corralitos	NS	631
Kobe	1995	7.2	JMA	NS	817

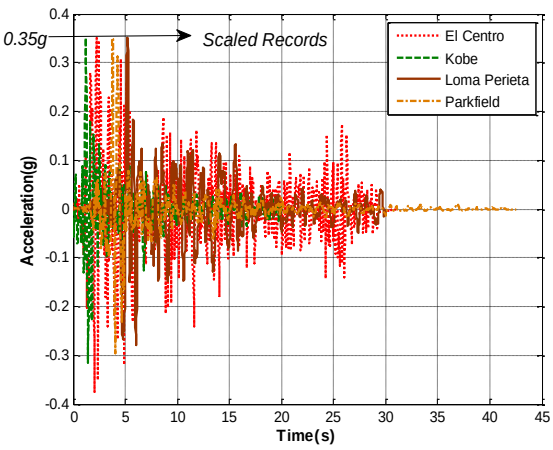


Fig. 1 The scaled selected earthquake records

models are presented in Table 3.

As it is obviously seen in Table 4, the properties of 5rd story of 5-story building are equal with the properties of 1st story of 1 story building. Subsequently, in order to simplify and define different models, they are particularly named as 12 to 54. For example, 12 and 54 mean one-story model with two-story model and five-story model with four-story model, respectively. In these models, fist story mass of model 12 are 2048 kg and 1638 kg, while second story of 2-story model is 1638 kg. It is also mentioned that the stiffness story of model is $0.85*10^6$ and $0.67*10^6$ N/m for the first story of 2- story and 1- story model.

The numerical analysis was conducted under the four earthquake records, i.e., El Centro (1940), Parkfield (1966), Loma Prieta (1989) and Kobe (1995) with a PGA of 307, 462, 631 and 817 cm/s^2, respectively (Table 4). The range of magnitude of earthquake records is from 6.2 for Parkfield record to 7.2 for Kobe record. In order to be consistent, the PGA of all records were scaled to 0.35 g (Mortezaei and Ronagh 2013).

Moreover, a mathematical program was developed to simulate two dynamic models which located close to each other and also separated by recommended separation distance (Standard No. 2800, 2017). It is assumed that the

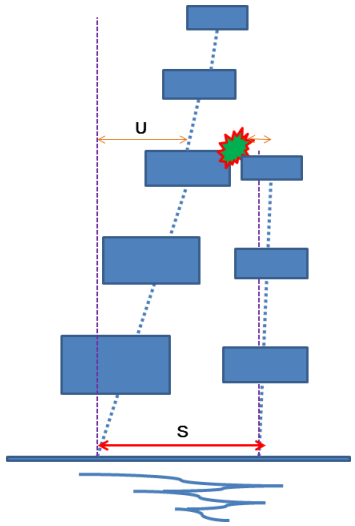


Fig. 2 The schematic of the 5 story model and 3 story model (Named 53), (U: lateral displacement, S: separation distance)

top story of shorter model collide with the same level of taller model (Fig. 2). Models were mathematically analyzed and the deformations of models were examined. Relative displacements of models are considered based on two different results. As mentioned, it is assumed that the heights of all stories are the same; hence there is no contact between floor and column. In fact, impact is physically defined as floor to floor, otherwise, in two adjacent buildings with non-equal heights, each collision between floor and column could result in serious injuries or collapses (Karayannis and Favvata 2005, Mohsenian and Mortezaei 2018, Favvata *et al*. 2009).

On one hand, models may have experienced collision during earthquake records. This shows that the separation distance between models needs to be increased. On the other hand, if no collision is observed during seismic loading, it shows that the separation distance can be reduced while structural pounding and impact between buildings can be avoided. Here, models are dynamically analyzed and separation distance is slowly decreased or increased based on mentioned results. Increasing or reducing the critical distances is carried out by 0.001 steps and models are modified in a new location by new separation distance.

In order to start dynamic analyses, peak lateral displacement of top story models among all records are calculated and listed as the Table 5. In this table, X_5, X_4, X_3, X_2 and X_1 are shown as the top story displacement of 5-, 4-, 3-, 2- and 1-story model. Then, all models are located close to each other with calculated separation distance (S) and

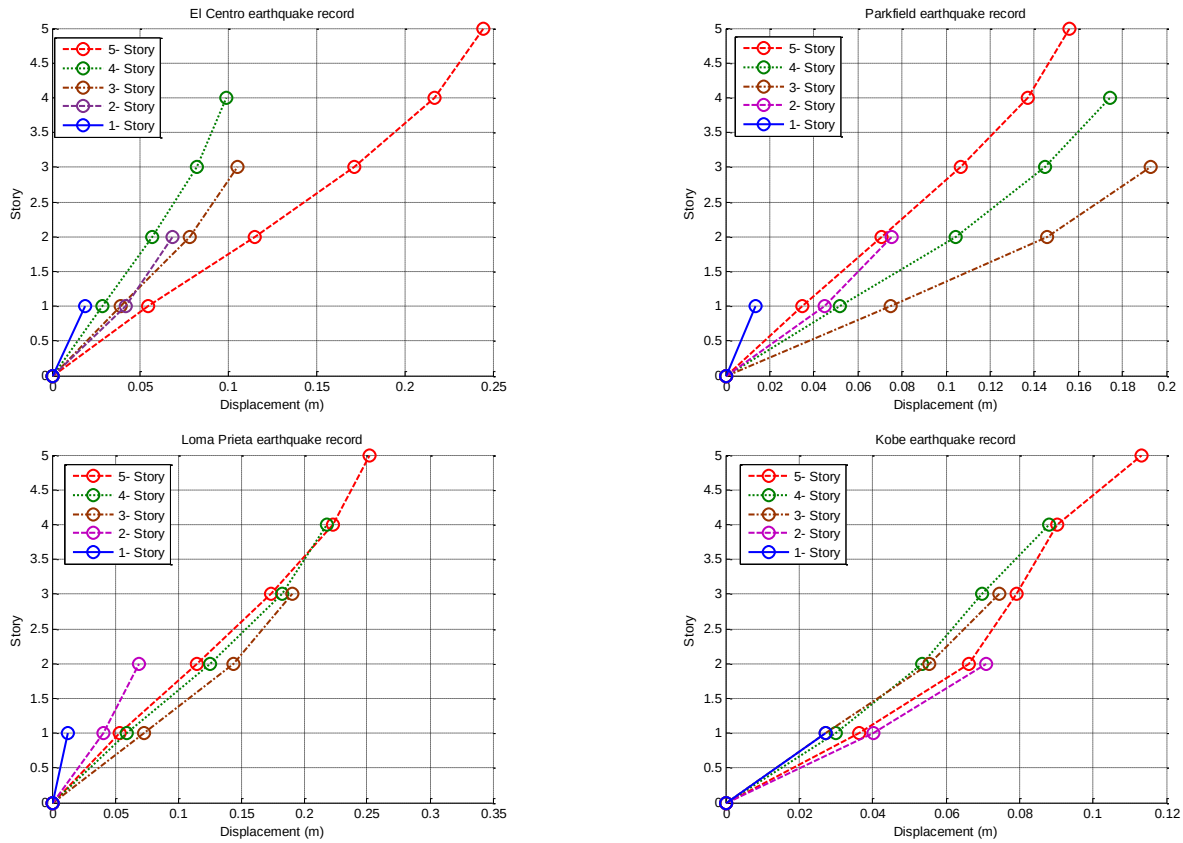


Fig. 3 Lateral displacement of the models during four different earthquake records

Table 5 Peak lateral displacement of different models

	El Centro	Parkfield	Loma Prieta	Kobe	*S* (cm)
X5	24.46	15.61	25.19	11.33	15
X4	9.86	17.42	21.79	8.89	12
X3	10.51	19.27	19.1	7.44	9
X2	6.81	7.53	6.89	7.1	6
X1	1.88	1.35	1.27	2.73	3

dynamic analyses based on the above process are repeated and the results are examined. Finally, the last value of separation distance is selected as an output and the analyses stopped when models are located close to each other without collisions.

As it is seen in Fig. 3, peak lateral displacement of five-story building is 24.46 cm, 15.61 cm, 25.19 cm and 11.33 cm for El Centro, Parkfield, Loma Prieta and Kobe earthquake, respectively and separation distance of models is 15 cm when one of the buildings is 5-story.

According to the figure 4, the majority of models have experienced collision during earthquake records which means the separation distance needs to be increased for preventing impact. For instance, four-story model and three-story model (43) have been separated by a 12 cm gap size and analyzed by El Centro record. It can be seen from Fig. 5 that impact occurred. Consequently, the gap size is increased to 18.28 cm to avoid collision between them.

Since the value of separation distance has to be accurately calculated, there is a need to develop an equation to determine the safety gap size between two adjacent structures.

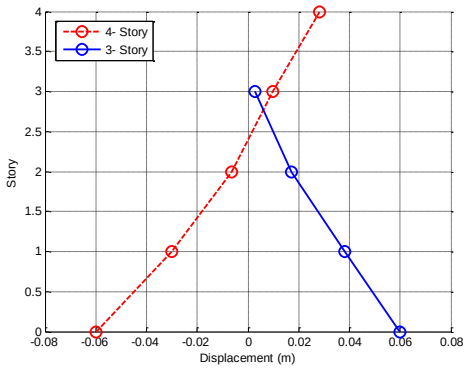
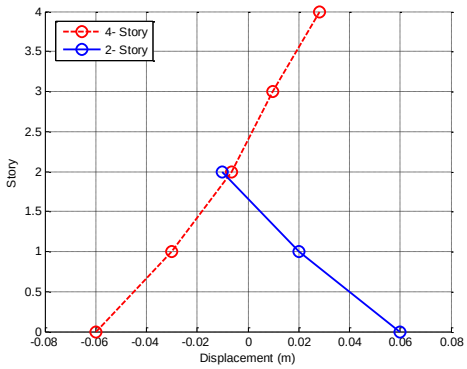
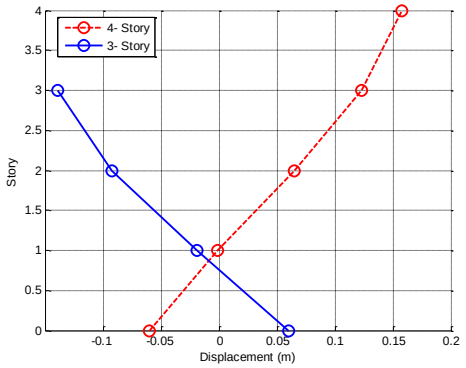
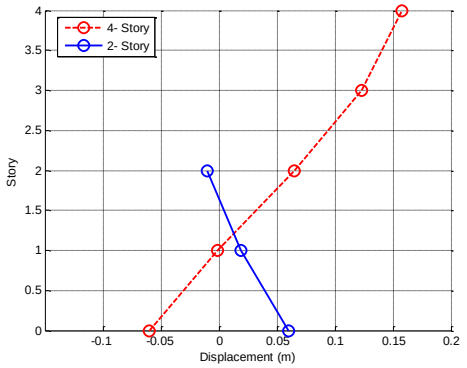
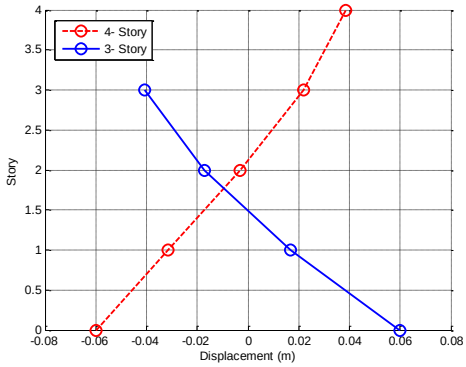
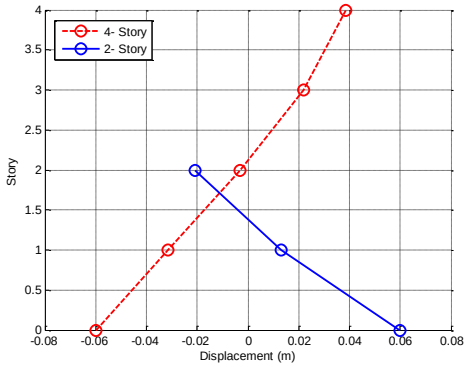
For this purpose, some parameters are considered to be used for the final equation, which can be defined by:

$$S = f(x_i, x_j, T_i, T_j, H_{\max}, PGA, \mu, \alpha)$$

The format of Eq. (4), which is a general layout, is utilized to calculate sufficient separation distance. In order to calculate μ, the following equation is used:

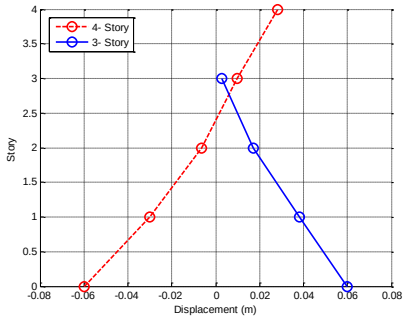
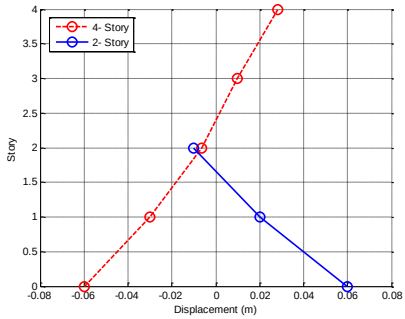
$$\mu = -(\alpha).\frac{T_i.T_j}{H_{\max}}.(PGA) \tag{10}$$

The alpha coefficient is obtained by a trial and error process. This means that taking into account values of T_i, T_j, H_{max} and a variation range for PGA, the iterative procedure continues until a minimum error value. Following an iterative procedure, different conditions based on various earthquake records are considered to examine the optimum value of α. Different values of the mentioned parameters in Equation (10) are utilized as input in the trial and error process, and the α-value will be determined as output, which must be sufficiently satisfied with peak ground acceleration (PGA). The output of this process is the graph shown in Fig. 6, which the α-value are depicted based on peak ground acceleration (PGA). So one can obtain the values of α and μ for both different buildings in height and under any kind of earthquake records, which consequently based on Eq. (4), the optimal distance between two buildings is obtained.

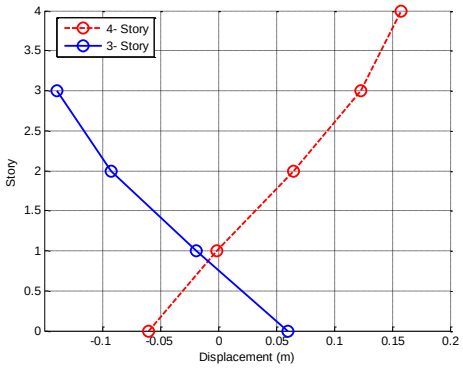
Record	S\Model	43	42
Parkfield			
		S_N=12.75	S_N= 12.34
Kobe	12		
		S_N=38	S_N= 15.6
El Centro			
		S_N=18.28	S_N= 12.54

**All S and S_N are cm*

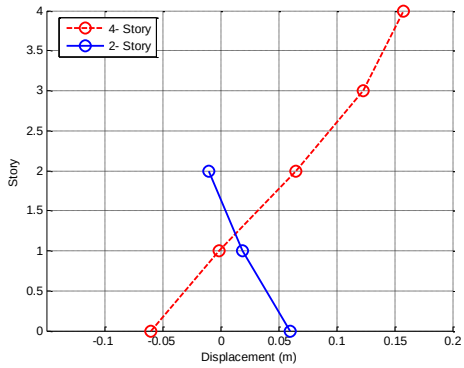
(a)

Record	S\Model	43	42
Parkfield			
		S_N=12.75	S_N= 12.34

Kobe



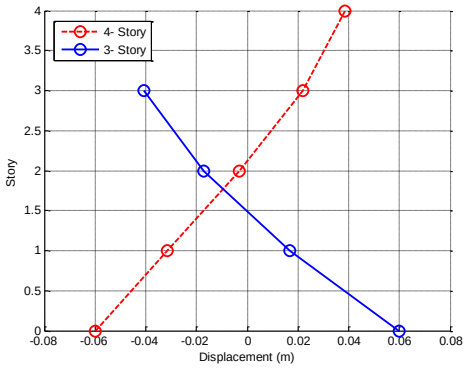
S_N=38



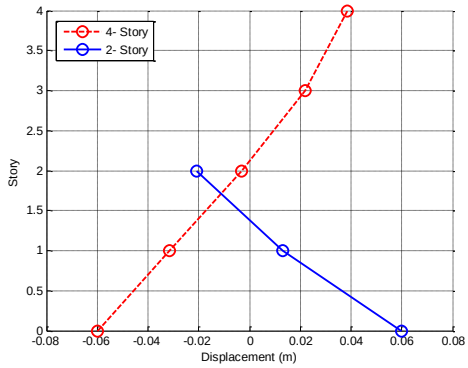
S_N= 15.6

12

El Centro



S_N=18.28



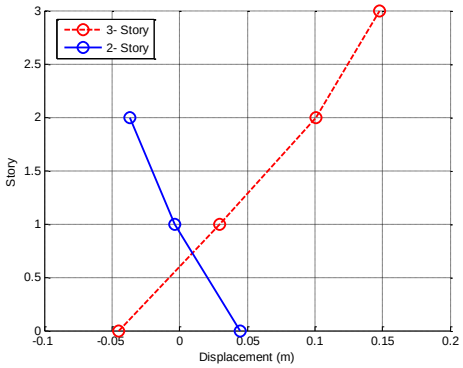
S_N= 12.54

**All S and S_N are cm*

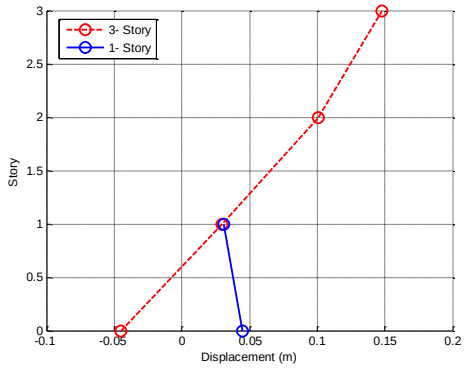
(b)

Record S\Model 32 31

Loma Prieta



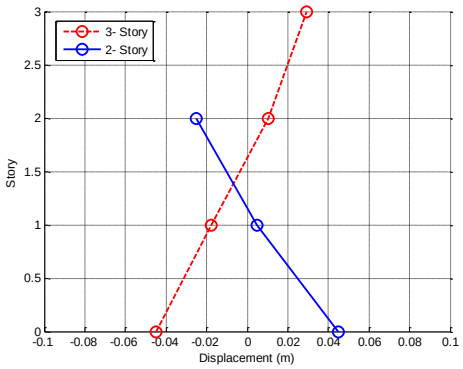
S_N=22.37



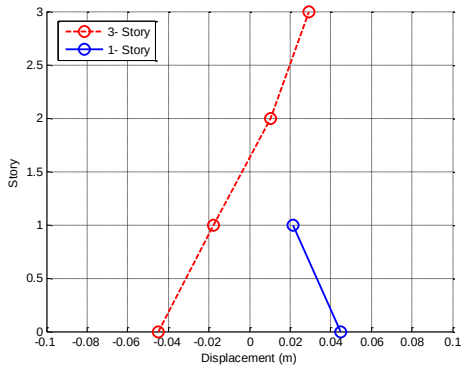
S_N= 9

9

Kobe

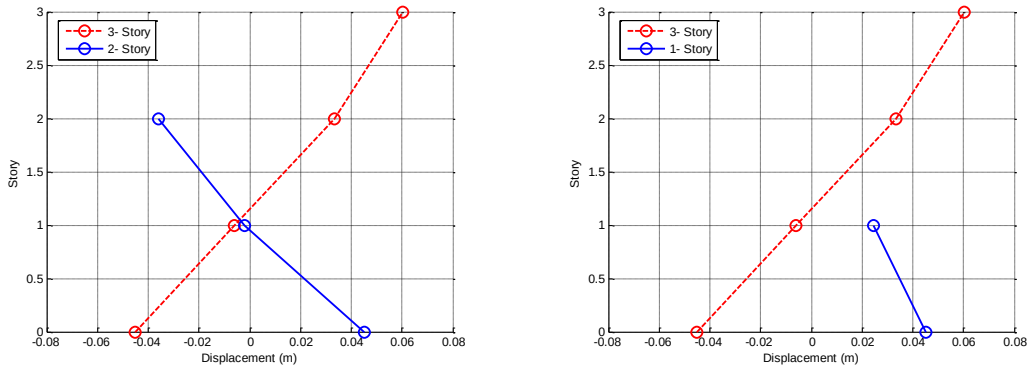


S_N=12.5



S_N= 5.6

El Centro



S_N=12.92 S_N= 5.94

*All S and S_N are cm

(c)

Fig. 4 Lateral displacement of the models with separation distance of (a) 15cm, (b) 12cm, (c) 9cm

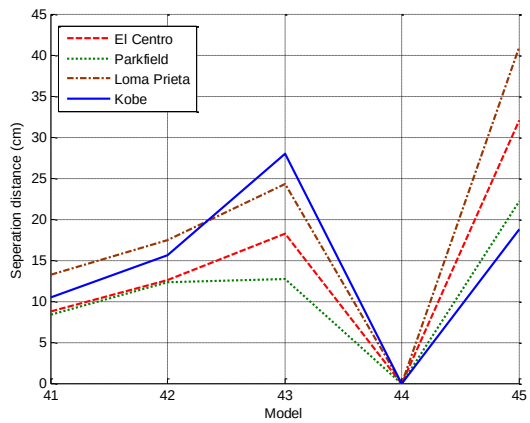


Fig. 5 Sufficient separation distance for 4 story model

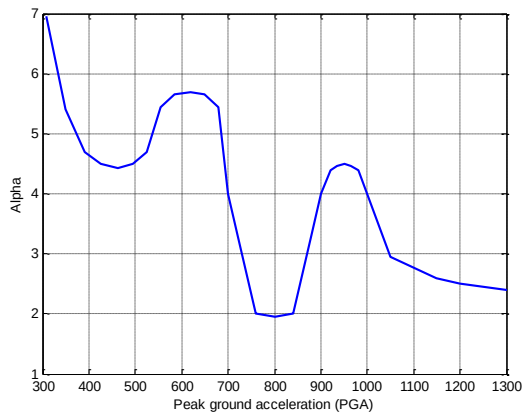


Fig. 6 The value of α based on peak ground acceleration (PGA)

4. Numerical analyses

In order to investigate the accuracy of the Equation (10), two irregular five- and three-story buildings (53) are selected and analyzed under the three different earthquake records, i.e. San Fernando, Duzce and Landers with PGA of 1202, 754.23 and 853 cm/s^2, respectively.

At first, the five-story model is numerically analyzed subjected to three mentioned earthquake records. Peak lateral displacements are 15.98 cm, 38.36 cm and 35.86 cm for San Fernando, Duzce and Landers earthquake records, respectively. On the other hand, peak lateral displacement of three-story model is 3.7 cm, 21.88 cm and 22.87 cm for San Fernando, Duzce and Landers earthquake records, respectively. The fundamental eigenperiod of the models are counted to be 1.21 *s* and 0.593 *s* for five- and three-story models, respectively. Then, the maximum height is logically assumed to be 1500 cm. Based on Figure 6, α is approximately estimated to be 2.45, 2.02 and 2.06 for San Fernando, Duzce and Landers earthquake records, respectively.

So, the value of separation distance between selected models is determined to be 20.87 cm, 56.33 cm and 56.51 cm under the San Fernando, Duzce and Landers earthquake records, respectively.

It can be seen from Fig. 7 that selected models have been separated by a safe separation distance which buildings are able to show their natural behavior, while pounding hazards can be controlled during seismic excitation. It seems that the suggested separation distance can be selected as an optimum gap size between buildings among all equations and distances, recommended by seismic codes.

In order to compare separation gap distances suggested by some major seismic codes, two buildings, i.e. three- and five-story, as well as El centro earthquake record are considered. Peak lateral displacement is *10.51cm* and *24.46cm* for three- and five-story models, respectively. So, the results of comparison are shown in Table 6. The results show that the proposed relationship is highly accurate.

Also, two four- and three-story irregular buildings (43), are selected and analyzed under the Loma Prieta earthquake. The peak lateral displacements and fundamental eigenperiods are 21.79 *cm*, 19.1 *cm*, 0.7064 *s* and 0.593 *s* for four-story and three-story buildings, respectively. PGA is 631 *cm/s*^{2}, therefore α is determined 5.61 based on Figure 6. The values of separation distance

Table 6 Comparisom of separation distance of some major seismic codes with proposed equation

	Proposed equation	Eurocode 8	Standard No. 2800	Canada	Australia	Turkey	Peru	Egypt
S	34.97	26.62	15	31	15	6	7	6

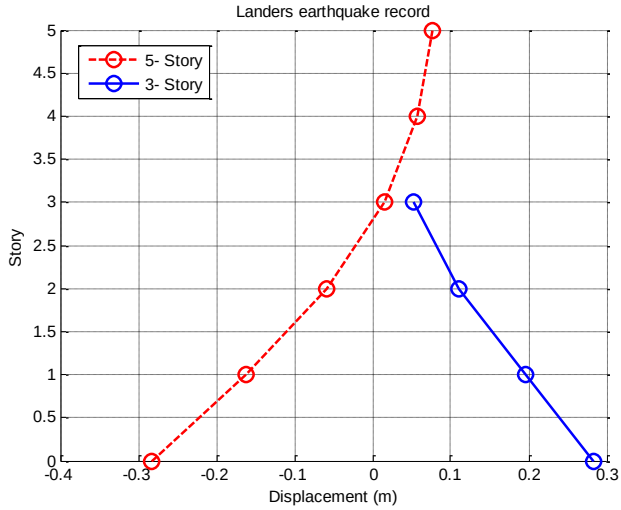
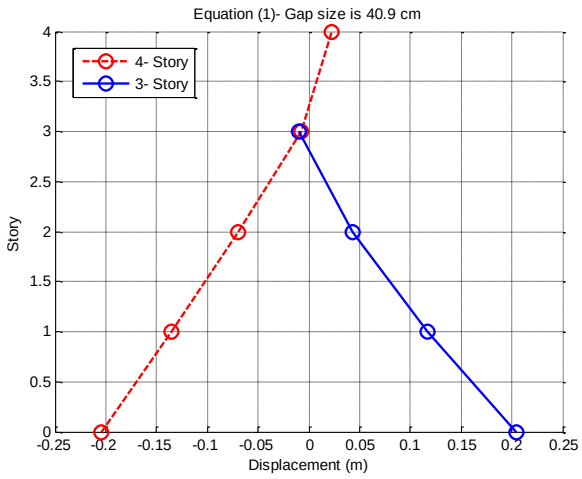
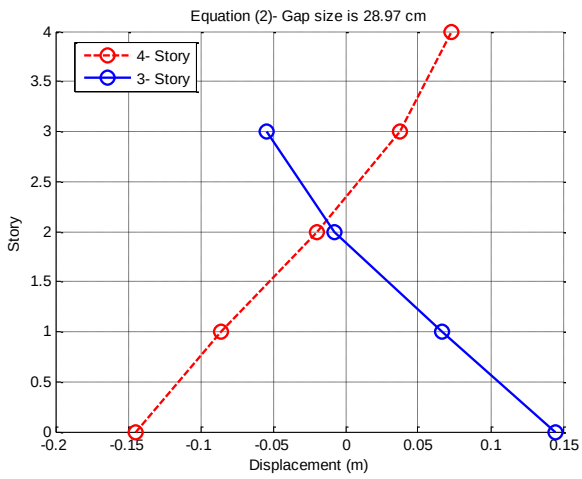


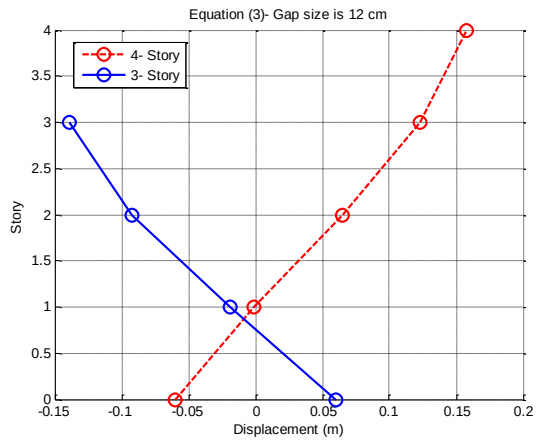
Fig. 7 Lateral displacement of selected model under three different records of (a) San Fernando, (b) Duzce and (c) Landers



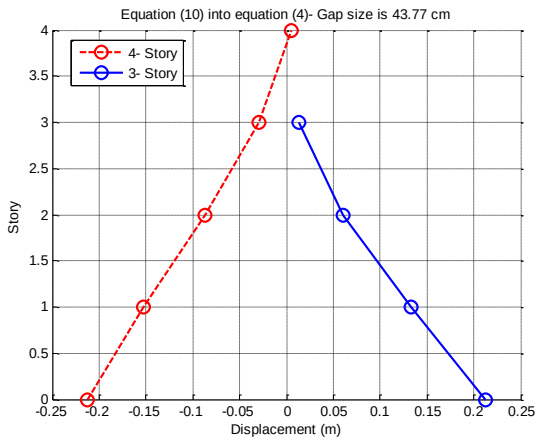
(a)



(b)



(c)



(d)

Fig. 8 Comparison of lateral displacement of model (43) under Loma Prieta earthquake records using separation distance relationship of (a) 1, (b) 2, (c) 3, and (d) 4

determined based on Eqs. (1), (2) and (3) and Equation (4) (by substituting Eq. (10) in Eq. (4)) are expressed as below:

$$\begin{cases} Equation(1) = 40.89cm \\ Equation(2) = 28.97cm \\ Equation(3) = 12cm \\ Equation(10) \rightarrow Equation(4) = 43.77cm \end{cases}$$

Relying on the Fig. 8, comparison of the results of lateral displacement of model (43) under the Loma Prieta earthquake records, using four suggested separation distance shows that the proposed formula can estimate optimum gap size among available equations without collision and also higher land occupancy percentage.

5. Conclusions

Evaluation of pounding hazards show that collision can be avoided by providing sufficient gap size between adjacent structures during seismic excitation. The majority of earthquake codes have directly recommended some equations to calculate separation distance based on peak lateral displacement as well as the height of buildings. On the other hand, some equations have been numerically suggested to determine gap size based on structural period and ductility of buildings. Most of these equations have focused on linear and nonlinear period of structures. Evaluation of separation distance values between two adjacent buildings, suggested by different relationships, indicates that the required distance is not properly satisfied because of pounding hazard and economical problems due to land ownership from a legal perspective. This is due to the fact that the gap size is more than the required one to avoid collisions. In this study, by focusing on the properties of structures and earthquake record, a new equation was proposed to determine the sufficient separation distance between two adjacent structures. By providing sufficient separation distance, the proposed equation could prevent pounding even in buildings showing large lateral displacement. The proposed equation depends significantly on the properties of adjacent buildings as well as peak ground acceleration of earthquake record.

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