JSEE Vol. 17, No. 1, 2015

Calculation of Separation Distance between Adjacent Buildings: A Review on Codal Provisions

Chenna Rajaram[1] **and Ramancharla P. Kumar**[2*]

1. Ph.D. Scholar, Civil Engineering, Earthquake Engineering Research Centre, International Institute of Information Technology, INDIA
2. Professor of Civil Engineering, Earthquake Engineering Research Centre, International Institute of Information Technology, INDIA,
* Corresponding Author; email: ramancharla@iiit.ac.in

Received: 08/06/2015
Accepted: 16/12/2015

ABSTRACT

Structures are being built very close to each other in metropolitan areas where the cost of land is very high. Due to the proximity of the structures, they often collide with each other when subjected to earthquakes. To mitigate the amount of damage from pounding, the most simplest and effective way is to provide minimum separation distance. Generally most of the existing buildings in seismically moderate regions are built without codal provisions. The main objective of the present study is to check the adequacy of provisions given in codes of various countries. For this purpose, four pairs of structures were selected. The gap between structures was estimated according to codes of different countries and the same were subjected to earthquake excitation. Some codal provisions failed to satisfy the safety requirements, whereas some were safe. Based on this study, recommendations were drawn.

Keywords:
Pounding; Ground motion; Frequency; Separation distance; Codal provisions

1. Introduction

Building codes provide a set of basic guidelines for practicing structural engineers and play a major role in transferring technology from research to practice. Existing seismic codes do not include definite guidelines to prevent structural pounding, due to the economic considerations including maximum land usage. Particularly in the high density areas of cities, many buildings, which were constructed very close to each other, could suffer damage due to the pounding during earthquakes. There are many buildings worldwide which are constructed very close to each other. In the past, many buildings have suffered severe structural pounding damage during earthquakes.

In the Alaskan earthquake of 1964, the Tower of Anchorage Westward Hotel was damaged due to the pounding with an adjoining three-storey ballroom portion of the hotel [1]. In the San Fernando earthquake of 1971, the second storey of the Olive View Hospital struck the outside stairway [2]. During the Mexico City earthquake [3] of 1985, more than 20 structures were damaged because of the pounding. During the Loma Prieta earthquake of 1989, a significant pounding was observed [4]. Pounding occurred between 6th level of a ten-storey building and at the roof level of an adjoining five-storey building, because the separation distance was 1.0 to 1.5 inches. During the Chi-Chi earthquake of 1999 in central Taiwan [5], the structural pounding was observed in a school building. The classrooms have pounded against each other because of insufficient space between them. During the Bhuj earthquake of 2001, pounding of adjacent structures was evident at Ayodhya Apartments in Ahmedabad, which suffered a significant damage. Damage occurred due to inadequate separation distance between them. The Sikkim earthquake [6] of 2006 caused damage to the walls and columns of a nine-storey masonry infill *RC* frame hostel building at Sikkim Manipal Institute of Medical Sciences (SMIMS) Tadong, Gangtok. Pounding damages were observed between two long wings in the building and corridors connecting the wings. During Niigata Chuetsu-Oki Japan earthquake of 2007 (Global risk Miyamoto [7]), damage occurred when the adjacent structures had floor slabs located at different elevations and insufficient separation distance between them. During the Wenchuan earthquake of 2008, pounding damage was observed in Hanwang town, where a two-storey building collided with an adjacent three-storey building and collision occurred just below the slab level [8]. During the recent Sikkim earthquake of 2011 [9], pounding damage was observed at unequal slab levels of adjacent buildings. Pounding damage was not only observed in buildings but also in bridges; two bridge decks collided and caused severe structural damage. Overall pounding damage in the structures can arise due to the following reasons:

1. Adjacent buildings with the same height and floor levels, Figure (1a).
2. Adjacent buildings with different heights but the same floor level, Figure (1b).
3. Adjacent buildings with different heights and floor levels, Figure (1c).
4. Buildings built in a row, Figure (1d).
5. Adjacent buildings with different dynamic characteristics.
6. Adjacent buildings with unequal distribution of mass and/or stiffness, Figure (1e).

Considering all the causes for structural pounding damage, the most efective way to mitigate and reduce the damage of structures from pounding is to provide a minimum separation distance between adjacent structures. In all of the above mentioned cases of the structural pounding, damage can be avoided or significantly reduced if a minimum separation distance is maintained. Hence it is important to calculate a safe separation distance between the adjacent structures. A large number of studies have been conducted on the separation distance between adjacent structures.

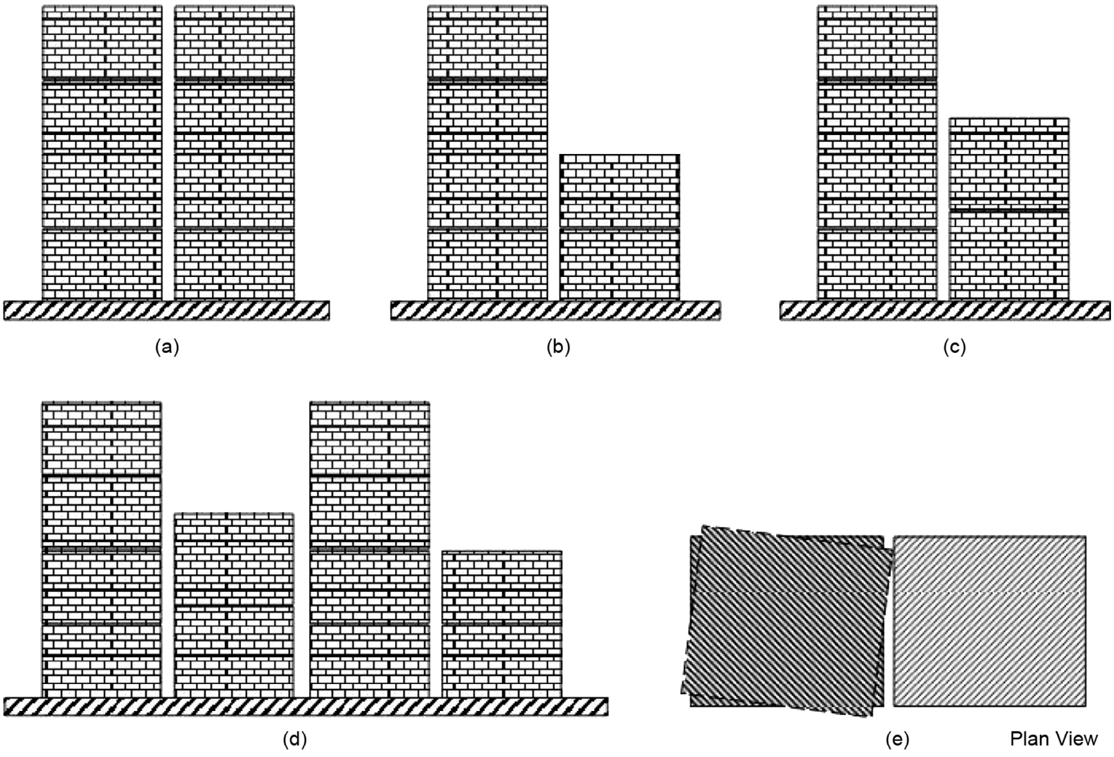


Figure 1. Representation of different places where pounding occurs.

A study was conducted in which single-degree of freedom (SDOF) in the structures built in a row were subjected to the pounding [10]. A gap size equal to the square root of sum of squares (SRSS) of the design peak displacements of the adjacent structures could be sufficient to avoid pounding. The effects of pounding diminish as the gap increases. Coupling reduces the possibility of pounding by maintaining a separation distance between the structures [11]. The linkage not only reduces the relative overlap deflection of the structures at large amplitudes, but also increases the base shear on the stiffer of the two structures at the excitation frequencies below the fundamental frequency. The work has been extended to multi-degree of freedom (MDOF) structures [10]. The effects of pounding are reduced as the separation distance increases, even if the code (Uniform Building Code and Euro No. 8) specified gap proved inadequate when there was strong shaking. After 1992, several researchers conducted studies on the separation distance [12-15] using SRSS and Double Difference Combination (DDC) methods. None of the above studies have worked on the pounding probability of the buildings.

In 2002, conditional probabilities of adjacent buildings separated by minimum code-specified separation distance under earthquakes with different peak ground acceleration (PGA) were investigated under 1000 artificial earthquakes [5]. It was revealed that the building separation specified by Taiwan Building Code (TBC) is approximately 1.6 times of the one specified by the Uniform Building Code (UBC) for the same building and soil properties. A new method was proposed to calculate the separation distance between adjacent buildings in terms of correlation coefficient ρ [16]. When compared to the existing methods, the proposed approach exhibited a number of convenient advantages. The disadvantage was that the proposed values of ρ are available only in charts. A study was conducted on elastic and inelastic responses of the buildings under three ground motions [17]. For both elastic and inelastic systems, the peak responses of the flexible buildings increase up to a certain value of the gap distance, and with further increase in gap, a decreasing trend can be observed. The minimum space between the adjacent buildings also affects the impact force [18]. It is concluded that the impact force depends on the velocity response of the structures at a particular time and minimum space between the structures. Recently, various pounding situations were analyzed [19] and it was found that the pounding can change the collapse risk as compared to the risk of the same building in a no pounding situation. The risk of a particular building may increase, decrease, or remain the same, depending on the neighboring building's dynamic properties. The risk increased in the stronger and decreased in the weaker buildings, and the risk was biased toward the no pounding risk of the heavier buildings.

From the above observations and literature, it is clear that the pounding is evident during earthquakes, particularly when the separation distance is small. There needs to be a clear understanding of the problem. The main focus of this paper is to calculate the separation distance from the seismic codes of different countries for different structures subjected to different ground motions, and also to provide suggestions for the codes that underestimate the separation distance.

2. Codal Provisions on Pounding

Most of the regulations for seismic design do not take into account the phenomenon of pounding and some others which do it, do not provide specific rules that must be followed. Amongst the exceptions are the codes of Argentina, Australia, Canada, France, India, Indonesia, Mexico, Taiwan and USA, which specify a minimum gap size between the adjacent buildings.

In some cases, the separation distance depends only on the sum of individual lateral displacements obtained from elastic analysis. The rule to determine the size is nevertheless variable, being in some cases the simple sum of the displacements of each building (eg. Canada and Israel), and in other cases a small value that may be either a percentage or a quadratic combination of the maximum displacements (e.g., France). The separation distance can be dependent on the building height (e.g., Taiwan), or a combination of two rules can be implemented, and there can even be a minimum separation distance that varies between 2.5 cm (e.g., Argentina) and 1.5 cm (e.g., Taiwan). These values can depend on the type of the soil and the seismic action. The list of codal provisions of various countries on pounding is tabulated in Table (1) [20].

3. Modeling of Structures

The analysis considers single-storey, two-storey and three-storey structures, and the details of the single-storey structure are shown in Figure (2). The single-storey structure has a total height of 3.12 m, including the thickness of the slab. The dimension of the column is 0.24 m x 0.24 m. For a two-storey structure, the total height is 6.24 m. The total height of a three-storey structure is 9.36 m having a column size of 0.3 mx0.3 m. The foundation reinforcement details are not considered and assumed to be fixed at ground surface level. The

Table 1. List of codal provisions on pounding [24-33].

Country	Provision on Pounding
Australia	Structures over 15 m shall be separated from adjacent structures or setback from building boundary by a distance sufficient to avoid damaging contact. This clause is deemed to be satisfied if the primary seismic force-resisting elements are structural walls that extend to the base, or the setback from a boundary is **more than 1% of the structure height**. *[clause 5.4.5]*
Canada	Adjacent structures shall be separated by the **sum of their individual lateral deflections obtained from an elastic analysis**. *[clause 4.1.9.2(6)]*
Egypt	Parts of the same building or buildings on the same site which are not designed to act as an integral unit shall be separated from each other by a distance of at least **2.0 times the sum of the individual computed deflections or 0.004 times its height whichever is larger**. *[clause 2.7.2]*
Ethiopia	To prevent collision of buildings in an earthquake, adjacent structures shall either be separated by **twice the sum of their individual deflections obtained from an elastic analysis**. *[clause 7.7]*
Greece	For buildings which are in contact with each other but there is no possibility for any columns to be rammed, the width of the respective joint, in the absence of more accurate analysis may be determined on the basis of the total number of storeys in contact above the ground as follows: **• 4 cm up to and including 3 storeys in contact** **• 8 cm from 4-8 storeys in contact** **• 10 cm for more than 8 storeys in contact** *[clause 4.1.7.2]*
India	R times the sum of the calculated storey displacements as per *clause7.11.1*. When floors levels of two similar adjacent units or buildings are at the same elevation levels, factor R in this requirement may be replaced by R/2. [*clause7.11.10.*]
Peru	The minimum distance shall **not be less than 2/3 of the sum of the maximum displacements of the adjacent blocks**, nor shall it be less than: **S=3+0.004(h-500) (h and S are in cm)** *[article 15.2]*
Serbia	The minimum width of the aseismic joint shall be **3.0 cm**. It shall be **increased by 1.0 cm for every increase of 3.0 meters of height above 5.0 m**. *[article 47]*
Taiwan	Pounding may be presumed not to occur wherever buildings are separated by a distance greater than or equal to **0.6x1.4$\alpha_y R_a$ times the displacement caused by the determined seismic base shear.** *[clause 2.5.4]* **The factor 0.6 is used because of low probability that two adjacent buildings will move in the opposite directions and reach the maximum displacement simultaneously.*
Turkey	Minimum size of gaps shall be **30 mm up to 6 m height**. From thereon a minimum **10 mm shall be added for every 3 m height increment**. [*clause 2.10.3.2*]

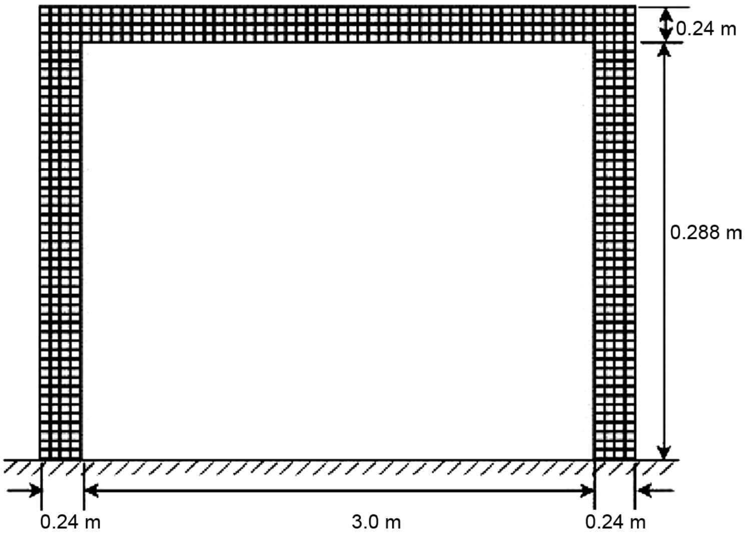


Figure 2. Geometry of single storey structure.

grade of concrete (M_{25}; $fck = 25$ N/mm^2), grade of steel (Fe_{415}; $f_y = 415$ N/mm^2) for reinforcement and Poisson's ratio ($\upsilon = 0.2$) are the same for both structures. It is assumed that the left-side structure is structure-1 and the right-side one is structure-2 throughout the analysis. It is assumed that the live load acting on structure-1 is 2 kN/m^2 and on structure-2 is 5 kN/m^2.

4. Selection of Ground Motions

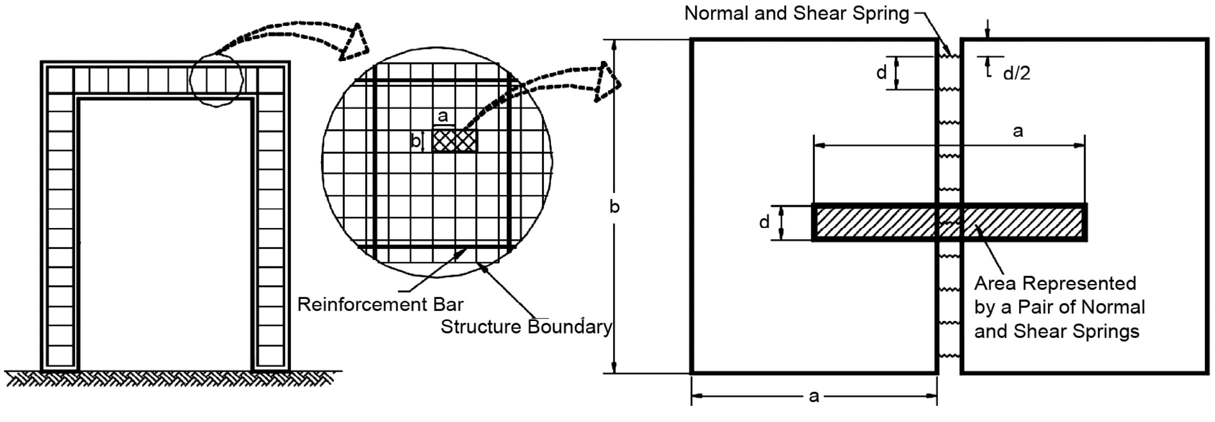
Amongst several ground motions, 10 moderate ground motions were chosen for the analysis whose PGA ranged from 0.25 g to 0.55 g. The selection of ground motions was based on the maximum zone factor (Z) specified in the seismic codal provisions of different countries mentioned in Table (1). The PGAs and the duration of ground motions range from low to high, and the frequency content ranges from resonating to non-resonating conditions [21]. The details of the ground motions are listed in Table (2).

5. Mathematical Formulation

The newly developed Applied Element Method (AEM) is a discrete method in which the elements are connected by a pair of normal and shear springs, Figure (3), which are distributed around the element edges [22]. These springs represent the stresses and deformations of the studied element. The element's motion is rigid body motion and the internal deformations are taken by springs only. It is advisable to increase the number of the elements than the number of the connecting springs for improving the accuracy of the results. The general stiffness matrix components corresponding to each degree of freedom are determined by assuming unit displacement and that the forces are at the centroid of each element, Figure (4). The element stiffness matrix size is 6×6. However, the global stiffness matrix is generated by summing up all local stiffness matrices

Table 2. Details of ground motions.

S. No	Earthquake	Year	Station	Component	Amplitude (g)	Duration (S)	Frequency (Hz)
1	Athens	1999	Kallithea	N46	0.265	4.1	1.5-4.5
2	Athens	1999	Sepolia Garage	Tran	0.31	4.44	2.0-6.0
3	Ionian	1973	Lefkada-Ote	NS	0.525	6.9	0.85-2.4
4	Kalamata	1986	Kalamata	N355	0.297	5.27	0.7-1.7
5	Umbro	1997	Nocera Umbra	NS	0.47	9.35	6.2-7.2
6	El Centro		Imperial Valley	S00E	0.348	29	1.15-2.2
7	Olympia		Washington	N86E	0.28	20.82	1.12-4.66
8	Parkfield		Parkfield	N85E	0.43	6.55	0.8-3.3
9	Northridge	1994	New Hall LA	Up	0.548	12.44	2.2-5.3
10	Loma Prieta	1989	Loma Prieta	270^0	0.276	9.78	0.65-1.72



(a) Element Generation for AEM

(b) Spring Distribution and Area of Influenceof Each Pair of Springs

Figure 3. Modeling of structure using AEM.

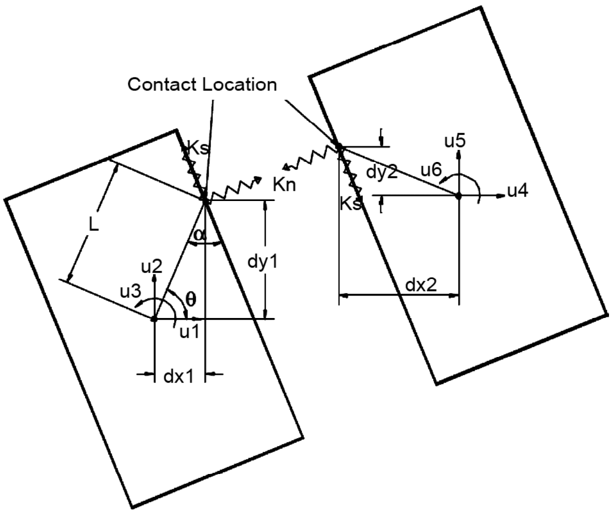


Figure 4. Element shape, contact point and degrees of freedom.

for each element. The above-mentioned structures are modeled in AEM.

6. Material Model

The material model used in this analysis is Maekawa compression model [22]. In this model, the tangent modulus is calculated according to the strain at the spring location. After peak stresses, spring stiffness is assumed to have a minimum value to avoid having a singular matrix. The difference between spring stress and stress corresponding to the strain at the spring location are redistributed in each increment in the reverse direction. For concrete springs subjected to tension, the spring stiffness is assumed to be the initial stiffness until it reaches the crack point. After cracking, stiffness of the springs subjected to tension is assumed to be zero. For reinforcement, bi-linear stress strain relationship is assumed. After yield of reinforcement, the steel spring stiffness is assumed to be 1% of the initial stiffness. After reaching 10% of strain, it is assumed that the reinforcement bar is cut. The force carried by the reinforcement bar is redistributed to the corresponding elements in the reverse direction. For cracking criteria, the principal stress based on the failure criteria is adopted [22]. The models for concrete, both in compression and tension and the reinforcement bi-linear model are shown in Figure (5). The general dynamic equilibrium equation for a building is given in Eq. (1).

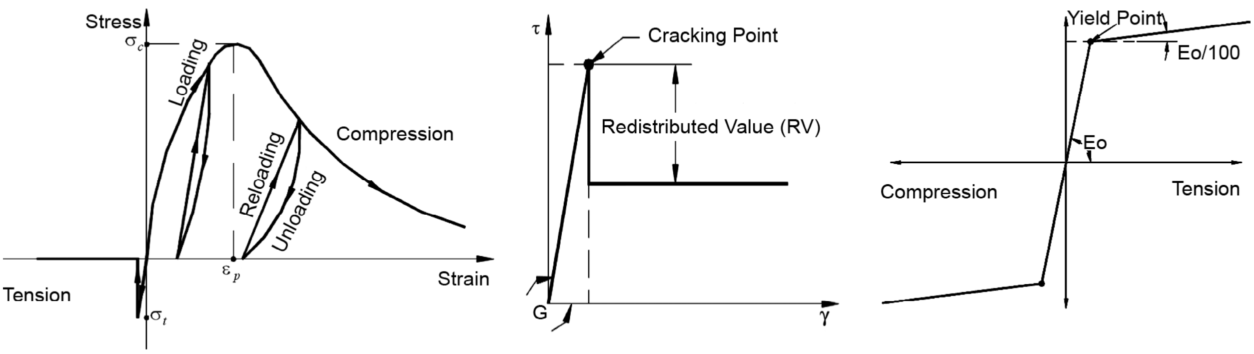
$$[M]\{\ddot{U}\}+[C]\{\dot{U}\}+[K]\{U\}= f(t)-[M]\{\ddot{U}_g\} \qquad (1)$$

where $[M]$ is the mass matrix, $[C]$ is the damping matrix, $[K]$ is the nonlinear stiffness matrix, $\Delta f(t)$ is the incremental applied load vector, ΔU and its derivatives are the incremental displacement, velocity and acceleration vectors respectively. The above equation is solved numerically using Newmark's β method [23]. For mass matrix, the slab elemental mass is assumed to be lumped at the joints. The mass matrix is given in Eq. (2).

$$\begin{bmatrix} M_1 \\ M_2 \\ M_3 \end{bmatrix} = \begin{bmatrix} D^2 t\rho & & \\ & D^2 t\rho & \\ & & D^4 t\rho/12 \end{bmatrix} \qquad (2)$$

where D is the element size, t is the element thickness and ρ is the density of material. From the above equation, it is noticed that $[M_1]$, $[M_3]$ and $[M_1]$ are the masses in X, Y and rotational direc-tions. The damping matrix is calculated from the first mode as follows:

$$C = 2\xi m\omega_n \qquad (3)$$



(a) Tension and Compression (b) Shear (c) Steel

Figure 5. Stress-strain relationship for both concrete and steel (Source: Hatem, [?]).

where ξ is damping ratio and ω_n is the first natural frequency of the structure.

The response of the structure is very close to the continuous/distributed mass system if the element size becomes small. If damping is present, the response of the structure will get reduced. The element size of the structure plays a vital role in numerical modeling [22]. Using a large element size decreases the displacement of the structure and finally leads to a larger failure load than the actual failure load. Finally, the element size is fixed at 0.06 m for both structures.

7. Collision Model

It is essential to check the collision between two elements during the analysis, in order to consider its effects. Collision springs are added between the colliding elements to represent the material behavior during contact [22]. As the collision check of irregularly shaped elements is more difficult and time consuming, the element shape during the collision is assumed to be a circle. This assumption is acceptable even in the case of relatively large elements because the sharp corners of the elements are broken due to the stress concentration during collision, and the edge of the elements becomes round shaped. The arrangement of collision normal and shear springs is shown in Figure (6). The normal spring stiffness is calculated from Eq. (4):

$$k_n = \frac{Edt}{D} \tag{4}$$

where 'E' is the minimum young's modulus of the material, 't' is the element thickness, 'D' is the distance between element centroids and 'd' is the contact distance assumed to be 0.1 times the element size. The shear spring stiffness is assumed to be 0.01 times the normal spring stiffness. The normal contact spring is not allowed to fail; instead, the compression failure of the distributed springs connecting to the elements is allowed to fail. Here the objective of the collision spring is to transmit the stress wave to other elements. The tensile force in the normal spring indicates that the elements tend to separate each other. Then, the residual tension is redistributed in the next increment.

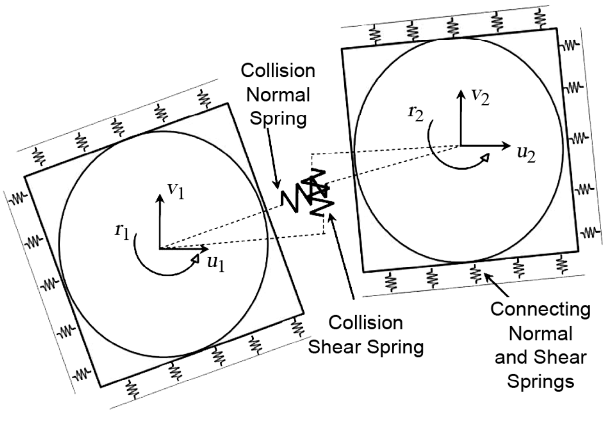


Figure 6. Arrangement of collision normal and shear springs during collision process.

The displacement response of each element at each degree of freedom is calculated using Newmark's β method. Using the geometric coordinate technique, contact between an element and its neighbour is checked instead of all elements [22]. Based on the calculated displacement of colliding elements, the collision force is calculated. The collision force is k_n times the relative displacement response at the contact point.

8. Effect of Structural Pounding Response on Frequency

A study has been conducted to understand the nonlinear effect of structural pounding response on frequency. For this purpose, a ground motion whose amplitude is 0.98 g, at station TCU129 during 1999 Chi-Chi earthquake is chosen for analysis. The predominant frequency of ground motion ranges from 0.21 s to 0.5 s. Two sets of structure are selected in such a way that one set falls in predominant frequency zone and the other falls in non-predominant frequency zone. The fundamental period of structures in both non-predominant (case-1) and predominant (case-2) zones is 0.132 s and 0.22 s for structure-1 and 0.161 s and 0.21 s for structure-2 respectively. Figures (7) and (8) show the non-linear pounding response of the structures in both cases. The non-linear pounding response of structures in case-1 is low, whereas, the responses are high in case-2 due to the presence of the structures in the predominant frequency zone. The dynamic effect of structures is higher in predominant frequency zone than in non-predominant frequency zone, though the structures are subjected to the same ground motion. It means that the structures are not affected by the amplitude of the ground motion, but they are affected by the frequency [8].

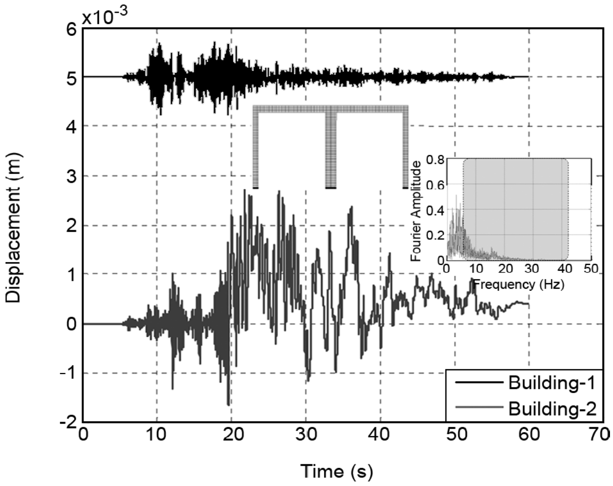


Figure 7. Pounding response of structures in non-predominant frequency region subjected to 1999 Chi-Chi earthquake.

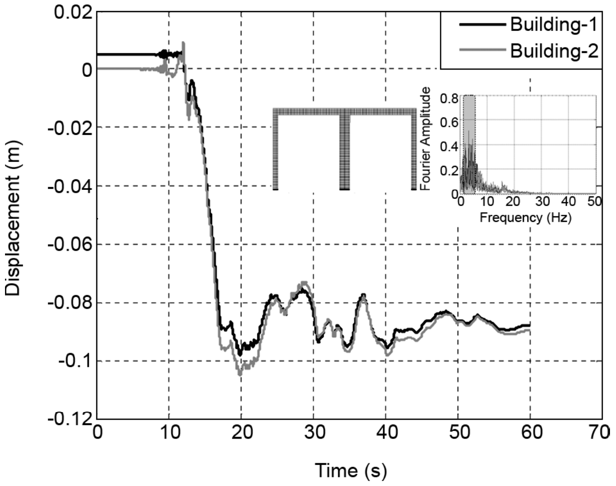
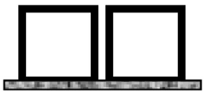
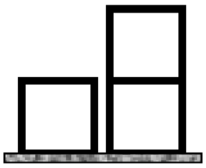
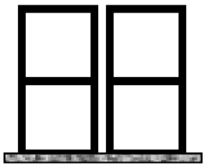
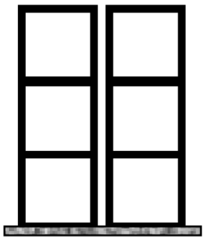


Figure 8. Pounding response of structures in predominant frequency region subjected to 1999 Chi-Chi earthquake.

9. Calculation of Separation Distance According to Codes

All the above structures are designed as per IS 456:2000. The same code can be used if other countries construct structures in India. Initially, the separation distances are calculated from seismic codes mentioned in Table (1). The separation distance required between adjacent structures for the above cases is shown in Table (3). From a review of seismic codes, these are insufficient to avoid pounding between the structures. The separation distance between adjacent structures is the sum of individual lateral deflections obtained from the elastic analysis suggested by Canadian, Ethiopian, Indian, Peruvian, and Serbian seismic codes. The lateral deflections are calculated from the designed base shear of seismic codes. The calculated separation distance is provided between the structures and subjected to the above ground motions, Table (2). Due to these ground motions, if the separation distance is insufficient, an interval of 5 mm separation distance is provided between the structures, and these are subjected to the same ground motions to estimate the minimum separation distance (MSD). The distance where collision ceases for the ground motion will give the MSD between them. The status

Table 3. Separation distances from codes.

Country Code				
Australia	3.0	3.0	6.0	9.0
Canada	0.6	1.1	1.6	4.7
Egypt	1.2	1.2	2.4	3.6
Ethiopia	2.1	4.5	6.9	8.0
Greece	4.0	4.0	4.0	4.0
India	0.6	1.1	1.8	4.7
Peru	2.2	2.2	3.4	4.6
Serbia	3.0	3.0	4.0	5.0
Taiwan	0.7	1.6	2.4	6.2
Turkey	3.0	3.0	4.0	5.0

*All units are in cms

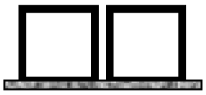
of the separation distance of the codes for all the cases is given in Tables (4) to (7).

10. Suggestions to Codal Provisions

From Table (4), it is clear that none of the seismic codes satisfy the minimum separation requirement except the Greek seismic code. The Canadian, Indian and Taiwanese seismic codes do not even bsatisfy the minimum separation when two single-storey structures are subjected to all ground motions. From the analysis, 40 mm is the MSD between two single-storey structures, which have survived the extreme ground motions without collision. Similarly, the same analysis is carried out for single-two storey structures when subjected to 10 chosen ground motions are tabulated in Table (5). The Canadian and Indian codal provisions do not satisfy the minimum requirement on separation distance. From the analysis, 16 mm is the MSD between single two-storey structures, which have survived the extreme ground motions without collision. In two single-storey structures case, though an MSD of 22 mm is provided between them, they did not survive the extreme ground motions without collision. For this case, the structures subjected to earthquakes 2, 5, and 9 require a greater separation distance, because there is a predominance of ground motion periods matching with the structure's period.

Similarly, the same analyses carried out for two two-storey structures and three-three storey structures when subjected to 10 chosen ground motions are tabulated in Tables (6) and (7). For this case, the structures subjected to earthquake 2, 3, 5, 6, 7, 8, 9 and 10 require a greater separation distance, because there is a predominance of ground motion periods matching with the structure's period. From the analysis of two two-storey structures, the separation distance is 60 mm for buildings which have survived

Table 4. Status on separation distance from codes for single-single storey structures.



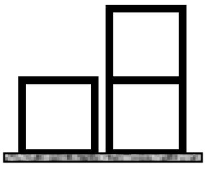
Country Code	1	2	3	4	5	6	7	8	9	10
Australia	√	√	√	√	x	√	√	√	√	√
Canada	x	x	x	x	x	x	x	x	x	x
Egypt	√	x	√	√	x	x	x	x	x	√
Ethiopia	√	x	√	√	x	√	√	√	x	√
Greece	√	√	√	√	√	√	√	√	√	√
India	x	x	x	x	x	x	x	x	x	x
Peru	√	x	√	√	x	√	√	√	x	√
Serbia	√	√	√	√	x	√	√	√	√	√
Taiwan	x	x	x	x	x	x	x	x	x	x
Turkey	√	√	√	√	x	√	√	√	√	√

* 1- Athens ground motion, 2- Athens(trans) ground motion, 3- Ionian ground motion, 4- Kalamata ground motion, 5- Umbro ground motion, 6- El Centro ground motion, 7- Olympia ground motion, 8- Parkfield ground motion, 9-Northridge ground motion and 10- Loma Prieta ground motion

√-satisfies the separation distance from codes

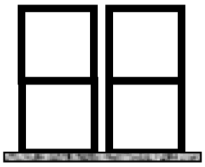
x- does not satisfy the separation distance from codes

Table 5. Status on separation distance from codes for single-two storey structures.



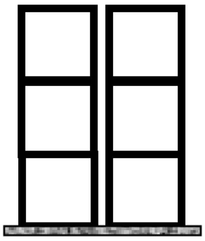
Country Code	1	2	3	4	5	6	7	8	9	10
Australia	√	√	√	√	√	√	√	√	√	√
Canada	√	√	x	x	√	√	√	√	x	x
Egypt	√	√	√	√	√	√	√	√	√	√
Ethiopia	√	√	√	√	√	√	√	√	√	√
Greece	√	√	√	√	√	√	√	√	√	√
India	√	√	x	x	√	√	√	√	x	x
Peru	√	√	√	√	√	√	√	√	√	√
Serbia	√	√	√	√	√	√	√	√	√	√
Taiwan	√	√	√	√	√	√	√	√	√	√
Turkey	√	√	√	√	√	√	√	√	√	√

Table 6. Status on separation distance from codes for two-two storey structures.



Country Code	1	2	3	4	5	6	7	8	9	10
Australia	√	√	√	√	√	√	√	√	√	√
Canada	√	x	√	x	x	x	x	√	√	x
Egypt	√	x	√	x	√	x	√	√	√	x
Ethiopia	√	√	√	√	√	√	√	√	√	√
Greece	√	√	√	√	√	x	√	√	√	x
India	√	x	√	x	x	x	x	√	√	x
Peru	√	√	√	x	√	x	√	√	√	x
Serbia	√	√	√	√	√	x	√	√	√	x
Taiwan	√	x	√	x	√	x	√	√	√	x
Turkey	√	√	√	√	√	x	√	√	√	x

Table 7. Status on separation distance from codes for three-three storey structures.



Country Code	1	2	3	4	5	6	7	8	9	10
Australia	√	√	√	√	√	√	√	√	√	√
Canada	√	√	√	√	√	√	√	√	√	√
Egypt	√	√	√	x	x	x	x	x	x	x
Ethiopia	√	√	√	√	√	√	√	√	√	√
Greece	√	√	√	x	x	x	x	x	x	x
India	√	√	√	√	√	√	√	√	√	√
Peru	√	√	√	x	x	x	x	x	x	x
Serbia	√	√	√	√	√	√	√	√	√	√
Taiwan	√	√	√	√	√	√	√	√	√	√
Turkey	√	√	√	√	√	√	√	√	√	√

Table 8. Modification factors on separation distance from codes for the structures.

Country Code	Single-Single	Single-Two	Two-Two	Three-Three
Australia	1.3	----	----	----
Canada	6.6	1.18	3.75	----
Egypt	3.3	----	2.5	1.3
Ethiopia	1.9	----	----	----
Greece	----	----	1.5	1.17
India	6.6	1.18	3.3	----
Peru	1.8	----	1.7	1.02
Serbia	1.3	----	1.5	----
Taiwan	5.7	----	2.5	----
Turkey	1.3	----	1.5	----

all the ground motions without collision. From the analysis of three-three storey structures, the separation distance is 47 mm for buildings which have survived all the ground motions without collision. The modification factors for separation distance of the above-mentioned structures are shown in Table (8).

11. Conclusions

Many studies have been conducted on the separation distance between adjacent structures to mitigate pounding. Although some modern codes include seismic separation requirement for adjacent structures, some of which have failed to provide the appropriate minimum separation distance.

In this analysis, different structures with equal storey levels are considered, which are classified by different country codal provisions on separation distance and also subjected to different ground motions having a PGA range of 0.25-0.54 g. An analysis has been done on the separation distance specified in different countries' codal provisions and the separation distances have also been calculated through a parametric study using AEM. The separation distances are modified with a modification factor where they are insufficient. The separation distance does not only depend on PGA but also depends on the characteristics of ground motion. The pounding response of structures is not affected by the amplitude of ground motion, but they are affected by the frequency.

References

1. Pantelides, C.P. and Ma, X. (1998) Linear and nonlinear pounding of structural systems. Computers and Structures, **66**(1), 1136-1146.
2. Jankowski, R. (2009) Non-linear FEM analysis of earthquake induced pounding between the main building and the stair way tower of the Olive View Hospital. *Engineering Structures*, **31**, 1851-1864.
3. Aguilar, J., Jurez, H., Ortega, R., and Iglesias, J. (1989) The Mexico earthquake of September 19, 1985 - statistics of damage and of retrofitting techniques in reinforced concrete buildings affected by the 1985 earthquake. *Earthquake Spectra*, **5**(1), 145-151.
4. Kasai, K. and Maison, B.F. (1997) Building pounding damage during the 1989 Loma Prieta earthquake. *Engineering Structures*, **19**(3), 195-207.
5. Lin, J.-H. and Weng, Ch.-Ch. (2002) A study on seismic pounding probability of buildings in Taipei metropolitan area. *Journal of the Chinese Institute of Engineers*, **25**(2), 123-135.
6. Kaushik, H.B., Dasgupta, K., Sahoo, D.R., and Kharel, G. (2006) Performance of structures during the Sikkim earthquake of 14 February 06. *Current Science*, **91**(4), 449-455.
7. Global Risk Miyamoto (2007) *Reconnaissance Report on 2007 Niigata Chuetsu-Oki Japan Earthquake*. Sacramento, California.
8. Rajaram, C. (2011) *A Study on Pounding between Adjacent Buildings*. M.Sc. Thesis, Civil Eng. Dept., International Institute of Information Technology - Hyderabad, India.
9. Murty, C.V.R., Raghukanth, S.T.G., Menon, A., Goswami, R., Vijayanarayanan, A.R., Gandhi, S.R., Satyanarayana, K.N., Sheth, A.R., Rai, D.C., Mondal, G., Singhal, V., Parool, N., Pradhan, T., Jaiswal, A., Kaushik, H.B., Dasgupta, K., Chaurasia, A., Bhushan, S., Roy, D. and Pradeep Kumar, R. (2012) *The Mw 6.9 Sikkim-Nepal Border Earthquake of September 18, 2011*. EERI Special Earthquake Report, 1-14.
10. Anagnostopoulos, S.A. (1988) Pounding of buildings in series during earthquakes. Earthquake Engineering and Structural Dynamics, **16**, 443-456.
11. Westermo, B.D. (1989) The dynamics of inter structural connection to prevent pounding. *Earthquake Engineering and Structural Dynamics*, **18**(5), 687-699.
12. Filiatrault, A. and Cervantes, M. (1995) Separation between buildings to avoid pounding during earthquakes. *Canadian Journal of Civil Engineering*, **22**(1), 164-179.
13. Kasai, K, Jagiasi A.R., and Jeng, V. (1996) Inelastic vibration phase theory for seismic pounding mitigation. *ASCE Journal of Structural Engineering*, **122**(10), 1136-1146.
14. Penzien, J. (1997) Evaluation of building separation distance required to prevent pounding during strong earthquakes. *Earthquake Engineering & Structural Dynamics*, **26**(8), 849-858.
15. Valles, R.E. and Reinhorn, A.M. (1997) *Evaluation, Prevention and Mitigation of Pounding Effects in Buildings Structures*. Technical Report No. NCEER-97-0001, National Center for Earthquake Engineering Research, University of Buffalo, Buffalo, USA.
16. Garcia, D.L. (2004) Separation between adjacent nonlinear structures for prevention of seismic pounding. *Proc. of 13th World Conference on Earthquake Engineering*, Vancouver, Canada. Paper 478.
17. Mahmoud, S. and Jankowski, R. (2009) Elastic and inelastic multistorey buildings under

earthquake excitation with the effect of pounding. *Journal of Applied Sciences*, **25**, 1-13.

18. Rajaram, C. and Pradeep Kumar, R. (2012) Pounding between adjacent buildings: comparison of codal provisions. *Indian Concrete Journal* (ICJ), **86**(8), 49-59.

19. Maison, B., McDonald, B., and Schotanus, M. (2013) Pounding of San Francisco type soft storey midblock buildings. *Earthquake Spectra*, **29**(3), 1069-1089.

20. International Association for Earthquake Engineering (IAEE)

21. Kramer, S.L. (1996) *Geotechnical Earthquake Engineering*. Pearson Publishers.

22. Tagel-Din Hatem (1998) *A New Efficient Method for Nonlinear, Large Deformation and Collapse Analysis of Structures*. Ph.D. Thesis, Civil Eng. Dept., University of Tokyo, Tokyo, Japan.

23. Chopra, A.K. (2001) *Dynamics of Structures*. Pearson Education, Inc.

24. Australian Standard, Structural Design Action, Part 4: Earthquake actions in Australia, AS 1170.4 - 2007, Standards Australia, Sydney.

25. Egyptian Society for Earthquake Engineering (1988) Regulations for Earthquake Resistant Design of Buildings in Egypt.

26. Greek Code for Seismic Resistant Structures, EAK (2000), Greece.

27. Indian standard plain and reinforced concrete - code of practice (fourth revision), IS:456-2000, Bureau of Indian standards, New Delhi.

28. Institute for Research in Construction (1995) National Building Code of Canada. National Research Council of Canada, Ottawa, Canada.

29. Ministry of Interior (1981) Code of Technical Regulations for Design and Construction of Buildings in Seismic Region, Serbia.

30. Ministry of Public Works and Settlement (2007) Specification for Buildings to be Built in Seismic Zones. Government of Republic of Turkey, Turkey.

31. National Building Code - Peru, Technical Standard of Building E.030, Earthquake Resistant Design, Peru.

32. National Building Council of Ethiopia (1995) Ethiopia Building Code Standard. EBCS:08.

33. Seismic Design Code for Buildings in Taiwan (2005) Seismic Force Requirements for Buildings in Taiwan - Part I, Taiwan.