Research on Engineering Structures & Materials
www.jresm.org

Research Article

Assessment of minimum required separation distance between adjacent reinforced concrete buildings

Esra Ozer *,a

Department of Civil Engineering, Tokat Gaziosmanpasa University, Tokat, Turkey

Article Info

Article History:

Received 02 May 2025

Accepted 03 Aug 2025

Keywords:

Seismic pounding;
Required gap distance;
Nonlinear time-history analysis;
Code-based approach;
RC buildings

Abstract

The aim of this study investigates the minimum required gap distance to prevent collision of three dimensional-(3D) adjacent reinforced concrete buildings considering torsional irregularity. In the scope of this study, four individual buildings are designed without torsional irregularity (regular) and four individual buildings are also designed with torsional irregularity. 24 different adjacent buildings model are derived from these individual buildings. Nonlinear behavior is considered with plastic hinges which are assigned to both ends of structural members. Bidirectional nonlinear time history analyses are carried out using spectrum compatible 11 ground motion pairs. As a result of the analyses, the required gap distance to prevent collision of adjacent buildings is calculated. These results shows that the minimum gap distances recommended in Turkish Building Earthquake Code-2018(TBEC-2018) is average 45% less compared to the analysis results. For this reason, it is proposed that a constant coefficient (α) in TBEC-2018 be revised to 2.89 for calculating gap distances more compatible with nonlinear analyses.

1. Introduction

Insufficient separation distance between adjacent reinforced concrete buildings poses significant risks during seismic events, leading to a phenomenon known as structural pounding. This occurs when buildings collide due to lateral movements induced by ground shaking, which can cause localized failures at contact points, structural deformations, or even total collapse [1,2]. Many design codes [3,4] provide guidelines on the minimum separation distances necessary to mitigate this risk. However, these recommendations are often not adhered to in practice, particularly in densely populated urban environments where land is scarce [5,6]. In addition, observations made after earthquakes also indicated that the provisions of the regulations may be inadequate [7,8]. It highlights the urgent need for adequate planning and construction practices [9,10]. Thus, understanding the risks associated with insufficient separation distance is essential for improving the resilience of urban infrastructure against earthquakes.

The characteristics of the buildings, including their height, structural configuration, and dynamic properties, critically affect the severity of this phenomenon. Research indicates that the story configuration between adjacent RC buildings plays a pivotal role in seismic pounding outcomes. In a study by Manoukas and Karayannis, it was shown that when adjacent RC frames have differing story heights, the dynamics of pounding can result in significant structural responses, often leading to adverse impacts on taller structures [11]. Sadeghi et al. evaluated the story height effect on pounding behavior via Monte Carlo simulation method and highlighted more critical of different story heights [12]. Moreover, varying stiffness, mass and reinforcement detailing characteristics among interacting buildings respect to code regulations can exacerbate relative displacements during seismic events [13-14]. Kazemi et al. underscored that the lateral load resistance system

*Corresponding author: esra.ozer@gop.edu.tr
[a]orcid.org/0000-0002-7778-0119
DOI: http://dx.doi.org/10.17515/resm2025-861ma0502rs

and fundamental natural period are influential factors that dictate the collision effects, highlighting the necessity for sufficient separation distances to minimize pounding [15]. The researchers found that without adequate spacing, the interaction stemming from differences in stiffness leads to increased vulnerability [15]. This finding is echoed in Hosseini et al.'s analysis, which revealed that non-uniform ground motions can considerably influence the pounding behavior of adjacent RC frames, causing a detrimental increase in damage indices due to collisions [16]. Ground conditions also play an essential role in the pounding response of structures and seismic performance [17]. Elwardany et al. investigated how soil-structure interaction (SSI) impacts seismic pounding, highlighting that flexible soil conditions can amplify the effects of pounding on adjacent buildings, potentially leading to more severe structural damage [18]. Furthermore, the non-linear responses of buildings under seismic loading scrutinized in various studies emphasize the significance of evaluating structural pounding alongside SSI effects [19-20]. Oz evaluated pounding effects together with SSI and highlighted the increase in relative story drift demands and acceleration values, particularly in shorter buildings [21]. Another emphasis in the studies relates to torsional irregularity can increase potential collision impacts [22-28]. However, studies considering torsional effects are quite limited and have generally been conducted for elastic and Single Degree of Freedom (SDOF) models [29-31]. Raheem et al. [32] investigates seismic performance of 3D irregular adjacent buildings. It was concluded that higher eccentricity leads to greater horizontal floor displacements and twisting motions. On the other hand, some researchers [33-34] have stated that the pounding effect may be reduced in irregular buildings by using tuned mass dampers or fluid viscous dampers. The number of studies using 3D irregular nonlinear models and considered ground motion have significantly limited [35-36]. However, studies recommend required gap distances [37-38] generally used regular building models.

In code regulations and research generally consider three methods for calculating required gap distances [2]. There are the Absolute Sum (ABS), the Square Root of the Sum of the Squares (SRSS), and the Double Difference Combination (DDC) methods. The ABS method provides a conservative estimate by considering only the individual dynamic characteristics of each building without accounting for their interaction [39]. The SRSS method offers a more sophisticated approach that combines the modal properties of both buildings, yielding practical results that may reduce the gap distance while ensuring safety, as suggested by relevant codes [40]. The DDC method integrates the effects of both buildings' responses during seismic events more comprehensively and has been considered the most accurate in predicting necessary separation distances to avoid pounding [2]. However, it is more complex to implement, which may deter its application in practice.

The incorporation of engineering strategies aimed at reducing collision risks, along with adherence to appropriate structural design codes, can enhance the resilience of buildings in urban environments susceptible to earthquake activity. For these reasons, the study investigates required gap distance with nonlinear 3D low and mid-rise buildings considering torsional irregularity. 528 nonlinear time-history analyses were performed with 11 spectrum compatible ground motion pairs. The required gap distance is calculated with the results of analysis. The results compared to gap distance proposed in TBEC-2018 [41] regulation. In line with this, a new approach was developed by questioning the validity of the code provisions. The proposed approach ensures more compatibility with nonlinear analysis results compared to TBEC-2018 [41] requirements.

2. Characteristics of Ground Motions

Ground motion record properties such as frequency content, time, amplitude significantly affect nonlinear time history analysis results [42]. For this reason, selecting and scaling criteria for ground motion records are very important. Generally, three different selecting ways are known. These may be summarized as selection by simulation, production of artificial ground motions and use of real ground motion records. The use of real ground motion records among these is suggested for more reliable results [43].

In this study, spectrum compatible real ground motion record selecting was made respect to TBEC-2018 [41] requirements. The earthquake level is selected for ground motions with 10% probability of exceedance in 50 years. First, parameters for elastic acceleration spectrum with %5 damping ratio were calculated respect to the accounted seismicity of the building models. Values of the short-period design spectral acceleration coefficient (S_{DS}), the design spectral acceleration coefficient for the 1.0 s period (S_{D1}), the short-period design spectral acceleration coefficient (S_S) and the design spectral acceleration coefficient for the 1.0 s period (S_1) are 1.135, 0.658, 1.135, 0.261, respectively. The corresponding of the FEMA-P-1051 [44] of S_{DS}, S_{D1}, S_S and S_1 parameters considered in the TBEC-2018 [41] are S_{MS}, S_{M1}, S_S and S_1, respectively. Target design spectrum is 1.3 times the design spectrum. PEER Ground Motion Database (PEER) [45] was used for selecting and scaling ground motion records. A ground motion pair includes two horizontal components, and these components are scaled the same scale factor. The resultant horizontal spectrum by SRSS method of each component was determined. The average of 11 ground motion pairs was scaled compatible with the target spectrum between $0.2T_p$-$1.5T_p$. T_p represents dominant period value of buildings. Additionally, the average spectrum has not less than 10% of the target spectrum. Fig. 1 shows the resultant horizontal spectrums, average spectrum, target spectrum and design spectrum. Other properties of ground motions considered in the study are given in Table 1. For code requirements, both components of scaled ground motion pairs were applied to the three-dimensional (3D) building at the same time in the direction of the principal axes.

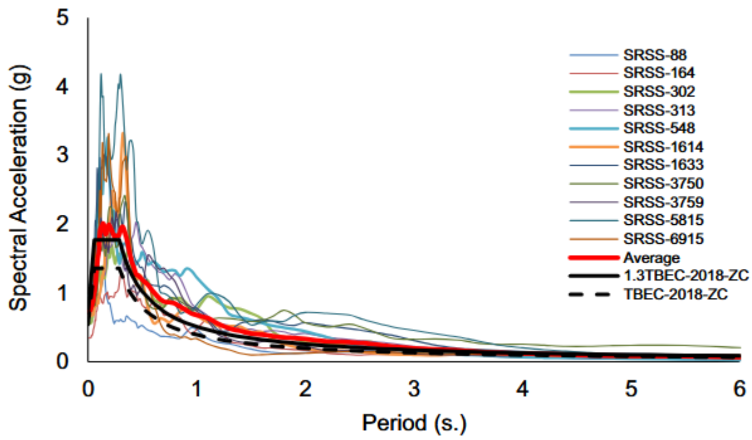


Fig. 1. Elastic acceleration spectrum of the scaled records for 5% damping

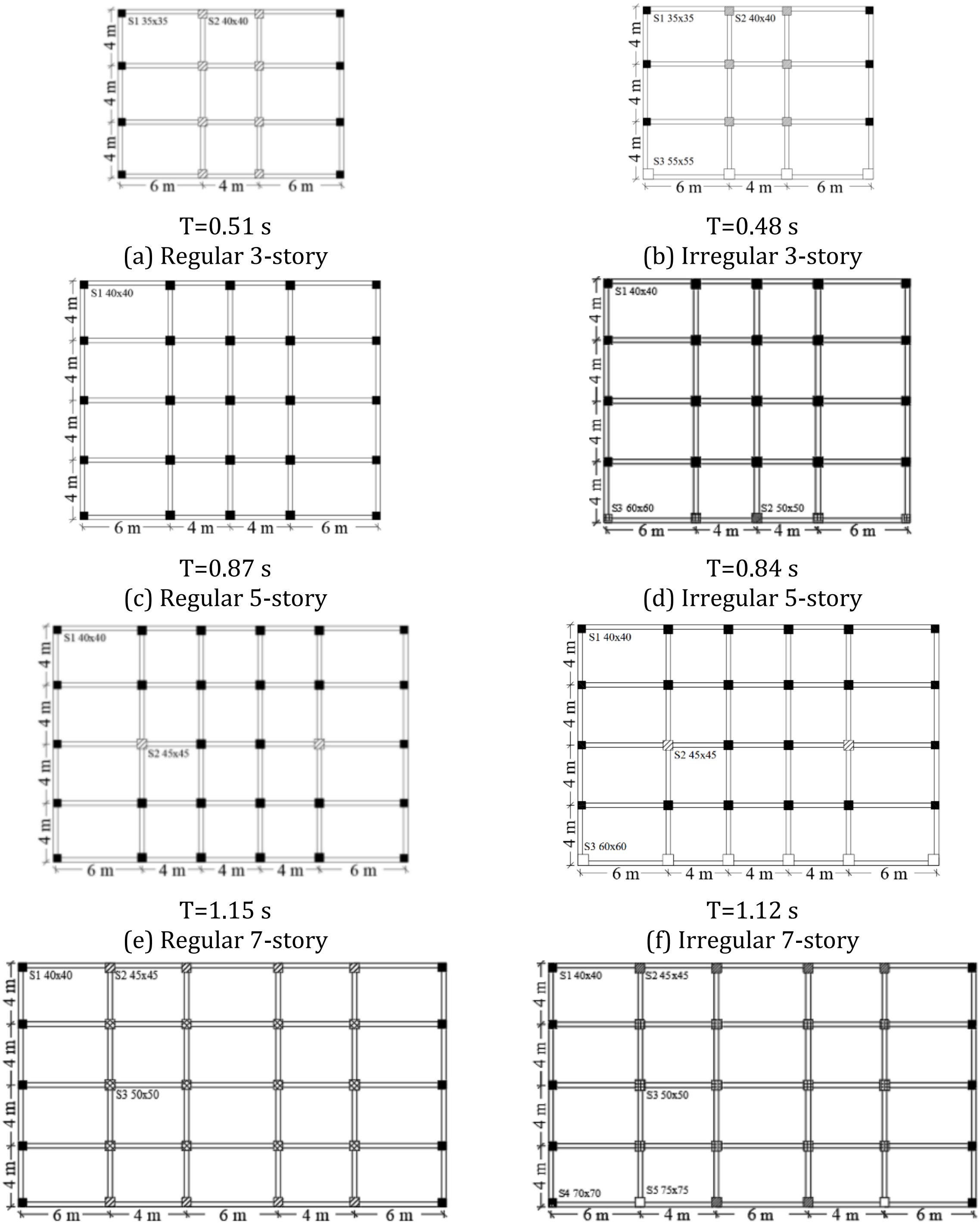
Table 1. Ground motion record properties used in the study [45]

No	RSN	Earthquake	Year	Location	M_w	Componenet H_1-H_2	PGA (g)	V_{s30} (m/s)	Scale Factor
1	88	San Fernando	1971	Santa Felita Dam	6.6	000-090	0.387	389.0	2.5
2	164	Imperial Valley-06	1979	Cerro Prieto	6.5	000-090	0.252	471.5	1.5
3	302	Irpinia_ Italy-02	1980	Rionero In Vulture	6.2	000-270	0.399	574.9	4.0
4	313	Corinth_ Greece	1981	Corinth	6.6	000-090	0.592	361.4	2.0
5	548	Chalfant Valley-02	1986	Benton	6.2	270-360	0.733	370.9	3.5
6	1614	Duzce_ Turkey	1999	Lamont 1061	7.1	E-N	0.525	481.0	4.0
7	1633	Manjil_ Iran	1990	Abbar	7.4	000-090	0.617	724.0	1.2
8	3750	Cape Mendocino	1992	Loleta Fire Station	7.0	270-360	0.531	515.7	2.0
9	3759	Landers	1992	Whitewater T.Farm	7.3	180-270	0.494	425.0	4.0
10	5815	Iwate_ Japan	2008	Yuzawa	6.9	EW-NS	0.791	655.5	4.0
11	6915	Darfield_ N.Zealand	2010	Heathcote V. PS	7.0	000-090	0.930	422.0	1.2

3. Details of Modelling and Analysis

3.1. Building Models

Three dimensional (3D) nonlinear low and mid-rise reinforced concrete (RC) residential buildings are considered in this study. Buildings consist of 3, 5, 7 and 9 stories. The story height was selected as 3.2 m in all floors of building models. Slab thickness is taken as 15 cm, and each slab weight is added to the related beam members as 4.7 kN/m. Live loads for residential buildings are determined as 2 kN/m² from TS498 [46]. In building design and analysis, TBEC-2018 [41] provisions were considered. Material properties are assumed to be 30 MPa for the concrete compressive strength and 420 MPa for the yield strength of both longitudinal and transverse reinforcements.



T=0.51 s
(a) Regular 3-story

T=0.48 s
(b) Irregular 3-story

T=0.87 s
(c) Regular 5-story

T=0.84 s
(d) Irregular 5-story

T=1.15 s
(e) Regular 7-story

T=1.12 s
(f) Irregular 7-story

T=1.33 s
(g) Regular 9-story

T=1.31 s
(h) Irregular 9-story

Fig. 2. Plan view and predominant period values of the considered buildings

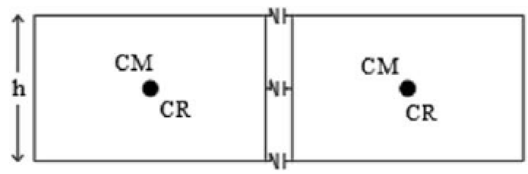
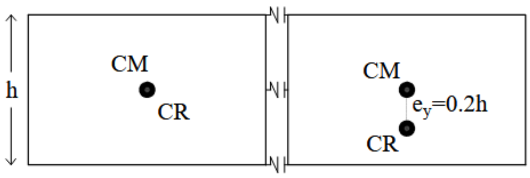
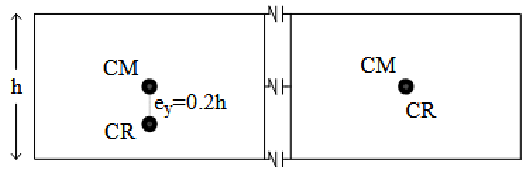
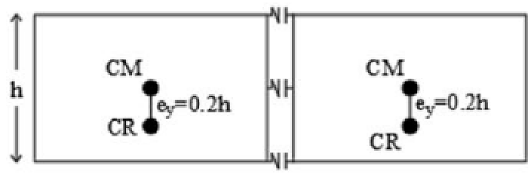
The longitudinal reinforcement ratio for column elements is between 1-1.15%. The high ductility buildings were modelled and analyzed in SAP2000 program [47]. The effective cross-section stiffness of column and beam members were assumed 0.70EI and 0.35EI as defined in TBEC-2018 [41] respectively. Soil type is assumed ZC that is similar to soil type C of FEMA-P-450 [48]. The design of buildings respect to elastic design spectrum with a return period of 475 years is made. Nonlinear behavior was considered with user-defined plastic hinges which were assigned to both end of structural members. Since time history analyses performed as bi-directional, plastic hinges at column members were applied considering M_2-M_3 interaction.

On the other hand, the difference between regular (e0) and irregular(e20) buildings is the distance between their mass center and rigidity center. While this distance in plan-view of regular buildings is negligible level, this distance in plan-view of irregular buildings 20% of building length in y-direction (perpendicular to possible collision direction). The plan views and dominant period values of models are illustrated in Fig. 2.

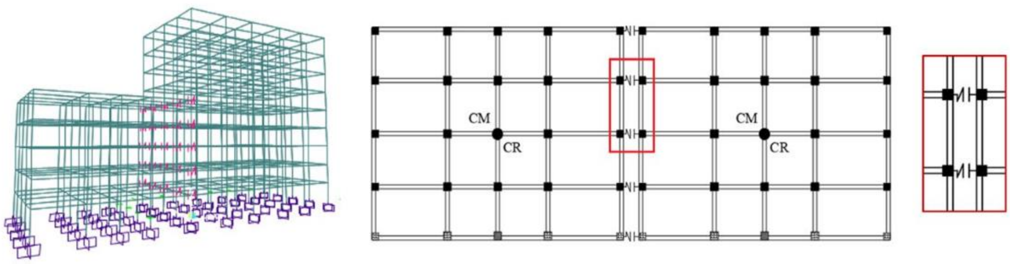
3.2. Adjacent Models and Link Elements

Adjacent binary models consist of regular and/or irregular buildings. 24 adjacent model combinations are summarized in Table 2. In table, e0e0-35 model represents regular 3-story building and regular 5-story building combination. While e0e20-57 model represents regular 5-story building and irregular 7-story building combination, e20e0-57 model represents irregular 5-story building and regular 7-story building combination. The individual buildings with the same story height are connected to each other by Kelvin link elements [49,50] from column to column at story slab levels as in 3D view.

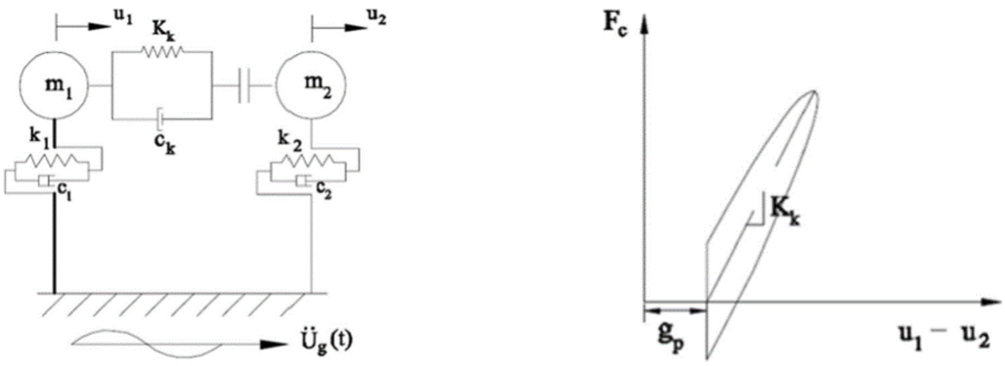
Table 2. Derived adjacent models with combination of individual buildings

General plan view of adjacent building combination	Adjacent Model		Individual Model							
			e_0				e_{20}			
			3	5	7	9	3	5	7	9
	35		+	+						
	37		+		+					
	39		+			+				
	57	e_0-e_0		+	+					
	59			+		+				
	79				+	+				
	35		+					+		
	37		+						+	
	39		+							+
	57	e_0-e_{20}		+					+	
	59			+						+
	79				+					+
	35			+			+			
	37				+		+			
	39					+	+			
	57	e_{20}-e_0			+			+		
	59					+		+		
	79					+			+	
	35						+	+		
	37						+		+	
	39						+			+
	57	e_{20}-e_{20}						+	+	
	59							+		+
	79								+	+

General 3D view and link details



Kelvin link element model in Fig. 3 consists of linear spring, damper and gap distance. The spring activates in case of insufficient gap distance and produces force according to Eq (1) [49,50]. This implies a collision. If gap distance is sufficient, it means collision does not occur, the spring force equals to zero [51-54].



(a) (b)

Fig. 3. (a) Kelvin model and (b)force–deformation relationship [47-48]

In the literature, many studies addressing concrete-to-concrete collisions have chosen a stiffness value between 1E10 and 1E11 N/m [53], [55]-[56]. This value as 1E10 was assigned to the link elements. Damping coefficient (c_k) is calculated respect to seismic weights in Table 3 and Eq (2)-Eq (3). The energy efficiency coefficient (e) was also taken as 0.65 for concrete-concrete collision as in many studies [53], [55]-[56]. However, since no collisions were expected for 4 m gap distance, these values are not significant in the distances obtained in the study.

$$F = \begin{cases} K_k(\ u_1 - u_2 - g_p) + c_k(\ \dot{u}_1 - \dot{u}_2), (\ u_1 - u_2) \geq g_p \\ 0, (\ u_1 - u_2) < g_p \end{cases} \quad (1)$$

$$c_k = 2\xi \sqrt{K_k \frac{m_1 m_2}{m_1 + m_2}} \quad (2)$$

$$\xi = -\frac{ln\ (e)}{\sqrt{\pi^2 + (ln(e))^2}} \quad (3)$$

Table 3. Seismic weights of individual buildings

Seismic Weight (kN)	Story			
	3-story	5-story	7-story	9-story
e0	4623.6	12753.8	19885.5	24734.4
e20	4775.4	13102.9	20047.6	25708.8

4. TBEC-2018 Requirements for Calculating Seismic Gap Distance

International regulations [3, 4, 57] and studies [2, 58] related to minimum gap distance are generally based on three different methods. These are absolute sums (ABS method) of the peak displacements of adjacent buildings, square roots of the sum of the squares (SRSS method) of the adjacent building peak displacements and double difference combination (DDC method) based on spectral displacement. It is known that these methods have many advantages and disadvantages compared to each other. This section as in the modeling and analysis stages investigates in the formulations and methods regarding the required gap distance (g_p) suggested in TBEC-2018 [41].

TBEC-2018 [41] proposes SRSS method based on reduced elastic displacement values for adjacent buildings. Minimum gap distance of adjacent buildings to prevent collision in TBEC-2018 [41] considering SRSS method is calculated respect to Eq (4). u and a represent reduced elastic displacement value and constant coefficient, respectively. Subscript '1' and '2' implies building with the longer oscillation period and building with the shorter oscillation period, respectively. The constant coefficient (a) varies depending on whether the floor slabs are at the same level on all floors of adjacent buildings. Since the floor levels are the same on all floors of the adjacent residential buildings with high ductility considered in this study, the value of the coefficient is 2. Additionally, TBEC-2018 [41] recommends also another formulation in Eq (5) based on building height. H in the equation represents building height. It should be also explained that while unit of building height is meter, the unit of gap distance obtained from equation is centimeter. More critical gap distance from both calculated values is considered in cases of design and seismic performance evaluation.

$$g_{p-(TBEC-2018-a)} = \alpha\sqrt{{u_1}^2 + {u_2}^2} \quad (4)$$

$$g_{p-(TBEC-2018-b)} = \begin{cases} 3, & H < 6\,m \\ (H-6)/3 + 3, & H \geq 6\,m \end{cases} \quad (5)$$

5. Results and Discussion

This study investigates required gap distance to prevent collision of adjacent buildings considering torsional effects. Adjacent models were derived from regular and irregular 3D nonlinear 3, 5, 7 and 9-story individual buildings. Nonlinear time-history analysis for 24 adjacent models were performed as bi-directional with spectrum-compatible 11 ground motion pairs in the SAP2000 [47] program. The required gap distances to prevent collision were obtained from 528 nonlinear dynamic analysis. The validity of TBEC-2018 [41] was evaluated with the nonlinear analysis results. Additionally, a new calculating method has been proposed for TBEC-2018 [41]. This calculating method achieves the more compatible gap distance with nonlinear analysis results to prevent collision compared to the TBEC-2018 [41] regulation requirements.

5.1. Required Gap Distance Based on Nonlinear Analysis

The required gap distances ($g_{p-required}$) to prevent collision were obtained from 528 nonlinear dynamic analysis respect to Eq (6). $u_1(t)$ and $u_2(t)$ parameters represent horizontal displacement demands of adjacent buildings at the story where the possible collision occurs and were calculated step by step throughout the earthquake duration. Average of calculated maximum values are given in Table 4. Additionally, required gap distances are categorized in Table 5 respect to number of story and eccentricity cases. The change is calculated as 16.1% and 12.4% at most respect to the number of story and eccentricity cases, respectively. The mean and standard deviation values for all models were determined as 86.4 mm and 15.8 mm, respectively.

$$g_{p-required} = max\,|u_1(t) - u_2(t)| \quad (6)$$

Table 4. Required gap distance of adjacent buildings respect to nonlinear analysis

Model		Average $g_{p\text{-required}}$ (mm)	Model		Average $g_{p\text{-required}}$ (mm)
e_0-e_0	3-5	97.5	e_0-e_{20}	3-5	89.6
	3-7	92.1		3-7	83.5
	3-9	68.5		3-9	71.7
	5-7	100.7		5-7	55.3
	5-9	104.9		5-9	101.7
	7-9	74.6		7-9	69.9
e_{20}-e_0	3-5	92.3	e_{20}-e_{20}	3-5	89.7
	3-7	84.1		3-7	80.3
	3-9	63.1		3-9	62.7
	5-7	106.2		5-7	107.7
	5-9	106.3		5-9	110.2
	7-9	84.4		7-9	76.1

Table 5. Average required gap distance respect to the number of story and eccentricity cases

Model	Proposed gap distance (mm)				
	e0-e0	e0-e20	e20-e0	e20-e20	Average
3-story	86.0	81.6	79.8	77.6	81.3
5-story	101.0	82.2	101.6	102.5	96.8
7-story	89.1	69.6	91.6	88.0	84.6
9-story	82.7	81.1	84.6	83.0	82.8
Average	89.7	78.6	89.4	87.8	86.4

5.2. Required Gap Distances Respect to TBEC-2018

In this section, the required gap distances respect to TBEC-2018 [41] were calculated in Table 6. The minimum required gap distance values obtained from Eq 2 and Eq 3 are given "a" and "b" column, respectively. More critical (maximum) of both gap distance values is also given "max" column. While average gap distance based on reduced elastic displacement demands is 66.3 mm, the average gap distance based on building height is 56.2 mm. Standard deviation values of both gap distance calculating approaches were also given in the table. The average gap distance to be considered in the design and seismic performance evaluation was determined as 66.5 mm. Additionally, many critical gap distances were obtained from reduced elastic displacement values as in Fig. 4 and Table 6. Further, it is possible to state that the difference between the approaches and required gap distance generally increases as the number of floors of adjacent buildings increases.

Table 6. Required gap distance of adjacent buildings respect to TBEC-2018 requirements

Model		g_p (TBEC-2018) (mm)		
		(a)	(b)	(max)
e_0-e_0	3-5	40.2	42.0	42.0
	3-7	50.4	42.0	50.4
	3-9	46.3	42.0	46.3
	5-7	71.4	63.3	71.4
	5-9	67.6	63.3	67.6
	7-9	109.1	84.7	109.1
e_0-e_{20}	3-5	48.5	42.0	48.5
	3-7	48.8	42.0	48.8
	3-9	45.5	42.0	45.5
	5-7	69.9	63.3	69.9
	5-9	67.7	63.3	67.7
	7-9	110.0	84.7	110.0
e_{20}-e_0	3-5	38.7	42.0	42.0
	3-7	49.1	42.0	49.1
	3-9	45.0	42.0	45.0
	5-7	83.7	63.3	83.7
	5-9	80.4	63.3	80.4
	7-9	108.2	84.7	108.2
e_{20}-e_{20}	3-5	47.3	42.0	47.3
	3-7	47.6	42.0	47.6
	3-9	44.1	42.0	44.1
	5-7	82.4	63.3	82.4
	5-9	80.5	63.3	80.5
	7-9	109.2	84.7	109.2
Average		66.3	56.2	66.5
Standard Deviation		23.7	15.9	23.4

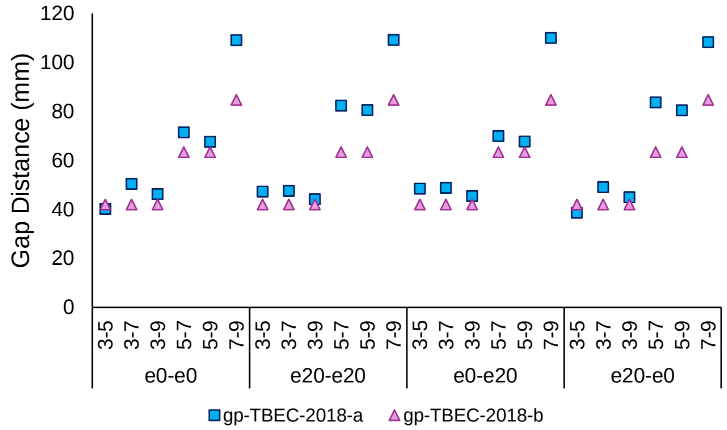


Fig. 4. The seismic gap distances calculated respect to TBEC-2018 regulation

5.3. Assessment of the Validity of TBEC-2018 Requirements and A New Approach

The validity of TBEC-2018 [41] provisions investigated with detail nonlinear analysis results. The nonlinear analysis results ($g_{p\text{-required}}$) are divided by gap distances ($g_{p\text{-TBEC-2018-max}}$) proposed in TBEC-2018 as in Fig. 5. Gap distances suggested in TBEC-2018 [41] are sufficient for only five models (generally 7and 9-story adjacent models) compared to nonlinear analysis results. For other models, TBEC-2018 [41] requirements are insufficient up to 2.3 times and average 1.4 times.

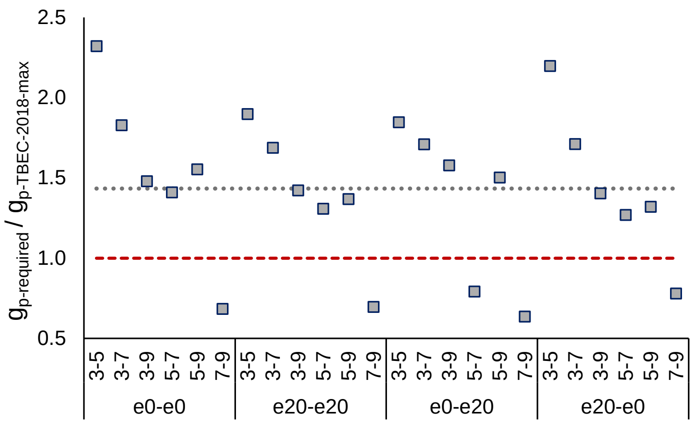


Fig. 5. The ratio of seismic gap distances obtained from the nonlinear analysis to proposed distances in the TBEC-2018 regulation

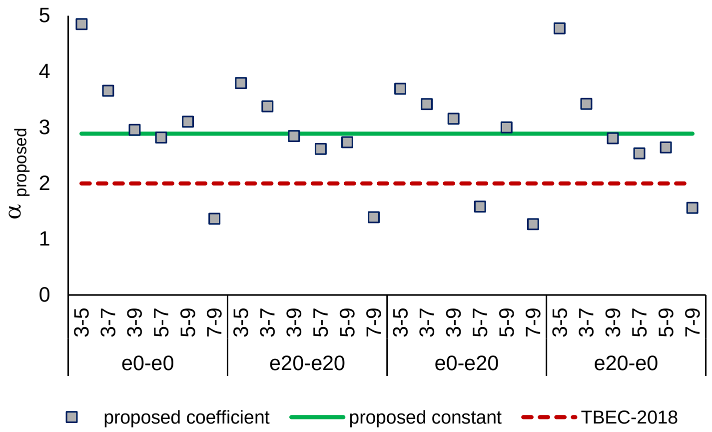


Fig. 6. The relationship between building period ratio and $\alpha_{proposed}$ coefficient

If the required gap distances obtained from nonlinear analyses are divided by half of the displacement demands recommended in $g_{p\text{-}TBEC\text{-}2018\text{-}a}$, revised coefficients ($\alpha_{proposed}$) more compatible with nonlinear analyses are obtained. Fig. 6 illustrates the proposed and revised coefficients for the adjacent models. Additionally, $\alpha_{proposed}$ are categorized in Table 7 respect to number of story and eccentricity cases. The change is calculated as 32.6% and 14.1% at most respect to the number of story and eccentricity cases, respectively. Average value of the revised coefficients is 2.89. For calculating safer and more valid gap distances compared to current, it is recommended that the relevant coefficient in TBEC-2018 [41] be revised to 2.89. However, it should be noted that the proposed coefficient may vary for different soil classes, earthquake levels, eccentricity ratios, and building models. Therefore, it is recommended that future studies increase the reliability of the results by increasing the model diversity.

Table 7. Proposed α coefficients respect to the number of story and eccentricity cases

Model	Proposed α coefficient				
	e0-e0	e0-e20	e20-e0	e20-e20	Average
3-story	3.82	3.42	3.67	3.34	3.56
5-story	3.59	2.76	3.32	3.05	3.18
7-story	2.61	2.09	2.51	2.46	2.42
9-story	2.48	2.48	2.34	2.32	2.40
Average	3.13	2.69	2.96	2.79	2.89

6. Conclusions

This study investigated to required gap distance of adjacent buildings considering torsional irregularity. 3D nonlinear 3, 5, 7 and 9-story buildings were subjected to 11 spectrum-compatible ground motion pairs. Nonlinear behavior of low- and mid-rise buildings is considered with plastic hinges assigned to both end of column and beam members is considered with plastic hinges. The individual buildings with the same story height are connected to each other by Kelvin link elements from column to column at story slab levels. Required gap distances to prevent collision are obtained from 528 nonlinear time-history analysis results. TBEC-2018 [41] requirements compared to nonlinear analysis results. In this way, validity of TBEC-2018 requirements is also investigated. Additionally, a new coefficient for possible TBEC-2018 [41] regulation was proposed. The findings of the study are summarized as below:

- It has been determined with nonlinear time-history analysis regarding the required gap distance between adjacent buildings that average gap distance should be 86.4 mm.
- The change of required gap distance is calculated as 16.1% and 12.4% at most respect to the number of story and eccentricity cases, respectively
- TBEC-2018 regulation recommends an average 66.5 mm gap distance between adjacent buildings considered the study for prevent collision.
- It has been determined with nonlinear time history analysis regarding the required gap distance between adjacent buildings that TBEC-2018 requirements are insufficient up to 2.3 times and average 1.4 times.
- Therefore, the existing constant coefficient (α) in TBEC-2018 proposed to be revised as 2.89 for calculating gap distances more compatible with nonlinear analyses. The change is calculated as 32.6% and 14.1% at most respect to the number of story and eccentricity cases, respectively.
- It should not be forgotten that the results obtained from nonlinear analysis may vary for different frequency contents, soil types, eccentricity ratios and earthquake levels. For this reason, the limits of code based proposed approach for more comprehensive and reliable gap distance calculating should be tested in future studies.

References

[1] Mohamed H, Romão X. Seismic fragility functions for non-seismically designed rc structures considering pounding effects. Buildings, 2021; 11(12), 665. https://doi.org/10.3390/buildings11120665

[2] Miari M, Choong KK, Jankowski R. Seismic pounding between adjacent buildings: Identification of parameters, soil interaction issues and mitigation measures. Soil Dyn Earthq Eng, 2019; 121:135–150. https://doi. org/ 10. 1016/j. soild yn. 2019. 02. 024

[3] American Society of Civil Engineers (ASCE7-16) ASCE7-16, Minimum Design Loads and Associated Criteria for Buildings and Other Structures in Seismic Design Requirements for Building Structures: Structural Engineering Institute, 2017; https://ascelibrary.org/doi/book/10.1061/9780784414248

[4] Eurocode 8 (EC8) Design of Structures for Earthquake Resistance - Part 1: General Rules, Seismic Actions and Rules for Buildings, 2004; European Committee for Standardization, Brussels.

[5] Doğan M, Günaydin A. Pounding of adjacent RC buildings during seismic loads. Journal of Engineering and Architecture Faculty of Eskişehir Osmangazi University, 2009; 22(1):129–145.

[6] Ozer E. Seismic pounding of adjacent buildings considering torsional effects. Bulletin of Earthquake Engineering, 2024; *22*(4), 2139-2171.

[7] V Jeng and WL. Tzeng. Assessment of seismic pounding hazard for Taipei City. Engineering Structures, 2000; 22(5), 459-471. https://doi.org/10.1016/S0141-0296(98)00123-0.

[8] EA Mavronicola, PC Polycarpou and P Komodromos. Spatial seismic modeling of base- isolated buildings pounding against moat walls: effects of ground motion directionality and mass eccentricity. Earthquake Engineering & Structural Dynamics, 2017; 46(7), 1161-1179. https://doi.org/10.1002/eqe.2850

[9] Khatami SM, Naderpour H, Barros R, & Jankowski R. Verification of formulas for periods of adjacent buildings used to assess minimum separation gap preventing structural pounding during earthquakes. Advances in Civil Engineering, 2019(1). https://doi.org/10.1155/2019/9714939

[10] Jin N, Yang Y. Optimizing parameters for anticollision systems between adjacent buildings under earthquakes. Shock and Vibration, 2018(1). https://doi.org/10.1155/2018/3952495

[11] Manoukas GE and Karayannis CG. Seismic interaction between multistory pilotis rc frames and shorter structures with different story levels—floor-to-column pounding. CivilEng, 2023; 4(2), 618-637. https://doi.org/10.3390/civileng4020036

[12] Sadeghi, A., Kazemi, H., Razmkhah, M. H., & Sadeghi, A. Probabilistic investigation of the pounding effect in steel moment resisting frames with equal and unequal heights. Research in Engineering Structures and Materials,2024; 10(4), 1431-1449.

[13] Ozmen HB, Inel M. Effect of concrete strength and detailing properties on seismic damage for RC structures, Res. Des. 2024; 1(1): 1-11. http://dx.doi.org/10.17515/rede2024-005en1124rs

[14] Frangu I, Bilgin H. Comparative assessment of seismic analysis procedures: Eurocode 8 vs. KTP.N2-89, Res. Des. 2024; 1(1): 23-32. http://dx.doi.org/10.17515/rede2024-002bu1104rs

[15] Kazemi F, Miari M, & Jankowski R. Investigating the effects of structural pounding on the seismic performance of adjacent rc and steel mrfs. Bulletin of Earthquake Engineering, 2020; 19(1), 317-343. https://doi.org/10.1007/s10518-020-00985-y

[16] Hosseini S, Naderpour H, Vahdani R, & Jankowski R. Evaluation of pounding effects between reinforced concrete frames subjected to far-field earthquakes in terms of damage index. Bulletin of Earthquake Engineering, 2021; 20(2), 1219-1245. https://doi.org/10.1007/s10518-021-01259-x

[17] Rouabeh A, Aouari I, Benahmed B, Palanci M. Improved PGA and PGV estimation in soft soils for earthquake engineering applications. Research in Engineering Structures and Materials*, 2025;* https://doi.org/10.17515/resm2025-857ea0429rs

[18] Elwardany H, Seleemah A, Jankowski R, & El-Khoriby S. Influence of soil–structure interaction on seismic pounding between steel frame buildings considering the effect of infill panels. Bulletin of Earthquake Engineering, 2019; 17(11), 6165-6202. https://doi.org/10.1007/s10518-019-00713-1

[19] Lu Y, Xiong F, Ran M, Ge Q, & Wang J. Seismic pounding damage to adjacent reinforced concrete frame–shear wall buildings and freestanding contents. Earthquake Engineering &Amp; Structural Dynamics, 2022; 51(6), 1436-1456. https://doi.org/10.1002/eqe.3622

[20] Madani B, Behnamfar F, & Riahi HT. Dynamic response of structures subjected to pounding and structure–soil–structure interaction. Soil Dynamics and Earthquake Engineering, 2015; 78, 46-60. https://doi.org/10.1016/j.soildyn.2015.07.002

[21] Karayannis CG, Naoum MC. Torsional behavior of multistory RC frame structures due to asymmetric seismic interaction. Eng Struct ,2018; 163:93–111. https:// doi. org/ 10. 1016/j. engst ruct. 2018. 02. 038

[22] Chau KT, Wei XX, Shen CY, Wang LX. Experimental and theoretical simulations of seismic torsional poundings between two adjacent structures. In 13th world conference on earthquake engineering 13WCEE, pp 1–6, 2004.

[23] Oz I. Seismic pounding effects of typical midrise reinforced concrete structures subjected to Soil–Structure interaction effects. Journal of Structural Engineering, 2025; *151*(2), 05024005.

[24] Wei XX, Wang LX, Chau KT. Nonlinear seismic torsional pounding between an asymmetric tower and a barrier. Earthq Spectra, 2009; 25(4):899–925. https:// doi. org/ 10. 1193/1. 32071 77
[25] Fiore A, Marano GC, Monaco P. Earthquake-induced lateral-torsional pounding between two equal height multi-storey buildings under multiple bi-directional ground motions. Adv Struct Eng, 2013; 16(5):845–865. https://doi.org/10.1260/1369-4332.16.5
[26] Kuo PT. Torsional effects in structures subjected to dynamic excitations of the ground. Ph.D. Thesis, Rice University, 1974.
[27] Tabatabaei R. Torsional vibration of eccentric building systems (pp. 169–192). InTech, 2011.
[28] Jing W, Wang Q, Xing S, Cheng X, Song Y. Control measures of collapse-pounding dynamic responses of adjacent structures under earthquake action. Soil Dyn Earthq Eng, 2023; 165:107715. https://doi.org/10.1016/j.soildyn.2022.107715
[29] Leibovich E, Rutenberg A, Yankelevsky DZ. On eccentric seismic pounding of symmetric buildings. Earthq Eng Struct Dyn, 1996; 25(3):219–233. https:// doi. org/ 10. 1002/ (SICI) 1096- 9845(199603) 25:3%3c219:: AID- EQE537% 3e3.0. CO;2-H
[30] Mouzakis HP, Papadrakakis M. Three dimensional nonlinear building pounding with friction during earthquakes. J Earthq Eng, 2004; 8(01):107–132. https:// doi. org/ 10. 1142/ S1363 24690 40013 53
[31] Hao H, Shen J. Estimation of relative displacement of two adjacent asymmetric structures. Earthq Eng Struct Dyn, 2001; 30(1):81–96. https://doi.org/10.1002/1096-9845(200101)30:1%3c81::AID-EQE997%3e3.0.CO;2-E
[32] Raheem SEA, Youssry A, Soghier MH, Fooly MY, Gamal YA. Evaluation of seismic demands for adjacent irregular buildings with transverse alignment eccentricity. Bulletin of Earthquake Engineering, 2025; 23(1), 301-326. https://doi.org/10.1007/s10518-024-02038-0
[33] Oz I, Raheem SEA, Turan C. Mitigation measure using tuned mass dampers for torsional irregularity impact on seismic response of L-shaped RC structures with soil–structure interaction. In*Structures*, 2025 September; Vol. 79, p. 109449). Elsevier. https://doi.org/10.1016/j.istruc.2025.109449
[34] Özer E. The effect on required gap distance in adjacent reinforced concrete buildings of fluid viscous dampers. Niğde Ömer Halisdemir University Journal of Engineering Sciences, 2024;*13*(4), 1231-1239. https://doi.org/10.28948/ngmuh.1499280
[35] Karayannis CG, Naoum MC, Torsional behavior of multistory RC frame structures due to asymmetric seismic interaction. Eng Struct, 2018; 163:93–111. https:// doi. org/ 10. 1016/j. engst ruct. 2018. 02. 038
[36] Mazza F, Labernarda R, Effects of near-fault acceleration and non-acceleration pulses on pounding between in-plan irregular fixed-base and base-isolated buildings. Struct Cont Health Mon, 2022; 29(9):e2992. https://doi.org/10.1002/stc.2992
[37] Favvata MJ. Minimum required separation gap for adjacent RC frames with potential inter-story seismic pounding. Eng Struct, 2017; 152:643–659. https://doi.org/10.1016/j.engstruct.2017.09.025
[38] Flenga MG, Favvata MJ. A risk-targeted decision model for the verification of the seismic performance of RC structures against structural pounding. Soil Dyn Earthq Eng, 2023; 175:108229. https://doi.org/10.1016/j.soildyn.2023.108229
[39] Jaradat Y, Sobhi P, & Far H. An investigation into adequacy of separation gap to preclude earthquake-induced pounding. Structural Engineering and Mechanics, 2023; https://doi.org/10.12989/sem.2023.86.1.029
[40] Masmoum MS, & Alama MSA. Tying Devices to Mitigate Pounding of Adjacent Building Blocks. *Engineering, Technology & Applied Science Research*, 2020; *10*(3), 5643-5647. https://doi.org/10.48084/etasr.3502
[41] Turkish Building Earthquake Code (TBEC-2018) Republic of Turkey Prime Ministry Disaster and Emergency Management Authory Presidential of Earthquake Department. Ankara, Turkey (in Turkish), 2018
[42] Ozmen HB. An Investigation on Soil Amplification through Site Factors Used in Seismic Design Codes, Adv. Civ. Eng., 2023(1), 6858371, https://doi.org/10.1155/2023/6858371
[43] Bommer JJ, & Acevedo AB. The use of real earthquake accelerograms as input to dynamic analysis. Journal of Earthquake Engineering, 2004; *8*(spec01), 43-91. https://doi.org/10.1080/13632460409350521
[44] American Society of Civil Engineers (ASCE) FEMA-P-1051. 2015 NEHRP Recommended Seismic Provisions:Design Examples. In, Washington DC, USA, 2016.
[45] Pacific Earthquake Engineering Research Center (PEER) Ground Motion Database. Available at: http://ngawest2.berkeley.edu/. 2019); Accessed 19.05.2019
[46] TS498. Design Loads for Buildings. Turkish Standards Institution. Ankara, Turkey, 1997.
[47] Sap 2000 CSI. Integrated software for structural analysis and design. Berkeley USA: Computers and Structures Inc; 2020. Version 2020.
[48] FEMA-P-450. Nehrp recommended provisions for seismic regulations for new buildings and other structures. Washington DC, USA, 2003.

[49] Muthukumar S, Desroches R. Evaluation of impact models for seismic pounding. In: 13th world conference on earthquake engineering, Vancouver, BC, Canada, 235, August 1–6, 2004.
[50] Muthukumar S, DesRoches R. A Hertz contact model with non-linear damping for pounding simulation. Earthq Eng Struct Dyn, 2006; 35:811–828. https://doi.org/10.1002/eqe.557
[51] Flenga MG, Favvata MJ. Probabilistic seismic assessment of the pounding risk based on the local demands of a multistory RC frame structure. Eng Struct, 2021; 245:112789. https://doi.org/10.1016/j.engstruct.2021.112789
[52] Flenga MG, Favvata MJ. A risk-targeted decision model for the verification of the seismic performance of RC structures against structural pounding. Soil Dyn Earthq Eng, 2023; 175:108229. https://doi.org/10.1016/j.soildyn.2023.108229
[53] Shakya K, Wijeyewickrema AC. Mid-column pounding of multi-story reinforced concrete buildings considering soil effects. Adv Struct Eng, 2009; 12(1):71–85. https://doi.org/10.1260/136943309787522687
[54] Miari M, Jankowski R. Analysis of floor-to-column pounding of buildings founded on different soil types. Bull Earthq Eng, 2022; 20(13):7241–7262. https://doi. org/10.1007/s10518 022-01482-0
[55] Van Mier JG, Pruijssers A, Reinhardt HW, Monnier T. Load Time Response of Colliding Concrete Bodies. Journal of Structural Engineering, 1991; 117(2), 354-374.
[56] Jankowski R. Nonlinear viscoelastic modelling of earthquake induced structural pounding. Earthquake Engineering and Structural Dynamics, 2005; 34(6), 595-611.
[57] UBC88, Uniform Building Code, International Conference of Building Officials, 1988. Whittier, CA
[58] Kumar MP, Kumar JC. Seismic pounding of the adjacent buildings with different heights. Int J Eng Res Sci Technol 2015;4:350–61.