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STRUCTURAL POUNDING OF MID-RISE RC BUILDINGS DURING EARTHQUAKES

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ABSTRACT

Inadequate separations cause lateral collision of adjacent buildings during earthquakes. This collision refers to seismic pounding and imposes an unexpected impact loading on buildings causing heavy damages or collapses. Building damages due to pounding have been reported from major past earthquakes such as 1964 Alaska, 1971 San Fernando, 1985 Mexico City, 1989 Loma Prieta, 1999 Chi-Chi and 1999 Kocaeli Earthquakes. Major ratio of existing building stock has potential pounding risk in possible future earthquakes in Turkey.

This study investigates the effects of pounding on seismic behaviour of inadequately separated mid-rise reinforced concrete buildings in Turkey. Three different models are used to evaluate seismic performance of adjacent buildings; 4-story building per 1975 Turkish Earthquake Code (TEC), 7-story building per 1975 and 1998 TEC are used to represent mid-rise reinforced concrete buildings. The selected buildings have reinforced concrete frame systems without shear walls. Nonlinear response history analyses are conducted using SAP2000. Beam and column elements are modelled as nonlinear frame elements with lumped plasticity by defining plastic hinges at both ends of beams and columns. Buildings are connected with link elements with 20 mm gap.

The 4- and 7-story buildings per 1975 TEC are connected by link elements with 20 mm gap for the first set. For the second set, 7-story building per 1998 TEC is connected to 4-story per 1975 TEC building by link element with 20 mm gap. Two different sets of buildings are modelled and subjected to nonlinear time history analysis using four different earthquake records. Displacement histories of the connected buildings at the roof level are compared to that of the standalone building with no collision. To evaluate the impact of collision, total axial force at link members and number of collisions at critical-story are also investigated.

Observations show that pounding force is significantly influential on seismic response of existing mid-rise reinforced concrete buildings as it increases roof displacements and may also cause permanent displacements at free direction. However, pounding interaction decreases the maximum roof displacement at the collision direction. The outcomes and observations of the current study also demonstrate the complexity of pounding behaviour of structures. It seems that the proper seismic performance evaluation of adjacent buildings is not possible without consideration of pounding interaction.

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INTRODUCTION

Adjacent buildings with inadequate separations are widely observed in crowded cities. Because of inadequate separations, lateral collision is possible between adjacent buildings during earthquakes. This collision refers to seismic pounding and imposes an unexpected impact loading on buildings causing heavy damages or collapses (Kasai et al., 1992) Building damages due to pounding have been reported from major past earthquakes such as 1964 Alaska, 1971 San Fernando, 1985 Mexico City, 1989 Loma Prieta, 1999 Chi-Chi and 1999 Kocaeli Earthquakes. Significant ratio of existing building stock has potential pounding risk in possible future earthquakes in Turkey (Cole et al., 2012; Ozmen et al., 2013) Therefore, understanding the seismic behaviour of adjacent building during strong motions is essential for earthquake engineering.

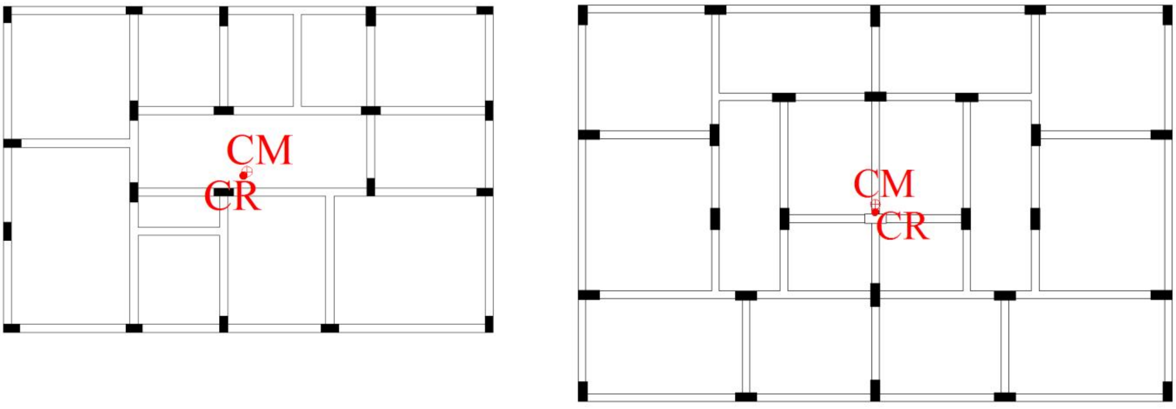
This study investigates the effects of pounding on seismic behaviour of inadequately separated mid-rise reinforced concrete buildings in Turkey. Three different models are used to evaluate seismic performance of adjacent buildings; 4-story building per 1975 Turkish Earthquake Code (TEC), 7-story building per 1975 and 1998 TEC are used to represent mid-rise reinforced concrete buildings. The selected buildings have reinforced concrete frame systems without shear walls. Nonlinear response history analyses are conducted using SAP2000. Beam and column elements are modelled as nonlinear frame elements with lumped plasticity by defining plastic hinges at both ends of beams and columns.

The 4- and 7-story buildings per 1975 TEC are connected by link elements with 20 mm gap for the first set. For the second set, 7-story building per 1998 TEC is connected to 4-story per 1975 TEC building by link element with 20 mm gap. Two different sets of buildings are modelled and subjected to nonlinear time history analysis using four different earthquake records. Displacement histories of the connected buildings at the roof level are compared to that of the standalone building with no collision. To evaluate the impact of collision, total axial force at link members and number of collisions at critical-story are also investigated.

The outcomes and findings of the study are useful for seismic behaviour assessment of adjacent buildings and contribute to understand the effect of pounding phenomenon. The authors also are aware of a need for a detailed research including different gap rates and buildings combinations to evaluate seismic performance of Turkish building stock which are built with inadequate adjacent separations.

DESCRIPTION OF STRUCTURES AND MODELLING APPROACH

One 4-story building using 1975 TEC and two 7-story buildings using 1975 and 1998 codes are selected to represent mid-rise buildings located in the high seismicity region of Turkey. The selected buildings are typical beam-column RC frame buildings with no shear walls. Outcomes of detailed field and archive investigation (about 500 buildings) established building models; number of columns, column and beam dimensions, floor area or other parameters reflects a typical constructed building (Inet et al., 2009). Plan views of the buildings are given in Figure 1.



4-story building plan view

7-story building plan view

Figure 1. Plan views of 4- and 7- story buildings

As shown in Figure 2, five points labelled A, B, C, D, and E define force-deformation behaviour of a typical plastic hinge. The values assigned to each of these points vary depending on type of element, material properties, longitudinal and transverse steel content, and axial load level on the element.

Note that number of plastic hinges to be generated for each building is in the order of 800 and 1800 for the 4- and 7-story buildings, respectively. Plastic hinge length is assumed to be equal to half of the section depth as recommended in 2007 Turkish Earthquake Code. Also, effective stiffness values are obtained per the code; 0.4EI for beams and values between 0.4 and 0.8EI depending on axial load level for columns.

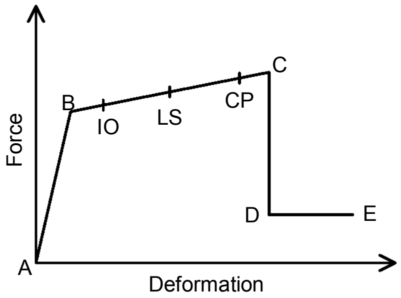


Figure 2. Typical strength-deformation relation for a plastic hinge

The building combinations used in this study are given in Figure 3. The buildings are connected by a link element with 20 mm gap between them corresponding to typical inadequate space for adjacent buildings. Every column connected to adjacent building throughout floor level. Thus, pounding force transferred to column members at floor level and other interactions are neglected. This is a reliable approach to observe influences of collision during strong motions (Muthukumar and Desroches, 2004; Pandelites and Ma, 1998).

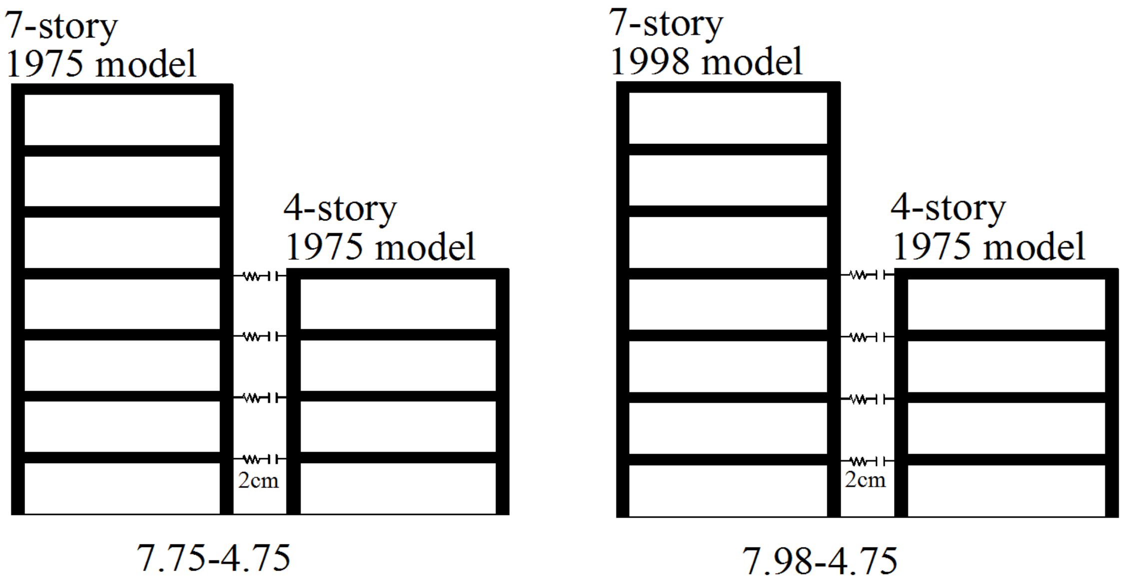


Figure 3. Building arrangements for pounding models

GROUND MOTIONS

The ground motion records used in nonlinear time history analysis are selected from destructive past earthquakes. General information about the ground motions is provided in Table 1.

Average response spectrum of ground motion records for 5% damping is plotted in Figure 4 as well as demand spectrum provided in Turkish Earthquake Code-2007 for design earthquake with 10%

probability of exceedance in 50 years on Z3 soil class (compatible to soil class C of FEMA-356). The figure also provides average spectrum for ground motions. As seen in the figure, average spectrum for the considered records is higher than the code spectrum of design earthquake within the period of interest for the mid-rise buildings. The code spectrum is provided to visualize the demand of selected records. No special effort has been given to fit the average of selected records to the code spectrum.

Table 1. Properties of ground motion used in the study

Identifier	**Earthquake**	**Date (dd/mm/yy)**	**Magnitude**	**Station**	**Comp. (°)**	**PGA (g)**	**PGV (m/s)**	**Dist. (km)**
GZ76GAZ.000	Gazli	17/05/76	M_W= 6.8	Karakyr	360°	0.608	0.654	3[2]
LP89HOOL.360	Loma Prieta	18/10/89	M_W = 6.9	Hollister-South & Pine	360°	0.371	0.624	28.8[1]
NR94PACO.360	Northridge	17/01/94	M_W = 6.7	Pacoima Kagel Canyon	360°	0.433	0.515	8.2[1]
NR94SEPU.360	Northridge	17/01/94	M_W = 6.7	Sepulveda VA	360°	0.939	0.766	8.9[1]

1 Closest distance to fault rupture 2 Hypocentral

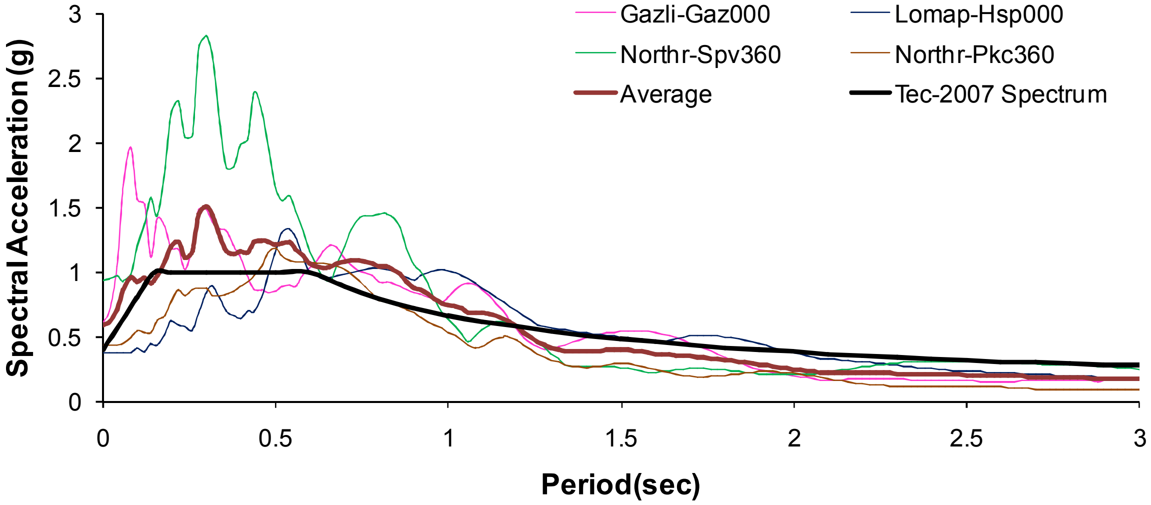


Figure 4. Response spectrum of ground motion records

RESULTS

Adjacent buildings with 20 mm gap and the reference (the standalone) building were subjected to the selected ground motion records without any scaling to evaluate pounding interaction. Displacement demands of roof level are obtained and compared in Figures 5 and 6 to see difference between pounding combination and reference building models. The 7.75-4.75 represents the adjacent model of 7- and 4-story buildings per 1975 TEC with 20 mm gap. The collision direction is +X for 7-story building and –X for 4-story building according to placement of adjacent buildings for both analysis cases.

The variation in magnitude and history of displacement demands with earthquake records is obvious in Figures 5 and 6. It is also clear that whereas pounding interaction may limit the maximum roof displacement at collision direction, it increases displacement demands at the free direction. This behaviour is directly related with the properties of structures and dynamic characteristics of ground motions. The effect of pounding is more severe on the 1975 4-story building compared to the 1975 7-story building. While maximum roof displacement increases 26.6% on average for 4-story building due to pounding at free direction, the average increase in displacement demands of the7-story buildings is only 10.8%. At collision direction, maximum displacement demands decreases 39.8% and 1% for the 4- and 7-story buildings, respectively.

The comparison of Figure 5 and Figure 6 indicates that the effect of pounding is more apparent on the 7.75-4.75 building combination than the 7.98-4.75 combination. This is the result of stronger 7-story building constructed per 1998 TEC. The comparison of 7-story buildings constructed per 1975 and 1998 codes clearly shows more rigid, more lateral load carrying capacity of the building per 1998 code. Thus, lateral displacements and magnitude of collision for the 7.98-4.75 building combination are limited compared to the 7.75-4.75 building combination.

The maximum roof displacement increases 11.9% on average for the 4-story building per 1975 code due to pounding at free direction while the average increase in displacement demands of the7-story building per 1998 code is only 6.9%. At collision direction, maximum displacement demands decreases 13.3% and 21.3% for the 4-story building per 1975 code and 7-story building per 1998 code, respectively.

It's hard to say that the limitation on maximum displacement demand at collision direction due the pounding interaction makes positive contribution on seismic performance of the adjacent buildings. It is also possible that the collision force has potential to damage most of structural or non-structural elements although it limits horizontal displacement at one direction. Thus, deformation and strength capacities of structures decrease significantly due to pounding effect. Although the permanent displacement and collapse mechanism are prevented by the adjacent building, structures have heavy damage potential under seismic demands at free direction. Indeed the observations emphasize that collapse or damage mechanism of adjacent buildings extensively occurs at free direction (Ozmen et al., 2013).

The story where the collision and maximum link forces occur is described as critical story. Total link force at critical story of pounding cases are given in Figures 7 and 8. Although the 4th story level is the critical story where the collision occurs in most cases, the critical floor is the 3rd story level in some cases. This is result of properties of structures and characteristics of ground motions. Evaluation of seismic performance of adjacent buildings with using link forces is not a specific issue of the current paper.

For most cases, structural members exceed the yield point during moderate or strong motions and respond to the collision demands with deformations. So that, the effect of pounding forces on base shear and story forces is not clear. But it causes significant changes on distribution of seismic forces and interstory and roof drift ratios of structures. It should be noted that, adjacent buildings have different response characteristics and plastic hinge distributions during strong motions. This topic is a part of another detailed study with greater number of buildings and different gap ratios.

The link forces give information about magnitude and number of collision during strong motions. Observations show that collision at column members at floor level do not occur simultaneously which is the clue of torsion behaviour that depended by pounding and characteristics of ground motions. It should be also noted that the models used in the analysis do not have any static irregularities. Although there is no specific evident between number of collision and magnitude of pounding force, total force of link members decreases for the second building set (7.98-4.75) compatible with limited number of collisions.

Maximum roof displacements for both free and collision directions, link forces and number of collision at critical floor are given in Table 2 and 3. It's obvious that pounding behaviour of buildings varies with properties of buildings and ground motions. For example, maximum number of collision and link forces occurs for Gazli Earthquake 1976-Gaz000 station for the first set (7.75-4.75) while maximum number of collision and link forces occur for different records for the second set (7.98-4.75). The table also shows that the number of collisions for the second set is more than that of the first set with smaller link forces.

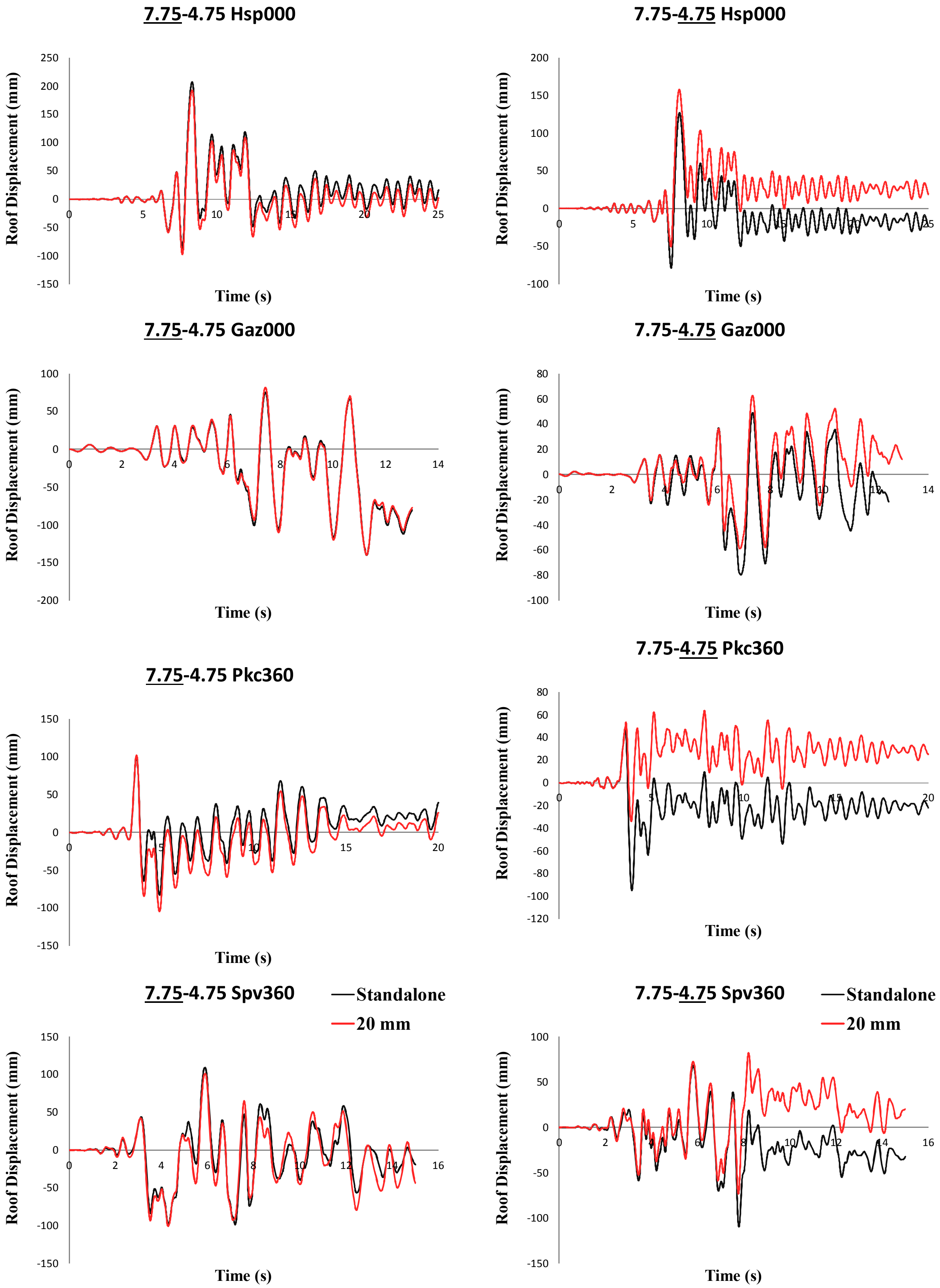


Figure 5. Comparison of roof displacements of 1975 TEC 7-story (on left column) and 1975 TEC 4-story (on right column) buildings with that of reference (standalone) buildings

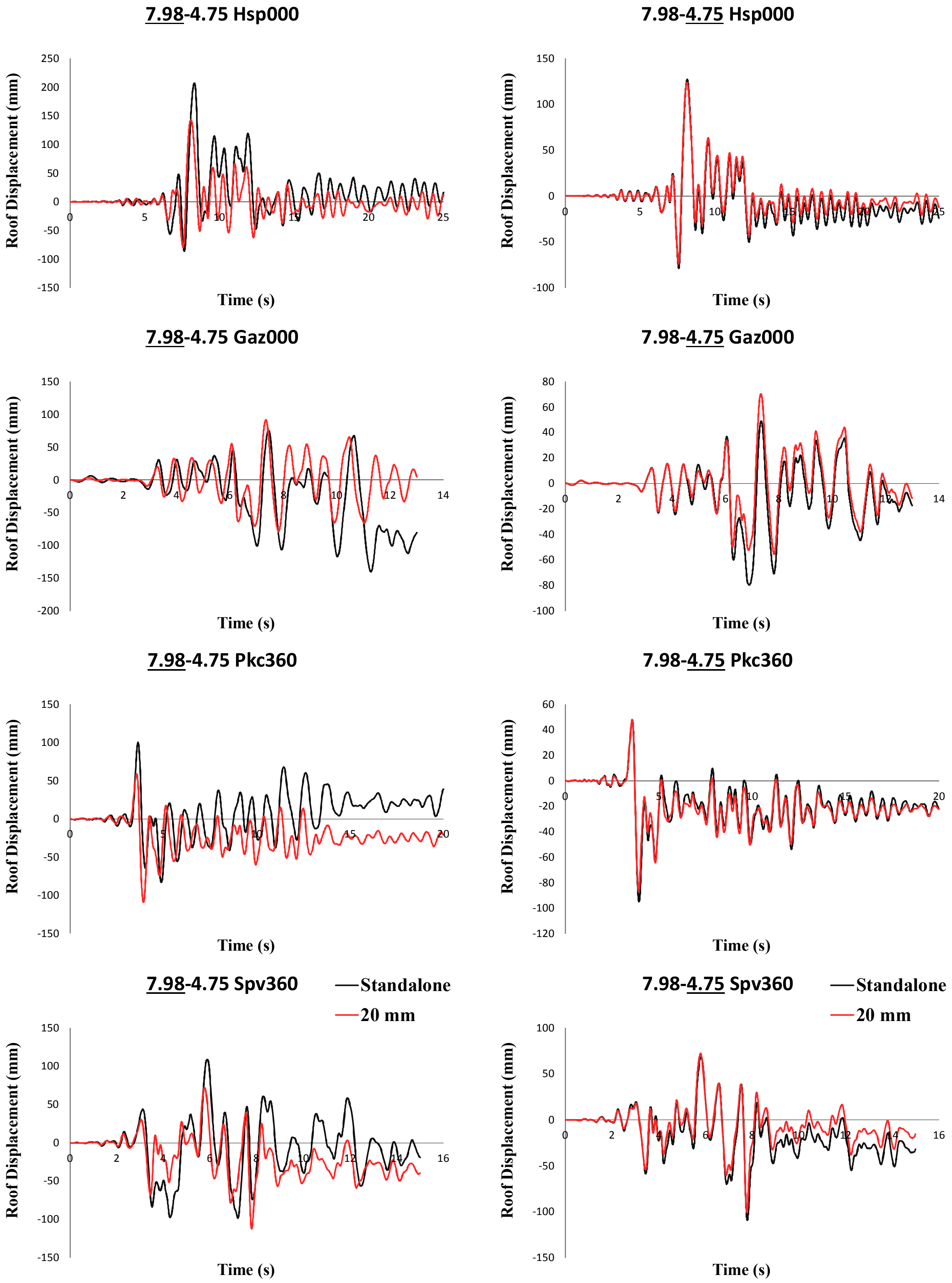


Figure 6. Comparison of roof displacements of 1998 TEC 7-story (on left column) and 1975 TEC 4-story (on right column) buildings with that of reference (standalone) buildings

The outcomes and observations of the current study demonstrate the complexity of pounding behaviour of structures. It seems that the proper seismic performance evaluation of adjacent buildings is not possible without consideration of pounding interaction. Modern earthquake codes imply safety space to avoid collision based on static analysis. Moreover, calculations are depended with number of story or total height of structures which do not reflect seismic behaviour of structures for most cases. The authors underline that observation of pounding interaction of adjacent buildings is only possible with nonlinear time history analysis with 3D models.

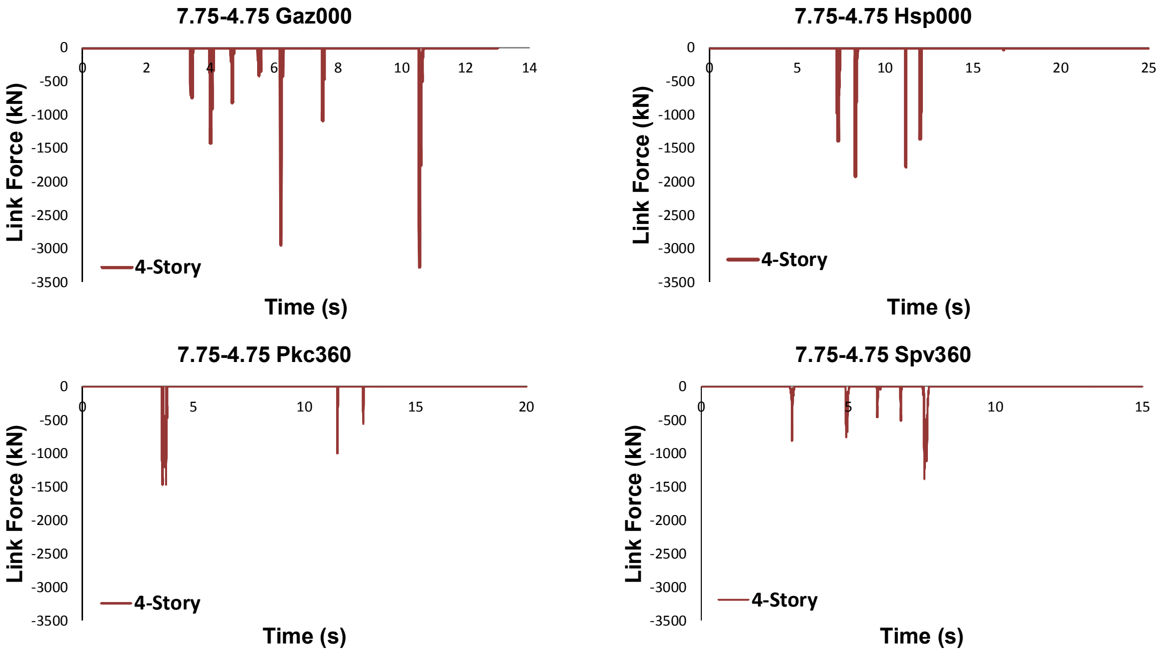


Figure 7. Total pounding force of the first set buildings (7- and 4-story buildings per 1975 code) at critical floor

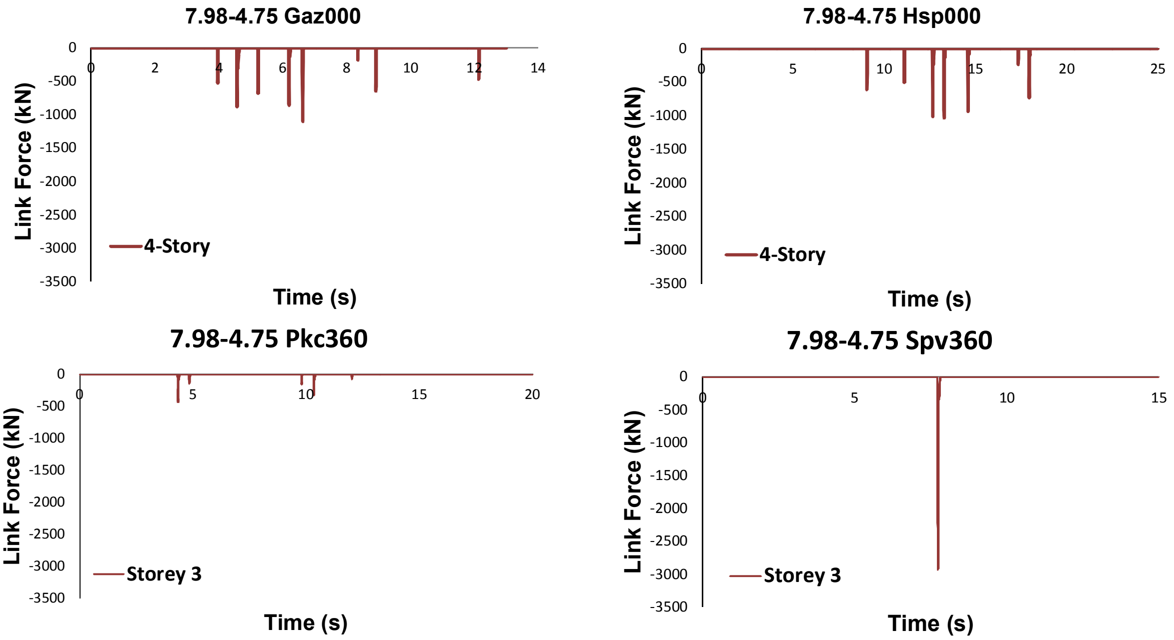


Figure 8. Total pounding force of the second set buildings (7-story per 1998 code and 4-story buildings per 1975 code) at critical floor

Table 2. Analysis Results for 7.75-4.75 pounding model and standalone cases

Model			Gaz000	Hsp000	Pkc360	Spv360
7.75	**Roof Displacement (mm)**	Collision Direction	192.4	81.6	102.1	101.1
		Free Direction	97.2	139.8	104.6	100.4
7.75 Standalone		Collision Direction	207.0	75.3	100.4	109.1
		Free Direction	84.6	140.1	82.8	98.1
4.75		Collision Direction	50.7	58.8	33.9	72.8
		Free Direction	157.7	62.8	63.9	82.1
4.75 Standalone		Collision Direction	78.7	79.6	94.9	109.1
		Free Direction	127.1	48.9	47.8	68.2
7.75-4.75	**Link Force (kN)**		3273	1920	1469	1381
	Number of Collision		7	4	3	5

Table 3. Analysis Results for 7.98-4.75 pounding model and standalone cases

Model			Gaz000	Hsp000	Pkc360	Spv360
7.98	**Roof Displacement (mm)**	Collision Direction	142.0	91.5	59.0	72.1
		Free Direction	79.3	78.7	109.1	112.1
7.98 Standalone		Collision Direction	207.0	75.3	100.4	109.1
		Free Direction	86.4	140.1	82.8	98.1
4.75		Collision Direction	73.8	55.4	86.4	100.8
		Free Direction	123.4	70.3	48.3	72.1
4.75 Standalone		Collision Direction	78.7	79.6	94.9	109.1
		Free Direction	127.1	48.9	47.8	68.2
7.98-4.75	**Link Force (kN)**		1102	1035	432	2928
	Number of Collision		8	7	5	1

CONCLUSIONS

The effect of pounding interaction on seismic behaviour of inadequately separated mid-rise buildings is investigated in this paper. The selected buildings have reinforced concrete frame systems without shear walls. Nonlinear response history analyses are conducted using SAP2000. Beam and column elements are modelled as nonlinear frame elements with lumped plasticity by defining plastic hinges at both ends of beams and columns.

Three buildings models are used to reflect two different combinations of pounding; 4-and 7-story buildings designed per 1975 Turkish Earthquake Code (TEC) and 7-story building designed per 1998 TEC. The first set is arranged as 4- and 7-story buildings designed using 1975 code (7.75-4.75) while the second set uses 7-story for 1998 code and 4-story of 1975 code (7.98-4.75). In both sets, 20 mm gap space is considered between the adjacent buildings. Columns are connected by link members at floor levels. The adjacent building sets and the standalone buildings are subjected to four different strong ground motion records.

The roof displacement demands for the adjacent and standalone cases are obtained and compared. To understand the magnitude of collision, total link forces and number of collisions are also determined. Based on evaluation of roof displacement demands, total link force and number of collisions for different sets and ground motions using nonlinear time history analyses results, the following observations are made:

- The outcomes show that whereas pounding interaction may limit the maximum roof displacement at collision direction, it increases displacement demands at the free direction. This behaviour is directly related with the properties of structures and dynamic characteristics of ground motions.
- The effect of pounding is more severe on the 1975 4-story building compared to the 1975 7-story building for the first set. While the maximum roof displacement increases 26.6% on average for 4-story building due to pounding at free direction, the average increase in displacement demands of the7-story buildings is only 10.8%. At collision direction, maximum displacement demands decreases 39.8% and 1% for the 4- and 7-story buildings, respectively.
- The effect of pounding is relatively limited on the second set (7.98-4.75). The maximum roof displacement increases 11.9% on average for the 4-story building per 1975 code due to pounding at free direction while the average increase in displacement demands of the 7-story building per 1998 code is only 6.9%. At collision direction, maximum displacement demands decreases 13.3% and 21.3% for the 4- and 7-story building, respectively.
- The comparison of displacement demands for the first and second sets indicates that the effect of pounding is more apparent on the 7.75-4.75 building combination than the 7.98-4.75 set. This is the result of stronger 7-story building constructed per 1998 TEC. The comparison of 7-story buildings constructed per 1975 and 1998 codes clearly shows more rigid, more lateral load carrying capacity of the building per 1998 code. Thus, lateral displacements and magnitude of collision for the 7.98-4.75 building combination are limited compared to the 7.75-4.75 building combination.
- It’s hard to say that the limitation on maximum displacement demand at collision direction due the pounding interaction makes positive contribution on seismic performance of the adjacent buildings. It is also possible that the collision force has potential to damage most of structural or non-structural elements although it limits horizontal displacement at one direction.
- Although the permanent displacement and collapse mechanism are prevented by the adjacent building, structures have heavy damage potential under seismic demands at free direction. Indeed the observations emphasize that collapse or damage mechanism of adjacent buildings extensively occurs at free direction.
- The link forces give information about magnitude and number of collision during strong motions. Observations show that collision at column members at floor level do not occur simultaneously which is the clue of torsion behaviour that depended by pounding and characteristics of ground motions. It should be also noted that the models used in the analysis do not have any static irregularities.
- Although there is no specific evident between number of collision and magnitude of pounding force, total force of link members decreases for the second building set (7.98-4.75) compatible with limited number of collisions.
- The outcomes and observations of the current study demonstrate the complexity of pounding behaviour of structures. It seems that the proper seismic performance evaluation of adjacent buildings is not possible without consideration of pounding interaction.

- Modern earthquake codes imply safety space to avoid collision based on static analysis. Moreover calculations are depended with number of storey or total height of structures which do not reflect seismic behaviour of structures for most cases. The authors underline that observation of pounding interaction of adjacent buildings is only possible with nonlinear time history analysis with 3D models.
- Pounding interaction should be taken into account to evaluate seismic performance of existing adjacent buildings. Otherwise, increase on displacement demands due to pounding and collapse mechanism at free direction is not taken into consideration.

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