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Analysis of seismic mid-column pounding between low rise buildings with unequal heights

Shan Jiang[*1], Changhai Zhai[2a], Chunwei Zhang[1a] and Ning Ning[1b]

[1]*School of Civil Engineering, Qingdao University of Technology, Qingdao 266033, P.R. China*
[2]*School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, P.R. China*

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Abstract. Floor location of adjacent buildings may be different in terms of height elevation, and thus, the slab may hit on the columns of adjacent insufficiently separated buildings during severe ground motions. Such impacts, often referred to as mid-column pounding, can be catastrophic. Substantial pounding damage or even total collapse of structures was often observed in large amount of adjacent low rise buildings. The research on the mid-column pounding between low rise buildings is in urgency need. In present study, the responses of two adjacent low rise buildings with unequal heights and different dynamic properties have been analyzed. Parametric studies have also been conducted to assess the influence of story height difference, gap distance and input direction of ground motion on the effect of structural pounding response. Another emphasis of this study is to analyze the near-fault effect, which is important for the structures located in the near-fault area. The analysis results show that collisions exhibit significant influence on the local shear force response of the column suffering impact. Because of asymmetric configuration of systems, the structural seismic behavior is distinct by varying the incident directions of the ground motions. Results also show that near-fault earthquakes induced ground motions can cause more significant effect on the pounding responses.

Keywords: earthquake; low rise buildings; mid-column pounding; non-linear response; parametric analysis

1. Introduction

During severe ground motions, inadequately separated buildings or bridges have been repeatedly observed to collide with each other. Investigation shows that pounding between adjacent structures or parts of the same structure may results in substantial damage or even total collapse of structures (Jeng 2000, Hao 2015, Ning 2016). Structural pounding between adjacent, insufficiently separated buildings has been repeatedly observed during recent strong earthquakes (Anagnostopoulos 1995). Evidence of pounding was found in over 15% of the 330 collapsed or severely damaged structures in the Mexico City earthquake of 1985 (Rosenblueth and Meli 1986). During the 1989 Loma Prieta earthquake, over 200 pounding occurrences involving more than 500 buildings were observed (Kasai and Masion 1990).

Pounding damage was often observed in large amount of adjacent low rise buildings in 2008 Wenchuan earthquake (Wang 2008) and 2011 Christchurch earthquake (Cole *et al.* 2012), as shown in Figs. 1(a)-(b). The photograph in Fig. 1(c) shows a pounding incidence between two adjacent buildings in the 2009 L'Aquila earthquake (EERI 2009). During that seismic event, the roof of a two-story building hit an adjacent four-story structure causing considerable damage to the columns of the latter at that level. The third and the fourth stories of the building did not experience significant damage.

(a) Wenchuan Earthquake (b) Christchurch Earthquake (c) L'Aquila Earthquake

Fig. 1 Damage of the low rise buildings due to pounding during strong earthquakes

At the present time, most researches intend to study the earthquake-induced pounding between buildings with equal height, and consequently pounding takes place between the floor masses of the colliding structures. Many analytical works on the pounding of single-degree-of-freedom (SDOF) structural system have been reported since 1980s (Anagnostopoulos 1988, Jing and Young 1991, Hao *et al.* 2000, Jankowski 2005, Ye *et al.* 2009, Zhai *et al.* 2015a, Yang and Xie 2011). Davis (1992) studied on the response of a linear SDOF oscillator with one-sided contact to the rigid barrier. Chau and Wei (2001) studied the colliding

∗Corresponding author, Ph.D.
E-mail: jiangshan@qut.edu.cn
[a]Professor
[b]Associate Professor

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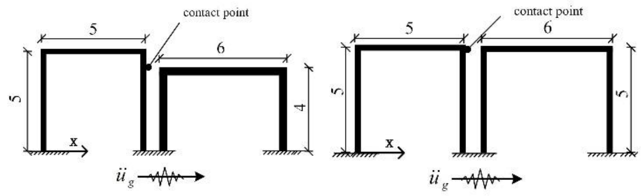
response of two elastic and inelastic SDOF oscillators. Muthukumar and DesRoches (2006) investigated the efficacy of various impact models for capturing the seismic pounding response of adjacent SDOF system. Then the multi-degree-of-freedom (MDOF) model is used to analyze seismic pounding of structures in more details (Filiatrault *et al.* 1994, Cole *et al.* 2011, Efaimiadou *et al.* 2013a, Jankowski 2009, Hao and Gong 2005, Gong and Hao 2005, Bi and Hao 2013, Polycarpou *et al.* 2014, Ghandil and Aldaikh 2017, Bi *et al.* 2013, 2017). Maison and Kasai (1992) studied the response of a high-rise building colliding against a massive low structure. Anagnostopoulos and Spiliopoulos (1992) used lumped mass models of 5-story and 10-story buildings to conduct the parametric study on pounding-involved structural behavior. Jankowski (2008) studied three-dimensional non-linear pounding response analysis of structures with equal height. Zhai *et al.* (2015b) investigated the structural response of MDOF pounding system based on dimensional analysis method.

However, floor locations of adjacent buildings may be different in terms of height elevation and sometime dominant mass may be allocated at different levels. In this case, the floors of one building will collide into the columns of adjacent buildings under strong ground motions. This phenomenon, often referred to as mid-column pounding. Such impacts can be catastrophic as it has been noted by Anagnostopoulos (1996). The current seismic codes (including Eurocode 8 2004) also recognize the case of mid-column pounding as the most crucial case for the integrity of the structural stability. The critical damage caused by mid-column pounding has been confirmed in past seismic damage investigation. However, compared to study of pounding between equal story heights structures, limited research has been focused on the mid-column pounding between adjacent buildings. Karayannis and Favvata (2005) studied the influence of the structural pounding on the ductility requirements of adjacent multi-story reinforced concrete buildings with unequal height, and Favvata (2017) evaluated the minimum required gap distances between the adjacent RC structures that suffer the inter-story pounding. Shakya and Wijeyewickrema (2009) analyzed the mid-column seismic pounding of reinforced concrete buildings in a row considering effects of soil. The influence of near-fault earthquake on the pounding response was also considered, but only two near-fault and two far-fault ground motions were used and the quantifiable results were not given in detail. Efraimiadou *et al.* (2013b) examined the effect of different structures configurations, including mid-column pounding configuration, on the collision between adjacent planar RC building frames subjected to strong earthquakes.

To the present, study on mechanism of structural mid-column pounding is quite insufficient, and the research is mainly on the mid-column pounding between high rise buildings. However, pounding damage between the low rise one-story or two-story buildings has been largely observed in the past earthquakes. It is a pressing need to investigate the mid-column pounding response between low rise buildings. The influences of difference in inter-story height, gap distance and input direction of ground motion on the effect of mid-column pounding between low rise buildings



(a) Mid-column pounding (b) Pounding at floor level

Fig. 2 Pounding between adjacent buildings with equal and unequal heights

have not been discussed. The near-fault effect should be studied in depth with more near-fault and far-fault ground motions, which is more statistically significant.

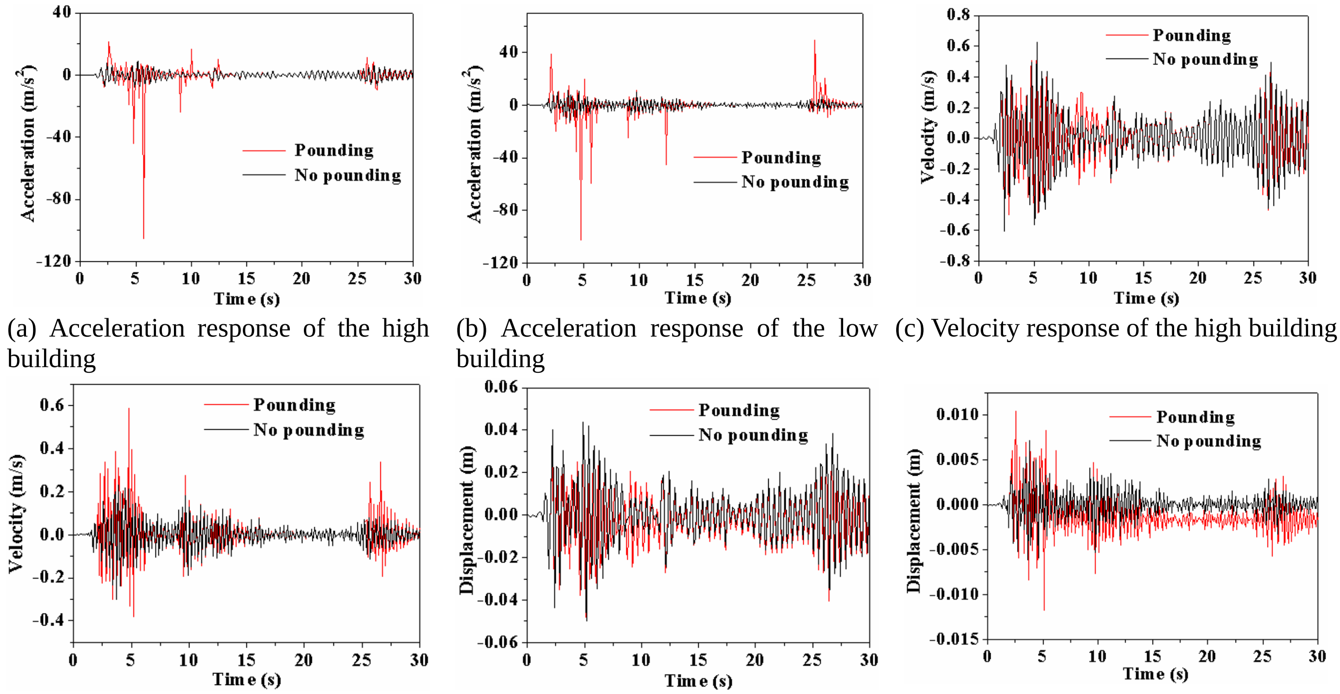
The aim of the present study is to conduct a detailed investigation on mid-column pounding responses of two adjacent low rise buildings with unequal height and different dynamic properties. The pounding behavior of adjacent structural models under El Centro earthquake is considered in detail, and parametric studies have also been conducted to assess the influence of difference in story height, gap distance, and input direction of ground motions. In addition, 10 near-fault ground motions and 10 far-fault ground motions of Chi-Chi earthquake have been selected to investigate the influence of near-fault effect on the structural pounding responses. On the other hand, the configuration and dynamic properties of system are not symmetric, the structural seismic behavior may be different when the input direction of ground motion changes. Thus, the input direction of ground motion is also analyzed.

2. Response analysis

2.1 Numerical model and ground motions

The numerical simulation of pounding-involved responses has been conducted for two adjacent structures with different height. Fig. 2(a) shows the physical model for pounding buildings with unequal height subjected to horizontal ground motion. The colliding building is simulated by a single-frame model. According to damage data, the collisions between adjacent low rise buildings ordinarily occur at the highest contact point, at the level of the lower building’s roof. Thus, only collisions between the top floor of low building and high building’s columns are considered in this study. The responses of the contact point on column and the responses of the top level of both buildings are the research emphasis in this study.

The height of the building is 5 m and 4m respectively, which give rise to mid-column pounding. Cross section size of columns is 0.4 m×0.4 m for the high building and 0.45 m×0.45 m for the low building, and beam section size is respectively 0.4 m×0.2 m and 0.5 m×0.25 m. The gap size between two adjacent buildings is assumed to be 0.05 m. The frequencies of the higher building and shorter building are 2.3 Hz and 4.1 Hz respectively. The corresponding frequency ratio of the buildings is 0.56. The FE models of the two buildings are developed by using the finite element code LS-DYNA. Convergence test shows that a size of 0.15



(a) Acceleration response of the high building

(b) Acceleration response of the low building

(c) Velocity response of the high building

(d) Velocity response of the low building

(e) Displacement response of the high building

(f) Displacement response of the low building

Fig. 3 Comparison of pounding-involved and independent vibration acceleration, velocity and displacement response of two buildings

m for all the building components can yield a good balance between the computational effort and accuracy, the mesh size of 0.15 m is therefore adopted in the numerical models. The Solid164 element is used to simulate all the components of the two buildings. It is assumed that reinforcement uniformly distributed over concrete element. Thus, *MAT PSEUDO TENSOR (MAT_16) in LS-DYNA is used to model the smeared RC material. The advantage of this material model is that it can model the complex behavior of concrete by specifying the unconfined compressive strength only when no detailed concrete material experiment data is available. In the present study, the unconfined compressive strength of the concrete is 30MPa. This model can significantly reduce the computational effort compared to modelling the concrete and reinforcement separately. In order to consider the load of adjacent floor, the Mass element is applied. Four masses are distributed uniformly along the beam for each model. The value of mass for the left model is $4\times1.5\times10^3$ kg. The value of mass for the right model is $4\times1\times10^4$ kg.

The commercial software LS-Dyna has a few contact algorithms to simulate the impact problems, such as the kinematic constraint method, the penalty method, and the distributed parameter method (LS-Dyna 2012). Discussion of merits and demerits of these three methods was presented in the study by Dogan *et al.* (2012). Among these contact algorithms, the penalty method employed via the contact_automatic_surface_to_surface keyword becomes popular. In this study, the penalty method approach is adopted to model the contact interfaces between meshes because of its effectiveness and simplicity for explicit analysis. With this method slave nodes penetration is restricted via the imaginary normal interface springs between the shooting nodes and contact surface. The contact algorithm of *CONTACT AUTOMATIC SURFACE TO SURFACE in LS-DYNA is employed to model the potential 3D arbitrary poundings between adjacent buildings. The static and dynamic Coulomb friction coefficients are set to be 0.5 in this study (Jankowski 2009).

In this section, the El Centro ground motion of May 19, 1940 is used as the input and to analyze the pounding response, and the input direction of ground motion is in normal direction of axis x (Fig. 2(a)). The peak acceleration of ground motion is scaled to 400 cm/s^2.

Under the ground motion excitation, the slab of the low building will hit the column of the high building. In this work, the responses of acceleration, velocity, displacement and impact force are analyzed for the pounding point of adjacent buildings. Local shear force impact is also investigated on the column of the high building which suffered from pounding.

2.2 Acceleration, velocity and displacement responses

Comparison is shown in Fig. 3 for pounding-involved and independent vibration (no pounding) acceleration, velocity and displacement responses of two adjacent structures. From Fig. 3, it can be seen that pounding has significant effect on the seismic responses of adjacent buildings. The acceleration responses are all amplified result from pounding of structures (Figs. 3(a)-(b)), and large acceleration pulses can be observed. According to the results, the maximum acceleration responses of the high and the low structures in the pounding case are respectively about 12.24 and 7.78 times as large as that in the no pounding case. The response amplification effect of the high building is more obvious than the low one.

As shown in Figs. 3(c)-(f), both velocity response and displacement response of the higher structure (more flexible building) are suppressed as the result of earthquake-induced pounding between structures, while the responses of the low structure (the stiffer building) are greatly amplified. The peak velocity and displacement response is respectively about 1.97 and 1.71 times compared with that of no-pounding case for the low building. The pounding-induced influence to the velocity and displacement responses of the low building is more significant than the higher one.

2.3 Shear force response

It is significant to study the local effect on the column of the high building that suffers impact due to the adjacent low structure in the mid-column pounding case. In this work, special attention has been given to the shear force response of the high building column. Fig. 4 presents the comparison between pounding-involved and independent vibrational shear force response. Larger shear pulses can be observed in the pounding case compared to the no pounding case. The maximum peak shear force of pounding case is 536.8 kN; about 1.86 times as large as the value in the case when there is no pounding.

3. Parametric Investigation

In this section, a parametric study is presented to investigate the effects of system properties and ground motion characteristics on the pounding responses. The El Centro ground motion of May 19, 1940 is used to study the influence of story height, gap distance and input direction of ground motion. In addition, 10 near-fault ground motions and 10 far-fault ground motions of Chi-Chi earthquake are selected to investigate the influence of near-fault effect on the structural pounding responses.

3.1 Effect of buildings' heights

Mid-column pounding occurs when the floors of adjacent buildings are at different levels, thus, the story height of adjacent buildings is one of the critical parameters in the mid-column pounding responses. Three case configurations of adjacent buildings (as shown in Fig. 5) are studied: (1) 5 m and 4 m; (2) 6 m and 4 m; (3) 8 m and 6 m. The gap size value is 0.02 m. Fig. 6 gives the peak values of acceleration, velocity and displacement responses in the three configurations. The pounding force responses in three configurations are 74.3, 197.4, 233 kN respectively. Results indicate that the story height of building has significant effect on the pounding-induced responses of adjacent structures. The peak acceleration of the high building and the pounding force in configuration 2 is respectively 4.26 and 2.66 times larger compared with that of configuration 1, which indicated that larger height difference of adjacent buildings will cause larger local responses. It can also be observed that the responses in configuration 3 are larger than the response in configuration 2, especially for the low building. It can be seen that, in this case, structural responses are more intense when the buildings are higher but with the same height difference of two buildings.

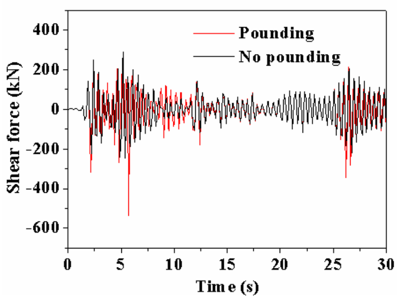
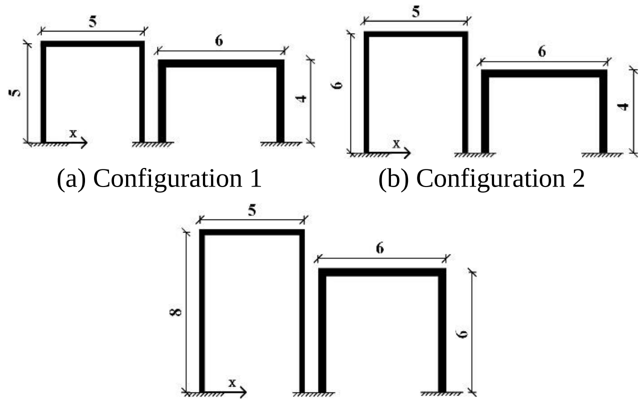


Fig. 4 Time history of shear force response on contact point in pounding-involved and independent vibration cases



(a) Configuration 1 (b) Configuration 2

(c) Configuration 3

Fig. 5 Three configuration models of colliding buildings (unit: m)

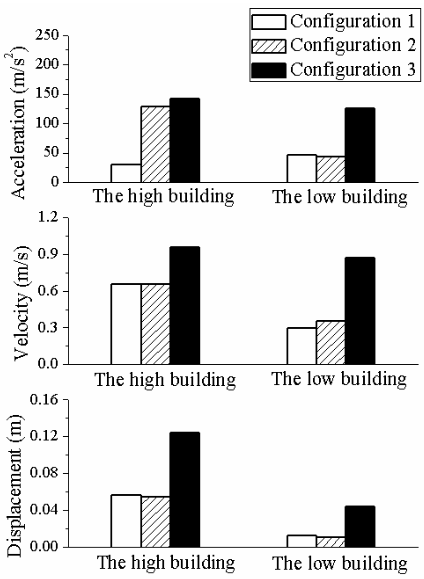


Fig. 6 Peak responses of acceleration, velocity, displacement for the configuration 1, 2 and 3

Table 1 Peak responses induced by pounding for equal and unequal height cases

Structure configuration	Acceleration (m/s^2)	Velocity (m/s)	Displacement (m)
Equal heights	20.60	0.516	0.020
Unequal heights	30.27	0.655	0.056
unequal heights / equal heights	1.47	1.27	2.8

In order to investigate the critical damage to the column suffered by mid-column hitting, pounding for the adjacent buildings with equal heights is also studied. Structural configurations of equal and unequal height are shown in Fig. 2. Table 1 presents the peak responses of the left building. Results indicate that pounding-induced acceleration, velocity and displacement responses in unequal case are obviously more significant than that in equal case. Columns, suffered from collision can cause larger responses when pounding happens between slabs and columns.

3.2 Effect of separation distance

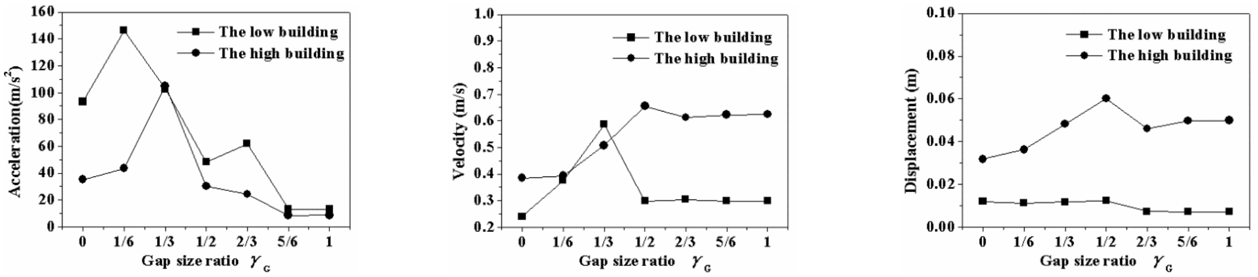
A parametric study is undertaken to examine the pounding-induced responses in a range of gap size values. The physical model for pounding buildings is shown in Fig. 2(a). The separation distance (g_p) is expressed in terms of a gap ratio parameter γ_G, as given in equation $\gamma_G=g_p/\Delta_{max}$, where Δ_{max} is the critical gap which is just sufficient to avoid pounding.

Fig. 7 shows the peak responses of acceleration, velocity, displacement, shear force of critical column and pounding force of colliding structures for different values of gap ratio γ_G. From Figs. 7(a)-(c), it can be seen that the peak acceleration, velocity and displacement responses of the high building happened when the gap ratio is γ_G=1/3, 1/2 and 1/2 respectively, and the peak responses of the low building can be observed when the gap ratio is 1/6, 1/3 and 1/2 respectively. From Figs. 7(d) and (e), it can also be observed that the maximum shear force of the critical column occurred when γ_G=1/3, and the maximum pounding force occurred when γ_G=1/6. It can be concluded that the maximum peak responses happened in a certain range of gap size but not in the case that no gap size exists (γ_G=0). The critical range associated with the largest structural response is related to the dynamic properties of colliding buildings and characteristics of the earthquake excitation.

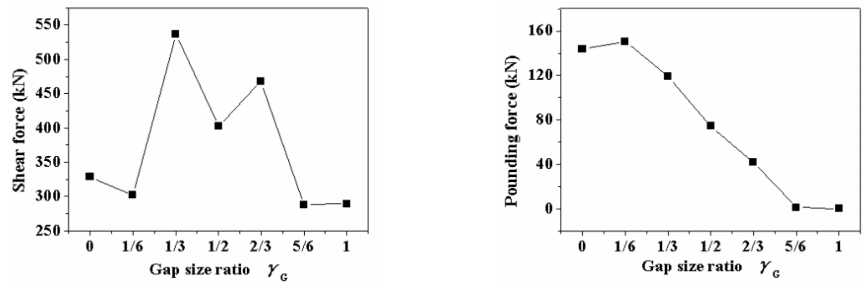
It should be noted that larger structural responses happen when $1/6\leq\gamma_G\leq1/2$, and the acceleration response is more sensitive to the gap size value than the other response quantities mentioned in this study. After the maximum responses, the acceleration responses sharply decrease. However, responses of velocity and displacement are almost unaffected by the increase of gap size i.e., $\gamma_G\geq2/3$. Results also illustrate that, an increase in the gap size is associated with a decrease in the pounding force response.

3.3 Effect of ground motion's input direction

It is a common case that the configuration and dynamic properties are not symmetric for adjacent buildings. Hence, the pounding response may be different when the input direction of ground motions is of normal or reverse direction, as shown in Fig. 8. Structural responses induced by pounding are compared for the two input direction of ground motion. The analysis results are presented in Fig. 9. It can be seen that the values of structural responses are much different when the input direction of ground motion is changed. For the high building, the acceleration response can obtained to 69.29 m/s^2 in case of reverse direction, which is 2.29 times as large as the value in the case of normal direction. However, the velocity response for reverse direction is smaller than the value for normal

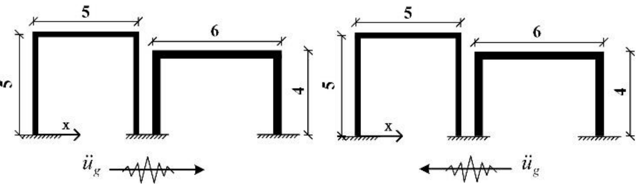


(a) Acceleration response (b) Velocity response (c) Displacement response



(d) Shear force (e) Pounding force

Fig. 7 Pounding responses of structures for different gap size ratio



(a) Normal direction (x) (b) Reverse direction (-x)

Fig. 8 Models of colliding buildings with different input direction of ground motion (unit: m)

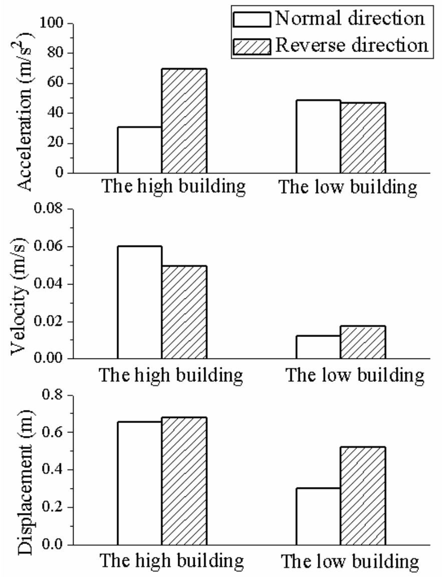


Fig. 9 Pounding-induced peak responses for different incident directions of ground motion

Table 2 Properties of selected near-fault ground motion records

Station number	Distance to the fault (km)	PGA (cm/s^2)	PGV (cm/s)	PGV/PGA
TCU036	16.69	136.22	59.6	0.438
TCU040	21	120.54	50.3	0.417
TCU050	10.33	144.06	36.9	0.256
TCU056	11.11	131.32	42.5	0.324
TCU061	17.75	138.18	40.3	0.292
TCU064	15.07	104.86	39.2	0.374
TCU087	3.18	125.44	40.8	0.325
TCU103	4.01	131.32	61.9	0.471
TCU116	11.86	145.04	45.3	0.312
TCU128	9.7	136.22	73	0.536

Table 3 Properties of selected far-fault ground motion records

Station number	Distance to the fault (km)	PGA (cm/s^2)	PGV (cm/s)	PGV/PGA
CHY004	50.89	98	15.8	0.161
CHY054	53.83	92.12	17.9	0.194
HWA002	53.85	92.12	11.9	0.129
HWA005	43.86	136.22	16.6	0.122
HWA015	54.86	102.9	15.5	0.151
HWA016	54.73	99.96	13.3	0.133
HWA017	53.91	82.32	9.4	0.114
HWA027	56.82	89.18	13.8	0.155
HWA031	50.36	98.98	14.1	0.142
HWA033	48.99	163.66	17.0	0.104

direction. For the low building, the velocity and displacement responses in case of reverse direction are more intense and the values are respectively 1.4 and 1.75 times to the values of normal direction case. The pounding force and shear force on contact point can be observed more intense in the case of reverse direction. The value of pounding force in reverse direction is 137.5 kN, which is 1.85 times compared with that in the case of normal direction. It can be concluded that the input direction of ground motion has significant effect on the pounding responses of the adjacent buildings. The unfavourable input direction of ground motions should be considered for the design practice.

3.4 Effect of near-fault pulse-like ground motion

Near-fault ground motions with pulses have larger damage potential than the far-fault ground motions from the past study. Most of the energy in near-fault ground motions is concentrated in a narrow frequency band and is seen as a distinct, high intensity velocity pulse, which will result in high seismic demands for buildings.

For this analysis, ten near-fault pulse-like records and ten far-fault records from the 1999 Chi-Chi Taiwan earthquake (M_w=7.6) are used to study the effect of near-fault ground motions on the pounding responses. The characteristics of the ground motion records are depicted in Tables 2-3. It can be found that the near-fault records have larger PGA/PGV ratios compared with the far-fault ground motions. The peak ground accelerations of selected records are all scaled to 400 cm/s^2 in this work. The physical model for pounding buildings is shown in Fig. 2(a), and gap size is assumed to be 0.02 m.

The objective is to study the differences in the pounding-induced responses subjected to the near-fault and far-fault ground motions. The peak values of acceleration, velocity, displacement, shear force and pounding force responses of both near-fault and far-fault motions are summarized in Tables 4-5. The mean values of peak structural responses are also compared, as shown in Fig. 10. Results indicate that the mean values of peak structural responses from the near-fault records are all relatively larger compared to the responses obtained from far-fault records. The mean acceleration responses of the high and low buildings caused by near-fault motions are respectively 1.93 and 1.49 times larger than the responses caused by far-fault motions. The mean pounding force from near-fault motions is about 1.74 times larger than the force obtained from far-fault motions. This trend is also obvious for the velocity and displacement responses of the low building, the mean values caused by near-fault motions are separately 1.21 and 1.26 times of the values caused by far-fault motions. The results show that near-fault earthquake ground motions can cause more significant effect on the pounding

Table 4 Peak responses of the high building by near-fault ground motion records

Station name	Acceleration (m/s^2)	Velocity (m/s)	Displacement (m)	Shear force on contact point (kN)	Pounding force (kN)
TCU036	96.26	0.528	0.0470	419.97	141.92
TCU040	93.59	0.531	0.0400	493.75	156.55
TCU050	48.33	0.457	0.0384	487.89	201.28
TCU056	56.16	0.796	0.0522	685.29	279.74
TCU061	53.89	0.659	0.0543	481.41	176.91
TCU064	65.46	0.529	0.0420	419.21	151.96
TCU087	51.1	0.569	0.0481	427.78	164.45
TCU103	53.2	0.531	0.0411	489.77	155.51
TCU116	292.32	0.514	0.0522	388.74	251.05
TCU128	135.77	0.629	0.0385	558.65	138.59
Mean values	94.61	0.574	0.0454	485.25	181.80

Table 5 Peak responses of the high building by far-fault ground motion records

Station name	Acceleration (m/s^2)	Velocity (m/s)	Displacement (m)	Shear force on contact point (kN)	Pounding force (kN)
CHY004	39.87	0.522	0.0412	392.38	73.41
CHY054	52.86	0.622	0.046	614.19	117.19
HWA002	12.17	0.404	0.0298	294.06	89.53
HWA005	47.13	0.383	0.035	387.40	179.94
HWA015	50.45	0.397	0.0325	236.21	52.34
HWA016	35.59	0.466	0.0349	333.87	61.53
HWA017	49.16	0.44	0.0406	551.41	100.33
HWA027	57.74	0.495	0.043	247.43	117.26
HWA031	56.53	0.676	0.0517	642.78	113.80
HWA033	88.47	0.690	0.0520	572.22	137.73
Mean values	48.99	0.510	0.0407	427.20	104.31

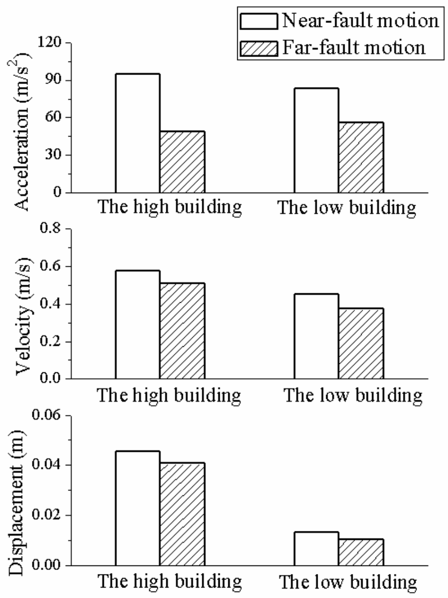


Fig. 10 Peak responses of acceleration, velocity and displacement for near-fault and far-fault ground motions

responses than far-fault earthquake ground motions. The near-fault pulse-like ground earthquake may cause relatively severe responses in a structure and result in much more damage.

4. Conclusions

In this paper, comprehensive analysis has been conducted on mid-column pounding responses of two adjacent low rise buildings with unequal heights subject to strong earthquake excitations. In mid-column pounding case, columns may suffer collisions which can cause more intense or severe responses compared to pounding that occurs at structural floor level, i.e., only between slabs of adjacent structures. Pounding-involved responses are investigated and compared to the case of independent vibrations. The results of the parametric investigation carried out for different values of structural parameters have been presented. The influence of ground motion characteristics on the pounding responses is also investigated. The effect of near-fault ground motion on the pounding responses is analyzed which involves ten near-fault and ten far-fault ground motion records to be considered.

- The shear force response on the contact point of column is amplified due to the pounding effect, which resulted in significant enlarged shear pulses. Similar phenomena can also be observed in the acceleration response.
- Stand-off distance is found to be a critical parameter. The maximum pounding-induced responses occurred in a certain range of gap or stand-off size but not in the case that no gap size exists between structures.
- Near-fault earthquake ground motions can cause significant effect on the pounding responses and result in severe damages. Changing the ground motion incident directions can also produce significant differences in structural responses. For the design practice, the unfavorable incident direction of ground motions should be considered. In situations where pounding may potentially occur, neglecting its possible effects may lead to less conservative building evaluation.

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