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*Technical Note*

# HEAVIER ADJACENT BUILDING POUNDING DUE TO EARTHQUAKE EXCITATION

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## ABSTRACT

Pounding between adjacent buildings is a detrimental issue for buildings in cities because they are closely located while vibrating out of phase due to different dynamic properties (mainly different mass and/or height) during earthquake excitation. This paper presents a numerical study on the pounding between the adjacent buildings with different masses during earthquake excitation. The buildings modeled via lumped mass procedure are connected by linear vico-elastic contact force model during pounding. Seismic responses of the buildings due to earthquake acceleration are obtained for different building configurations and the results are discussed and compared. Pounding effect is amplified for the lighter building while pounding effect is negligible for the heavier building.

**Keywords:** Heavier adjacent building; building pounding; seismic response; earthquake excitation

## 1. INTRODUCTION

Adjacent buildings with narrow separation gap pound together during earthquake excitation if they vibrate out of phase due to different dynamic properties. For instance damages of the buildings because of pounding during 1985 Mexico City and 1989 Loma Prieta earthquakes were reported by Rosenblueth and Meli [1] and Kasai and Maison [2], respectively. Even in recent earthquakes, despite great improvements in building codes, there are several reports of building damage due to pounding [3-5].

Jeng and Tzeng [6] categorized pounding of the adjacent buildings into five major types:

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i. heavier adjacent building pounding, ii. taller adjacent building pounding, iii. mid-column building pounding, iv. eccentric building pounding, and v. end/corner building pounding. Different dynamic properties of the adjacent buildings are implicitly derived from the name of first two pounding types. When the adjacent buildings possess different masses or heights, their period become different, so they vibrate out of phase; and thus, they pound together if they are closely located.

Building pounding has been subject of many researches since past couple of decades. Generally, researchers are interested in modeling of the adjacent buildings numerically in order to evaluate their seismic responses. Effects of mass distribution on pounding structures [7], pounding of seismically isolated buildings [8-9], eccentric building pounding [10-11], mid-column building pounding [12-13] and corner building pounding [14] are some examples. However, evaluations of the seismic responses of the adjacent buildings with different relative story masses are limited.

One of the primary numerical investigations on the building pounding was carried out by Anagnostopoulos [15]. A row of one story adjacent buildings were simulated by idealized mass damping and spring system. Anagnostopoulos and Spiliopoulos [16] extended the previous study by adding the system of multistory buildings (MDF). The most significant result of these studies was that the end building pounding found to be very serious because the end building suffered from one sided pounding rather than two sided pounding. A secondary conclusion of the latter study was that the effects of pounding on the end buildings became negligible when the mass of the building in the middle were reduced by a factor of 5, while increment of the mass of the middle building by a factor of 5 resulted in approximately 60% higher response amplification for the end building [16].

Pounding of the University of California Medical Center building to its adjacent rigid building was investigated by Maison and Kasai [17]. Maison and Kasai extended their work and considered both adjacent buildings with flexible behavior [18]. Through a parametric study of pounding of two flexible adjacent buildings, they found pounding induced drifts, story shears and overturning moments in the stories above the potential pounding location as critical factors which must take into consideration in order to have safe design of taller building. Considering different relative story mass ratios, they concluded while building responses were increased due to pounding, higher relative story masses amplified pounding effects.

A more recent study was performed by Jankowski [19] to investigate pounding-involved response of two equal heights adjacent buildings with substantially different dynamic properties. Greater mass caused dynamic phase difference between the adjacent buildings which raised the risk of building pounding. Lighter building experienced substantial amplification of the response and even permanent deformation due to yielding while heavier building was nearly unaffected due to pounding.

Despite worthy contributions in the building pounding problem, the type of heavier adjacent building pounding demands more attention since few studied cases did not cover the area. The parametric studies by Anagnostopoulos and Spiliopoulos [16] and Maison and Kasai [18] basically provide pounding of a building configuration. Either study compares three relative story mass ratios together and draws a rough conclusion since the main focus of the research is not evaluation of heavier adjacent building pounding. On the other hand, Jankowski [19] concentrates specifically on the effects of heavier adjacent building pounding on the seismic responses of the adjacent buildings. The seismic responses of the adjacent buildings with equal heights are elaborated. However, effect of taller adjacent buildings with different masses that are more common in metropolitan areas is not noted in this research. Not to mention that even with the same story masses, taller building possesses heavier total mass than the shorter building. Besides, buildings are usually deigned based on building codes so the periods of buildings are close together if building heights are equal (for residential buildings, increment of the building mass usually results in increment of its stiffness, thus, nearly same periods).

In this study it is attempted to evaluate the seismic responses of two different configurations of the adjacent buildings with varying masses; equal heights adjacent buildings and unequal heights adjacent buildings. Initially, analytical model of the pounding of the adjacent buildings subjected to earthquake excitation is presented. Finally, the seismic responses of either building in each configuration with varying masses are obtained numerically and discussed.

## 2. ANALYTICAL MODEL

*2.1 Analytical model of the adjacent buildings without pounding*

The adjacent buildings are assumed two dimensional planar shear buildings which are supposed to have arbitrary height at each story but same floor levels. Movements of these buildings are restricted in horizontal direction as indicated in Figure 1(a). Moreover, each story of any building has its concentrated mass, viscous damper and linear spring and consequently its own displacement and force (Figure 1(b)). Governing equation of motion of these adjacent buildings due to earthquake acceleration of $\ddot{u}_g(t)$ is:

$$\boldsymbol{m_b}\boldsymbol{\ddot{u}_b} + \boldsymbol{c_b}\boldsymbol{\dot{u}_b} + \boldsymbol{k_b}\boldsymbol{u_b} = -\boldsymbol{m_b}\boldsymbol{v_b}\ddot{u}_g(t) \tag{1}$$

where $\boldsymbol{m_b}$, $\boldsymbol{c_b}$ and $\boldsymbol{k_b}$ are mass, damping and stiffness matrices, respectively and $\boldsymbol{\ddot{u}_b}$, $\boldsymbol{\dot{u}_b}$, $\boldsymbol{u_b}$ and $\boldsymbol{v_b}$ are acceleration, velocity, displacement and influence vector of building, respectively. This equation of motion consists of $(n+m)$ equations where first $n$ equations are coupled and last $m$ equations are coupled too, however, first $n$ equations are independent from last $m$ equations when the buildings do not pound. More sensible insight to the equation is presented by its expansion as:

$$\begin{bmatrix} \boldsymbol{m_{ln}} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{m_{rm}} \end{bmatrix} \begin{Bmatrix} \boldsymbol{\ddot{u}_{ln}} \\ \boldsymbol{\ddot{u}_{rm}} \end{Bmatrix} + \begin{bmatrix} \boldsymbol{c_{ln}} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{c_{rm}} \end{bmatrix} \begin{Bmatrix} \boldsymbol{\dot{u}_{ln}} \\ \boldsymbol{\dot{u}_{rm}} \end{Bmatrix} + \begin{bmatrix} \boldsymbol{k_{ln}} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{k_{rm}} \end{bmatrix} \begin{Bmatrix} \boldsymbol{u_{ln}} \\ \boldsymbol{u_{rm}} \end{Bmatrix} = -\begin{bmatrix} \boldsymbol{m_{ln}} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{m_{rm}} \end{bmatrix} \begin{Bmatrix} \boldsymbol{v_{ln}} \\ \boldsymbol{v_{rm}} \end{Bmatrix} \ddot{u}_g(t) \tag{2}$$

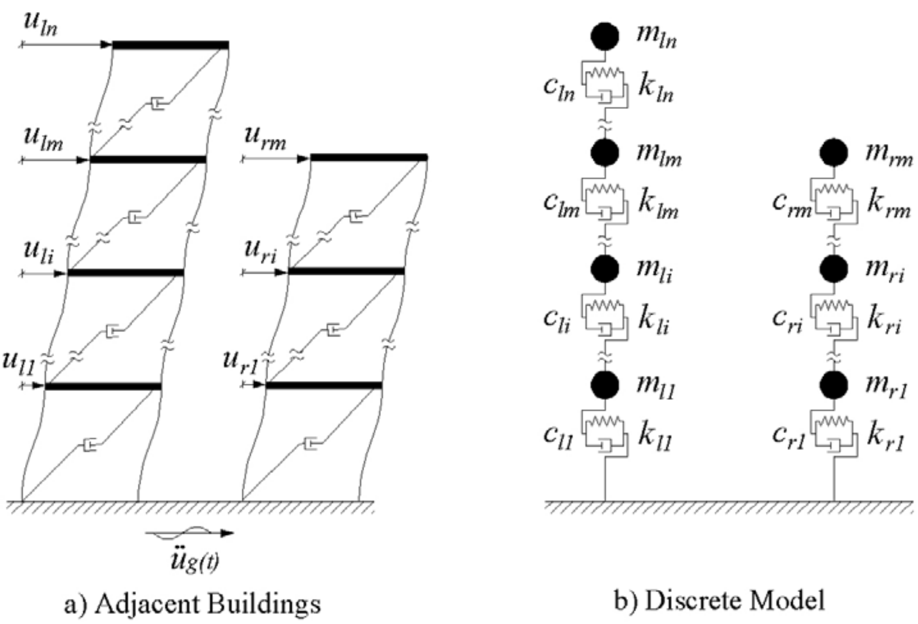


Figure 1. Analytical model of the adjacent buildings

Definitions of variables of Eq. (1) is still valid for Eq. (2) while subscript $l$ stands for left building with $n$ stories so $n$ DOFs and subscript $r$ denotes for right buildings with $m$ stories so $m$ DOFs ($n \geq m$). The mass and stiffness matrices of the left building are derived as follow (those corresponding to the right building are the same as those for the left building, except that the subscripts $l$ and $n$ are replaced by $r$ and $m$, respectively):

$$\boldsymbol{m_{lb}} = \begin{bmatrix} m_{l1} & 0 & 0 \\ & \ddots & 0 \\ SYM. & & m_{ln} \end{bmatrix} \tag{3}$$

$$\boldsymbol{k_{lb}} = \begin{bmatrix} k_{l1}+k_{l2} & -k_{l2} & 0 & \dots & 0 & 0 \\ & k_{l2}+k_{l3} & -k_{l3} & \dots & 0 & 0 \\ & & k_{l3}+k_{l4} & \dots & 0 & 0 \\ & & & \ddots & \vdots & \vdots \\ & SYM. & & & k_{l(n-1)}+k_{ln} & -k_{ln} \\ & & & & & k_{ln} \end{bmatrix} \tag{4}$$

In addition, damping matrix is Rayleigh damping matrix which is proportional to both mass and stiffness matrices:

$$\boldsymbol{c_b} = \begin{bmatrix} \boldsymbol{c_{ln}} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{c_{rm}} \end{bmatrix} = \begin{bmatrix} a_{l0}\boldsymbol{I_n} & \boldsymbol{0} \\ \boldsymbol{0} & a_{r0}\boldsymbol{I_m} \end{bmatrix} \begin{bmatrix} \boldsymbol{m_{ln}} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{m_{rm}} \end{bmatrix} + \begin{bmatrix} \alpha_{l1}\boldsymbol{I_n} & \boldsymbol{0} \\ \boldsymbol{0} & \alpha_{r1}\boldsymbol{I_m} \end{bmatrix} \begin{bmatrix} \boldsymbol{k_{ln}} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{k_{rm}} \end{bmatrix} \quad (5)$$

where $\boldsymbol{I_n}$ and $\boldsymbol{I_m}$ are identity matrices of $n$ and $m$ size, respectively. $a_0$ and $a_1$ are Rayleigh coefficients which can be determined from buildings modal damping ratios and frequencies.

The seismic responses of the adjacent buildings subjected to earthquake acceleration is obtained by Eq. (1), however, pounding of buildings is not involved in this equation.

### *2.2 Analytical model of pounding forces*

Pounding between the adjacent buildings can be simplified as pounding of different masses corresponding to each building at the same floor. Four contact force models are available to simulate the pounding forces that have been widely used in numerical analysis of pounding of adjacent buildings; i. linear elastic, ii. linear visco-elastic, iii, nonlinear elastic and iv. nonlinear elastic with nonlinear damping. Studies by Muthukumar and DesRoches [20] and Jankowski [21] show that difference between different contact force models are not significant, nonetheless, nonlinear elastic with nonlinear damping and then linear visco-elastic models give more accurate results. Moreover, there is a general agreement between that the contact force model do not affect the seismic responses of the adjacent buildings. At this research study, the linear visco-elastic contact force model is used because it is efficient and practical and gives pounding force considering energy dissipation during pounding. Relationship between pounding force and displacement of the linear visco-elastic contact force model is shown in Figure 2. The only deficiency of linear visco-elastic contact model is providing tension forces at the end of pounding with no physical meaning which is ignorable.

The linear visco-elastic contact force model consists of a linear spring representing contact stiffness and a viscous damper representing energy dissipation during pounding. Figure 3(a) demonstrates analytical model of buildings connected by the linear visco-elastic contact force model. Contact force model is inactive when the adjacent buildings vibrate individually free, however, it is activated when the separation gap is closed and the adjacent buildings pound together. Immediately after pounding, pounding forces are developed as:

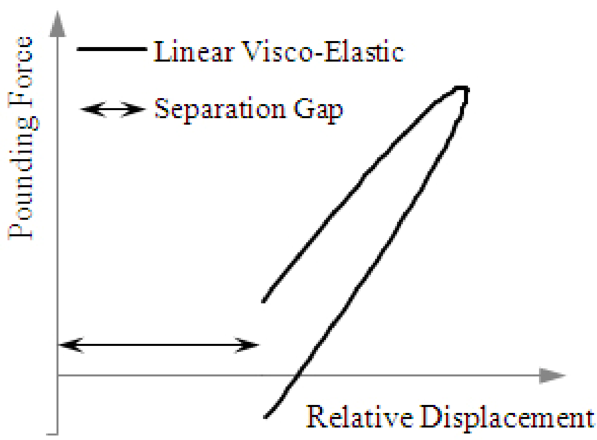


Figure 2. Pounding force and displacement relationship

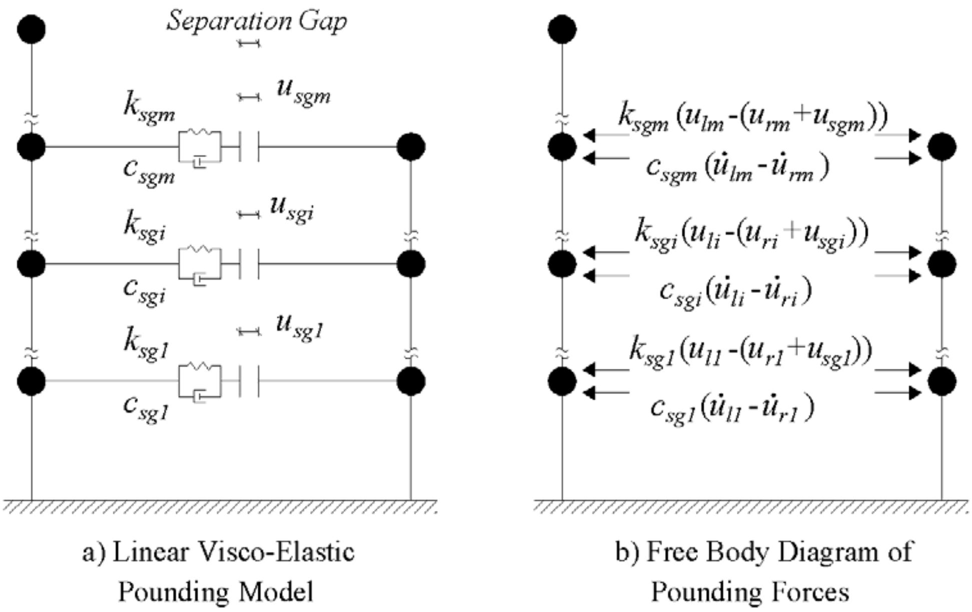


Figure 3. Analytical model of pounding forces

$$F_{pi} = k_{sgi}\delta u_i + c_{sgi}\delta \dot{u}_i \tag{6}$$

where $\delta u_i$ and $\delta \dot{u}_i$ are relative displacement and relative velocity at *i*th floor and $k_{sgi}$ and $c_{sgi}$ are contact stiffness and damping of *i*th floor, respectively. Relative displacement is as follow:

$$\delta u_i = u_{li} - \left(u_{ri} + u_{sgi}\right) \tag{7}$$

where $u_{sgi}$ is separation gap at *i*th floor. In a similar way, relative velocity is derived as follow:

$$\delta \dot{u}_i = \dot{u}_{li} - \dot{u}_{ri} \tag{8}$$

Contact stiffness, $k_{sgi}$, is a term without unique calculation procedure. It could be several times the either axial stiffness of the pounded diaphragm [17-18, 20] or lateral stiffness of the pounded floor [15-16, 22]. Contact stiffness equal to 10000 MN/m is taken in this study. Contact damping, $c_{sgi}$, is correlated to coefficient of restitution (*e*, the ratio of the contact and separation velocities) which ranges between one for pure elastic and zero for pure plastic poundings. Typical values in various applications for structural engineering are ranging between 0.5 and 1.0 [16, 23-24]. Coefficient of restitution equal to 0.65 is taken in this study.

Pounding force which acts at the pounding point is equal in both buildings but opposite direction. Free body diagram of pounding forces developed between adjacent buildings is shown in Figure 3(b). Whole system should be in equilibrium at any instance; equilibrium of pounding forces is then satisfied by:

$$\boldsymbol{c}_{\boldsymbol{p}}\dot{\boldsymbol{u}}_{\boldsymbol{b}} + \boldsymbol{k}_{\boldsymbol{p}}\boldsymbol{u}_{\boldsymbol{b}} = \boldsymbol{k}_{\boldsymbol{p}}\boldsymbol{u}_{\boldsymbol{sg}} \tag{9}$$

where $\boldsymbol{u}_{\boldsymbol{sg}}$ is separation gap vector, $\boldsymbol{c}_{\boldsymbol{p}}$ is damping matrix and $\boldsymbol{k}_{\boldsymbol{p}}$ is stiffness matrix of contact force model, respectively as follow:

$$\boldsymbol{u}_{\boldsymbol{sg}}{}^{\boldsymbol{T}} = \{u_{sg1} \quad \dots \quad u_{sgm} \quad 0 \quad \dots \quad 0\} \tag{10}$$

and

$$\boldsymbol{k}_{\boldsymbol{p}} = \begin{bmatrix} \boldsymbol{k}_{\boldsymbol{sg}} & 0 & -\boldsymbol{k}_{\boldsymbol{sg}} \\ 0 & 0 & 0 \\ -\boldsymbol{k}_{\boldsymbol{sg}} & 0 & \boldsymbol{k}_{\boldsymbol{sg}} \end{bmatrix} \tag{11}$$

where:

$$\boldsymbol{k}_{\boldsymbol{sg}} = \begin{bmatrix} k_{sg1} & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & k_{sgm} \end{bmatrix} \tag{12}$$

$\boldsymbol{c}_{\boldsymbol{p}}$ is as like as $\boldsymbol{k}_{\boldsymbol{p}}$ except $k_{sgi}$ is replaced by $c_{sgi}$. $\boldsymbol{u}_{\boldsymbol{sg}}$, $\boldsymbol{c}_{\boldsymbol{p}}$ and $\boldsymbol{k}_{\boldsymbol{p}}$ as just appeared are for the case of pounding between adjacent buildings where all adjacent floors are in contact. For the case where some adjacent floors are not in contact corresponding components are equal to zero. Therefore, these vector and matrices change based on the pounded floors.

### *2.3 Analytical model of pounding of adjacent buildings*

Equation of motion of the adjacent buildings (Eq. (1)) and equation of pounding forces (Eq. (9)) were developed separately in previous sections. By linear superposition of these two equations, equation of motion of the pounding of the adjacent buildings is obtained as follow:

$$\boldsymbol{m}_{\boldsymbol{b}}\ddot{\boldsymbol{u}}_{\boldsymbol{b}} + (\boldsymbol{c}_{\boldsymbol{b}} + \boldsymbol{c}_{\boldsymbol{p}})\dot{\boldsymbol{u}}_{\boldsymbol{b}} + (\boldsymbol{k}_{\boldsymbol{b}} + \boldsymbol{k}_{\boldsymbol{p}})\boldsymbol{u}_{\boldsymbol{b}} = -\boldsymbol{m}_{\boldsymbol{b}}\boldsymbol{v}_{\boldsymbol{b}}\ddot{u}_g(t) + \boldsymbol{k}_{\boldsymbol{p}}\boldsymbol{u}_{\boldsymbol{sg}} \tag{13}$$

Before using this equation, two states of the buildings must be diagnosed; no-pounding and pounding states. Boundary between these two states is defined by the following condition for *i*th floor:

no-pounding state: $$u_{li} - (u_{ri} + u_{sgi}) < 0 \tag{14a}$$

pounding state: $$u_{li} - (u_{ri} + u_{sgi}) \geq 0 \tag{14b}$$

When the buildings do not pound during earthquake excitation and the separation gap is open, no-pounding state condition is satisfied (Eq. (14.a)); and therefore the pounding matrices, $\boldsymbol{k}_{\boldsymbol{p}}$ and $\boldsymbol{c}_{\boldsymbol{p}}$, in Eq. (13) are zero and Eq. (13) reduces to Eq. (1). On the other hand, if the pounding state condition is satisfied (Eq. (14.b)) during the earthquake excitation, the separation gap is closed and all terms and parameters of Eq. (13) are effective.

Attention should be paid that all floors do not necessarily pound together at the same time. Obviously, pounding is more likely to occur at the top floor of the shorter building and corresponding floor of the adjacent building. Subsequently, lower floors are subjected to pounding one by one during the excitation. Anyhow, possibility of pounding should be checked to find out if other combinations of pounding occur. Pounding forces are developed only at the pounded floors that satisfy Eq. (14.b).

## 3. NUMERICAL STUDY

The seismic responses of the adjacent buildings during earthquake excitation are obtained from Eq. (13). This equation is conceptually nonlinear because its characteristics are changed periodically from no-pounding to pounding state and vice versa during the analysis. This equation is solved numerically via time-stepping integration method of Newmark [25] with linear acceleration over a time step. The time step equal to 0.01 sec is taken for the seismic analyses during no-pounding state and 0.001 sec during pounding state which ensures accuracy of the results and computational efficiency of the computer program code with minimum time required for the analysis and minimum storage capacity of the output results. The equations and the solutions were implemented via a computer program code has been written.

Two different configurations of the buildings are considered here and the seismic responses of the buildings in each configuration are computed, evaluated and discussed. First configuration is comprised of two 5-story adjacent buildings and the second configuration is comprised of a 10-story building adjacent to a 5-story building. The right building is the 5-story building in both configurations while the left building is the 5-story building for the first configuration and the 10-story buildings for the second configuration. The buildings are supposed to be residential buildings with 100 ton mass per story for the basic configurations which gives fundamental periods of the buildings as tabulated in Table 1. The fundamental periods presented in Table 1 imply that the left building in each configuration behaves relatively flexible while right building relatively stiff. It must be noted that where the mass of each building is increased its stiffness is increased accordingly so the fundamental period of the building is kept constant during the analyses.

Three fundamental periods come into the picture with each configuration; two fundamental periods for either individual building and one fundamental period for pounded buildings (Table 1). It is found that the fundamental period of the pounded buildings falls between the fundamental periods of the individual buildings so the pounded buildings behave stiffer than the individual left building while more flexible than the individual right building. Increasing mass of the buildings, although the fundamental periods of the individual buildings are kept constant, the fundamental period of the pounded buildings is shifted toward the heavier building. For example, the fundamental periods of the 10-story and 5-story individual buildings are 1.026 sec and 0.534 sec, respectively. When these buildings pound together and their story masses are equal (L=R) the fundamental period is 0.854 sec, an approximately average of the fundamental periods of the individual buildings. By increasing the story mass of the left building about 10 times the story mass of the right building (L=10R), the fundamental period of the pounded buildings shifts toward the heavier left building and becomes 0.997 sec. On the other hand, the fundamental period of the pounded buildings shifts toward the heavier right building and becomes 0.653 sec if the story mass of the right building is increased about 10 times the story mass of the left building (10L=R). Same goes for the configuration of two 5-story adjacent buildings. Therefore, the heavier building governs movement of the adjacent buildings during the pounding because it shares more mass than the lighter building.

Table 1: Fundamental periods of the building for different configurations

| **Building configuration** | **Fundamental Period (sec)** | | | | |
|---|---|---|---|---|---|
| | **Individual left building (5 or 10-Story)** | **Pounded buildings** | | | **Individual right building (5-Story)** |
| | **L** | **L=10R** | **L=R** | **10L=R** | **R** |
| 5-5 | 0.61 | 0.602 | 0.568 | 0.54 | 0.534 |
| 10-5 | 1.026 | 0.997 | 0.854 | 0.653 | 0.534 |

Finally, acceleration record time history of El Centro earthquake (I-ELC180 1940) is selected and applied to the building configurations. The seismic responses of the adjacent buildings are obtained for two different building configurations (equal and unequal heights adjacent buildings) which will be discussed in the following sections.

*3.1 The equal heights adjacent buildings*

Initially configuration of the two 5-story adjacent buildings with equal heights is considered and the seismic responses of the buildings due to El Centro earthquake are obtained. Envelops of maximum displacements and story shears are shown in Figures 4 and 5, respectively. When the adjacent buildings are separated from each other about 0.084 m and wider, each building vibrates individually free as shown by continues lines (N-P) in the figures. In contrast, when the separation gap is less than 0.084 m, the adjacent buildings pound together as shown by dotted lines (L=R) in the figures. Both buildings experience smaller displacements after pounding in pounding side while larger displacements in no-pounding side (Figure 4) (the pounding side is referred to positive values for the left building whereas negative values for the right building). The adjacent building prevents further movement of other building since the buildings are adjusted very close together in the pounding side, whereas, the buildings push each other away leading to larger displacements in the no-pounding side. As a consequence of changes of the displacements, the story shears are decreased in the pounding side whereas increased in the no-pounding side (Figure 5).

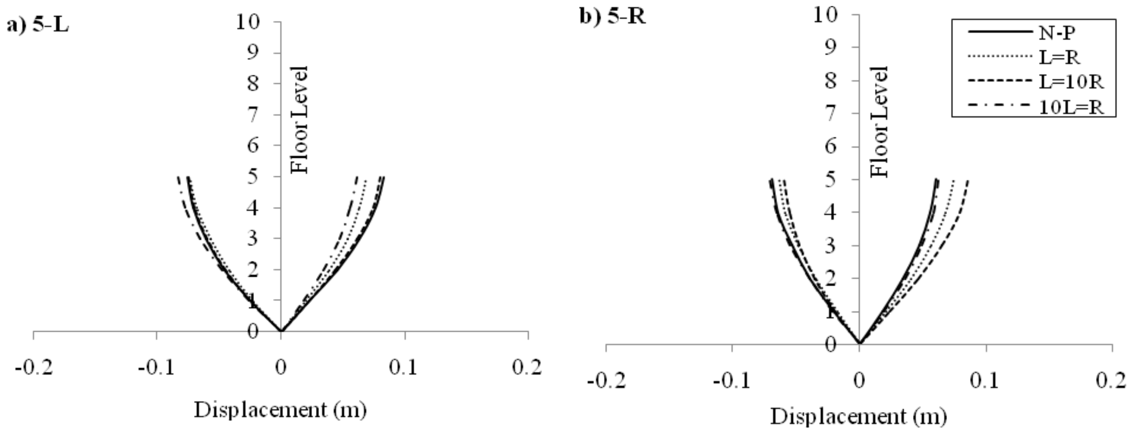


Figure 4. Envelops of the maximum displacements of the equal heights adjacent buildings (5-L is the 5-story left building and 5-R is the 5-story right building)

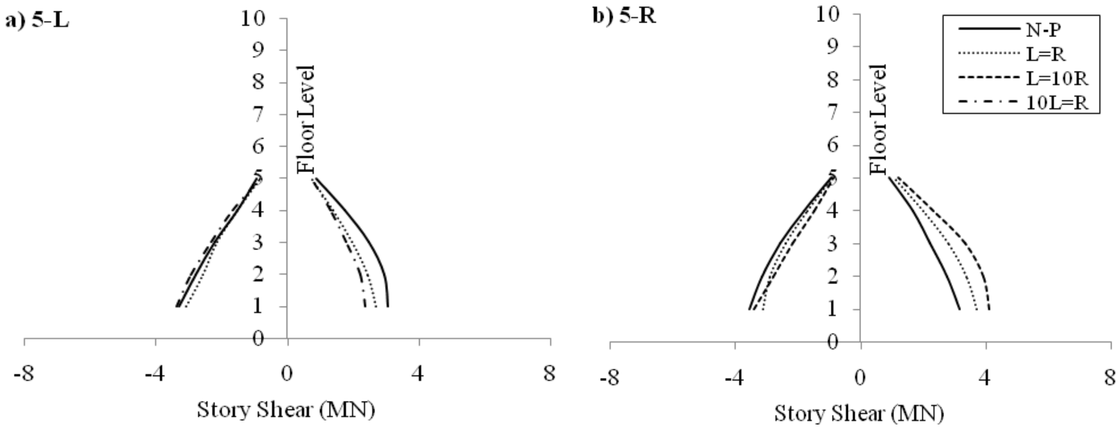


Figure 5. Envelops of the maximum story shears of the equal heights adjacent buildings (5-L is the 5-story left building and 5-R is the 5-story right building)

When the story mass of both buildings are equal (L=R) both buildings suffer from the pounding in an almost same degree. However, increment of the story mass of either building results in different seismic responses for the buildings. When the story mass of the left building is increased about 10 times the story mass of the right building (L=10R), the displacements (Figure 4(a)) and the story shears (Figure 5(a)) of the heavier left building remain unchanged after pounding while the displacements (Figure 4(b)) and the story shears (Figure 5(b)) of the lighter right building are amplified more than 19% of the values corresponding to equal story masses (L=R). For example, increment of the displacement of the top floor of the right building is 23% and 42% due to pounding for the equal story masses adjacent buildings (L=R) and heavier adjacent buildings (L=10R), respectively. On the other hand, when the story mass of the right building is increased about 10 times the story mass of the left building (10L=R), the displacements (Figure 4(a)) and the story shears (Figure 5(a)) of the lighter left building are amplified more than 13% of the values corresponding to the equal story masses adjacent buildings (L=R), while the displacements (Figure 4(b)) and the story shears (Figure 5(b)) of the heavier right building are remained unchanged.

A clearer insight of the seismic responses of the adjacent buildings is given by the first 15 sec of time histories of the displacements of the top floors of the adjacent buildings as shown in Figure 6. When the buildings are separated from each other about 0.084 m, each building vibrates individually free. Different phases and amplitudes of the displacements due to different fundamental periods of the adjacent building are observed in Figure 6(a) (N, L=R). Anyhow, the adjacent buildings tend to pound together in several different times if the separation gap gets narrower (separation gap is considered zero for pounding cases, however, to make the responses distinguishable, the displacements of the right building are added by 0.05 m in Figure 6(b, c and d)).

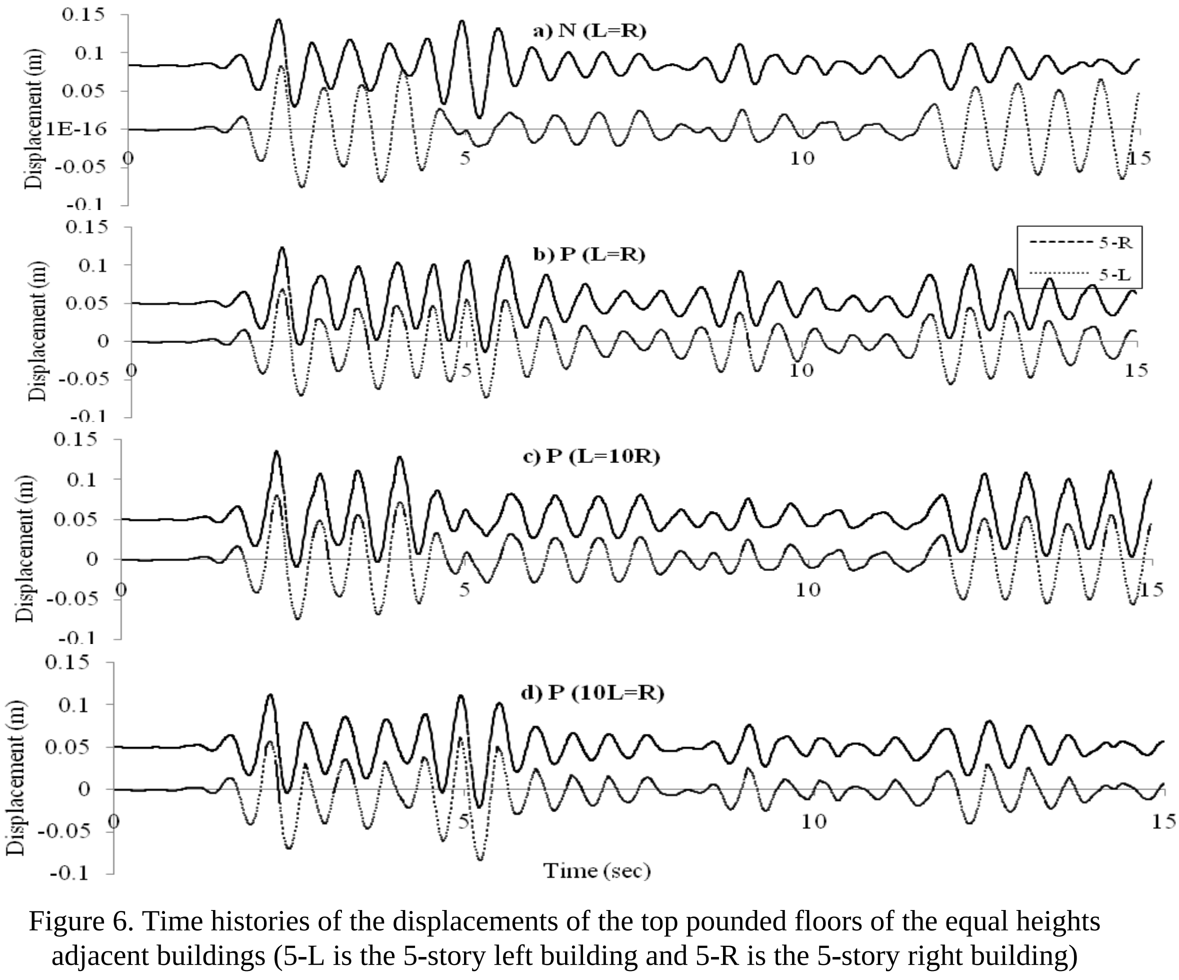


Figure 6. Time histories of the displacements of the top pounded floors of the equal heights adjacent buildings (5-L is the 5-story left building and 5-R is the 5-story right building)

When the story mass of both buildings are equal (Figure 6(b), P, L=R) both buildings accompany each other during the pounding and both buildings demonstrate similar displacement histories (phase and amplitude) since the fundamental period of the pounded buildings is somewhat an average of the fundamental periods of the individual buildings.

However, increment of the story mass of the left building about 10 times the story mass of the right building (Figure 6(c), P, L=10R), provides a fundamental period for the pounded buildings nearer to the heavier left building so the displacement histories of the pounded buildings is similar to those corresponding to the heavier left building. On the other hand, the displacement history of the pounded buildings is similar to the displacement history of the right heavier building if the story mass of the right building is increased about 10 times the story mass of the left building (Figure 6(d), P, 10L=R).

In addition, variations of the displacements and story shears of the top floors of the buildings are obtained for the buildings with varying story masses and presented in Figures 7 and 8, respectively. In these figures, positive values of the seismic responses of the adjacent buildings at the top floor due to pounding are normalized to the seismic responses of the adjacent buildings vibrated individually free which are called displacement ratios and story shear ratios.

As shown in Figures 7(a) and 8(a), the displacement ratios and story shear ratios of the left building are both below one since the displacements and story shears of the top floor of the left building are reduced in the pounding side (positive values) due to pounding. When the left building is heavier than the right building (L-Heavier), the displacement ratios and story shear ratios of the left building are tend to one by increasing of the story mass of the heavier left building meaning that its seismic responses get unchanged due to pounding. On the other hand, the displacement ratios and story shear ratios of the left building tend to decrease by increasing of the story mass of the heavier right building (R-Heavier).

For the right buildings, the displacement ratios and story shear ratios are above one because both displacements and story shears are increased due to pounding in the no-pounding side (positive values) (Figures 7(b) and 8(b)). When the right building is heavier (R-Heavier), its displacement ratios and story shear ratios tend to one by increasing of the story mass of the heavier right building. Whereas, the displacement ratios and story shear ratios of the right building are increased by increasing of the story mass of the heavier left building (L-Heavier).

It is noticeable in both Figures 7 and 8 that variations of the displacement ratios and story shear ratios are relatively sharp for the story masses up to 500 ton while they are relatively smooth for the story masses beyond 500 ton. By increasing the story mass of the heavier building about 5 times the story mass of the basic building (the lighter building with the story mass of 100 ton) pounding effect is amplified accordingly. Nonetheless, increasing the story mass ratios beyond 5 times seems ineffective for this case.

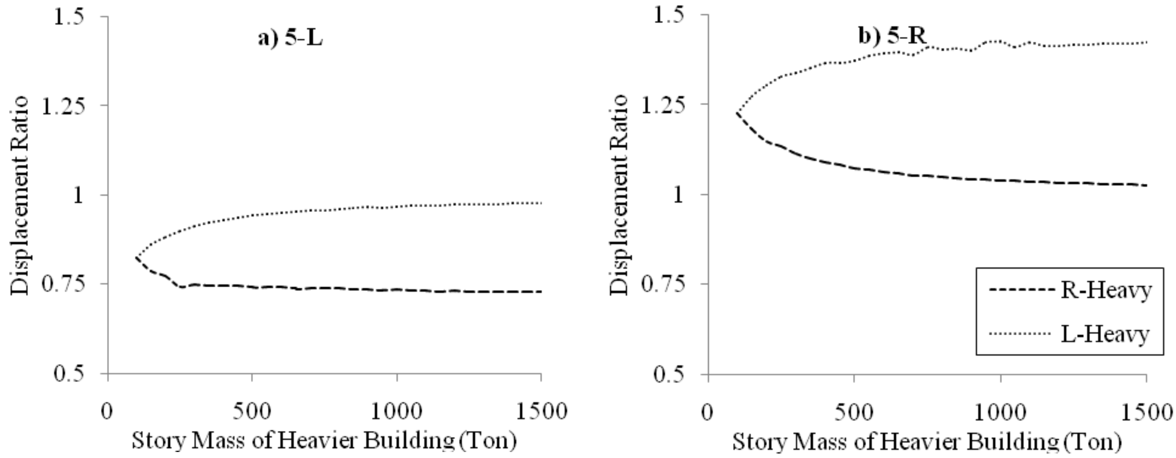


Figure 7. Variation of the maximum displacements of the top floors of the equal heights adjacent buildings (5-L is the 5-story left building and 5-R is the 5-story right building)

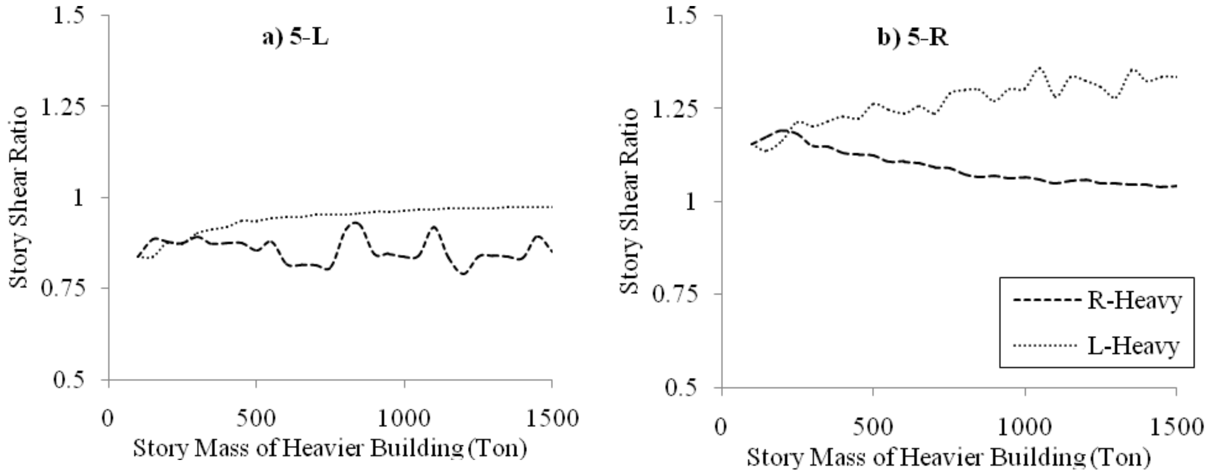


Figure 8. Variation of the maximum story shears of the top floors of the equal heights adjacent buildings (5-L is the 5-story left building and 5-R is the 5-story right building)

*3.2 The unequal heights adjacent buildings*

Configuration of a 10-story (left) building adjacent to a 5-story (right) building is considered in this section to evaluate the seismic responses of the adjacent buildings with unequal heights subjected to earthquake induced pounding. Envelops of maximum displacements and story shears are shown in Figures 9 and 10, respectively. When the buildings are separated from each other about 0.128 m and wider, each building vibrates individually free as shown by continues lines (N-P) in the figures.

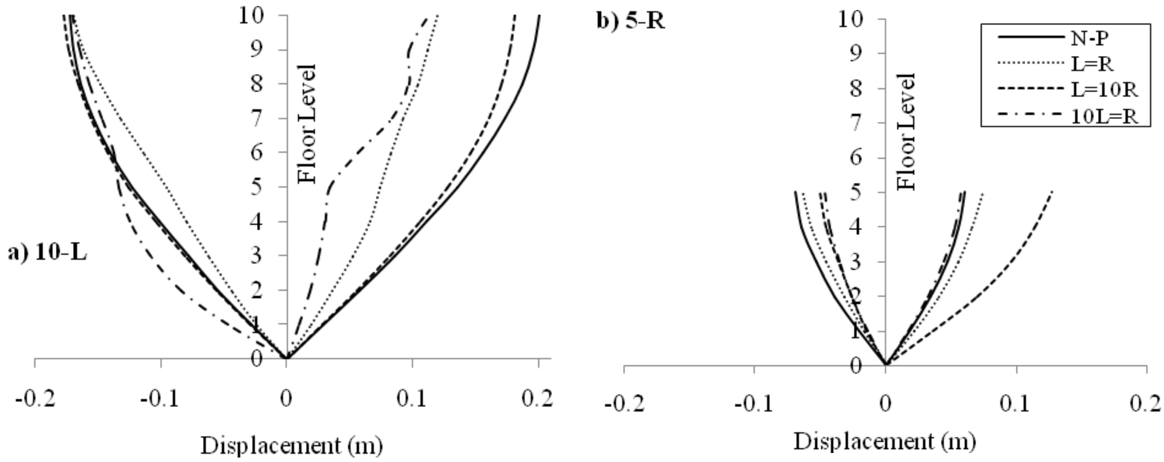


Figure 9. Envelops of the maximum displacements of the unequal heights adjacent buildings (10-L is the 10-story left building and 5-R is the 5-story right building)

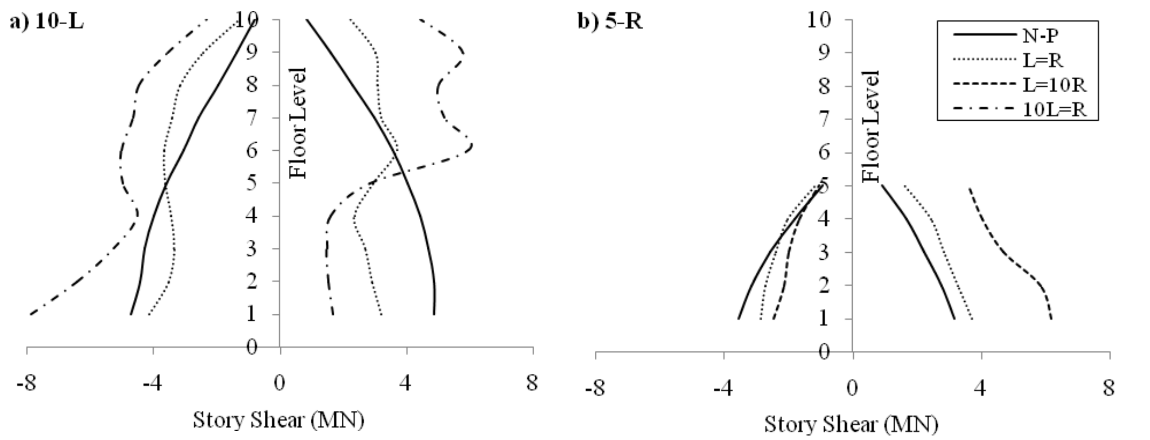


Figure 10. Envelops of the maximum story shears of the unequal heights adjacent buildings (10-L is the 10-story left building and 5-R is the 5-story right building)

Comparison between configuration of the adjacent buildings with equal and unequal heights demonstrates that wider separation gap is required for the unequal height adjacent buildings (0.128 m) than the equal height adjacent buildings (0.084 m) to prevent pounding because unequal height adjacent buildings are vibrating very out of phase which is implied from their fundamental periods.

The 10-story left building suffers from pounding differently in different floors; through-pounding floors and above-pounding floors. Along the through-pounding floors, the displacements are reduced in the pounding side but increased in the no-pounding side (Figure 9(a)) and the story shears follow a similar pattern (Figure 10(a)). The displacements of the above-pounding floors are reduced but their story shears are increased sharply. The above-pounding floors can move without obstruction while the through-pounding floors are stopped by the adjacent building which causes a sudden jump of displacement between 5th and 6th floors resulting in whiplash like forces; thus, the story shears of the above-pounding floors are sharply increased. In addition, it is noted that the 5-story right building behaves similarly as it does in the configuration of the equal height buildings.

By increment of the story mass, effect of the pounding is reduced for the heavier building while is increased for the lighter building. Effect of the heavier adjacent building pounding is highlighter for the unequal than the equal heights adjacent buildings because total mass of the 10-story building is already 2 times the total mass of the 5-story building even if their story mass is the same. Let’s consider the 5-story right building in both equal and unequal height adjacent building configurations as a comparison. When the story mass of both building are the same (L=R), the displacement of the top floor of the 5-story building is increased about 23% for both building configurations. Increasing the story mass of left heavier building about 10 times the story mass of right lighter building (L=10R), the displacement of the right lighter building is increased about 42% and 111% for the equal and unequal heights adjacent buildings, respectively, because the mass of the heavier building in unequal heights buildings is 2 times the mass of the equal heights buildings.

Time histories of the displacements of the 5th floor of the 10-story and 5-story adjacent buildings are shown in Figure 11. Response of each building is totally different from the other since the buildings vibrate very out of phase. As same as the equal heights adjacent buildings, the seismic responses of the unequal heights adjacent buildings are changed due to pounding. Effect of the heavier adjacent building is clearer in Figure 11 than Figure 6. When the left building is heavier (P, L=10R), the displacements of the right lighter building are completely affected by the adjacent heavier building (Figure 11(c)). Not only the left heavier building prevents movement of the lighter building in the pounding side but also pushes it away easily to the no-pounding side. On the other hand, a same reaction but vice versa is observed when the right building is 10 times heavier than the left building (P, 10L=R) as shown in Figure 11(d).

Variations of the displacement ratios and story shear ratios of the top floors of the unequal heights adjacent buildings with varying masses are shown in Figures 12 and 13, respectively. As same as the equal heights adjacent buildings, the displacement ratios and story shear ratios of the unequal heights adjacent buildings approach to the one if the building is heavier. Whereas, the displacement ratios and story shear ratios deviate from one if the building is lighter. While effect of the heavier adjacent building converged at the story mass ratio about 5 in the equal heights buildings, it is observed that increasing the mass ratio even up to 7 is effective in the unequal heights building because the total mass of the buildings are different in the unequal heights buildings.

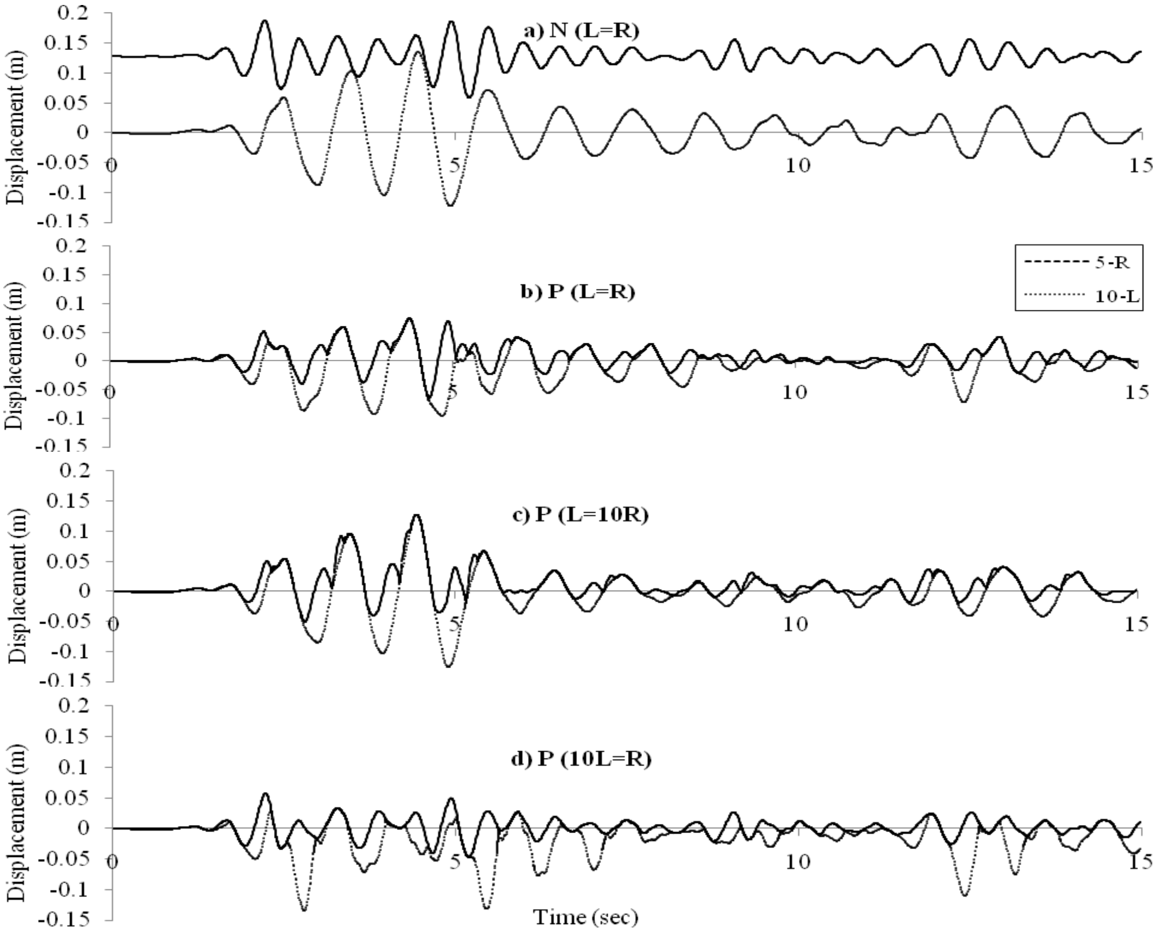


Figure 11. Time histories of the displacements of the 5th floors of the unequal heights adjacent buildings (10-L is the 10-story left building and 5-R is the 5-story right building)

## 4. CONCLUSION

Analytical model of the adjacent buildings is presented in this paper whilst the buildings are connected by linear visco-elastic contact force model. Contact force model is activated when the separation gap is closed and the adjacent buildings pound together. The seismic responses of the adjacent buildings subjected to acceleration time history of El Centro earthquake are obtained. It is found that the building condition became critical due to pounding because the seismic responses of the adjacent buildings are amplified.

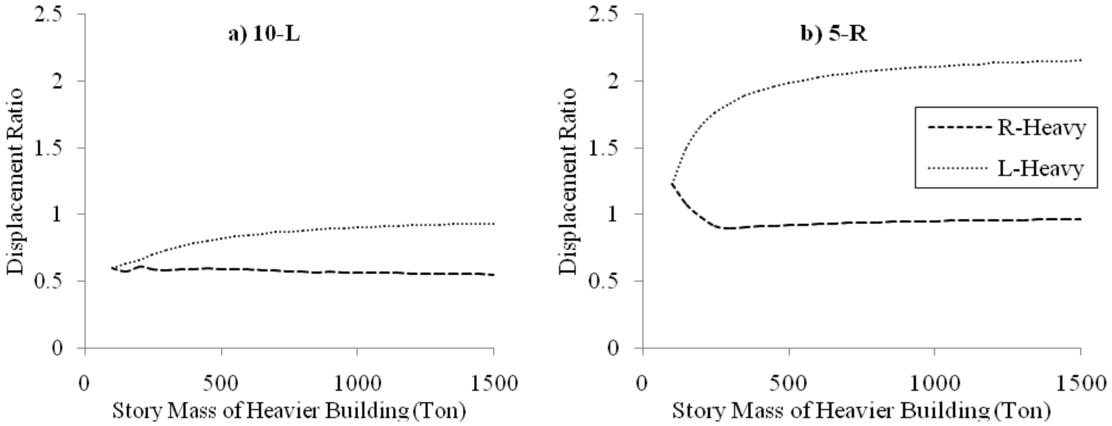


Figure 12. Variation of the maximum displacements of the top floors of the unequal heights adjacent buildings (10-L is the 10-story left building and 5-R is the 5-story right building)

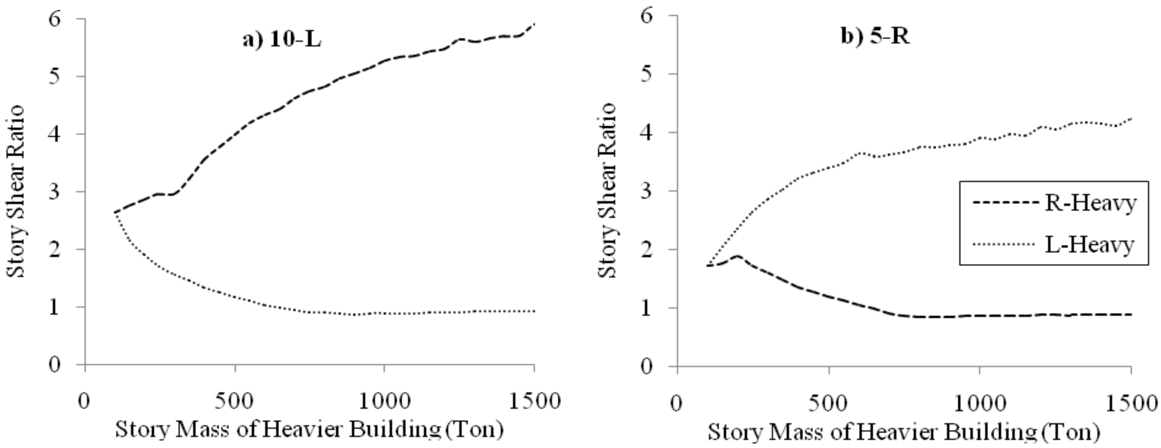


Figure 13. Variation of the maximum story shears of the top floors of the unequal heights adjacent buildings (10-L is the 10-story left building and 5-R is the 5-story right building)

Two adjacent building configurations (equal and unequal heights adjacent buildings) are analyzed and their seismic behaviours are evaluated. By increasing of the story mass of one building, effect of pounding is amplified in the lighter building whereas suppressed in the heavier building. The seismic response of the lighter building is totally affected by the heavier building when the story mass ratio is more than 5 and 7 for equal and unequal heights buildings, respectively. The lighter building is prevented to move in the pounding side while is pushed away in the no-pounding side by the heavier building. On the other hand, the heavier building is less affected by the lighter building. Moreover, the configuration of unequal heights adjacent buildings is more sensitive to the heavier adjacent building pounding because firstly, the buildings vibrated very out of phase and secondly, even with the same story mass, the total mass of the buildings are different.

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