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Pounding of Adjacent Buildings of Different Heights under Seismic Effect

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Abstract : *The problem of pounding between adjacent buildings, as it leads to damage of buildings, and sometimes total collapse is particularly important in Egypt, due to the presence of large areas in Cairo, and other cities, where buildings are erected totally adjacent to each other, with very small, or even no distance between them.*

The structural behavior of buildings under the effect of pounding is simulated using 3-D finite element analysis of the buildings, while modeling the pounding effect at several points along each floor level, by introducing special nonlinear gap elements between the 2 buildings at these points. Time-history analysis of several buildings is performed in 3-D, under the effect of actual earthquake records scaled according to the Egyptian code of practice specifications for Cairo area. A parametric study is conducted to assess the effect of building height, and separation distance on the pounding behavior of the buildings. In addition, the effect of the torsional behavior of buildings on the pounding phenomenon is investigated for the case where the strong structural elements in one of the buildings are shifted to one side so as to cause high torsional movements. A detailed discussion of all analysis results is presented, together with comparisons with the provisions of the local Egyptian Code of Practice. Final conclusions related to the structural behavior of buildings subjected to pounding are presented with emphasis on the actual case of zero gap distance which is highly common in Cairo's old districts.

Keywords: *Finite Element Modeling, Pounding, Nonlinear analysis, Gap element*

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I. Introduction And Problem Description

Examination of damage induced by past earthquakes hitting large metropolitan areas revealed that collisions between adjacent buildings during earthquake have been one of the causes of severe structural damage. This collision is commonly called "structural pounding". In some cases, the additional forces generated by the impact interactions have led to structural collapse. In other cases, the buildings sustained minor local damage, but indicating that structural pounding may be a serious threat to the structures if a stronger earthquake takes place.

Pounding condition may take place from one of the next reasons:

1- Insufficient separation gap between adjacent buildings which leads to collision between them.
2- The fact that code provisions for building separations is not sufficient enough to accommodate collision of adjacent buildings during strong earthquakes.
3- The variety of dynamic properties of the adjacent structures which leads buildings to vibrate out of phase.
4- Strict architectural requirements of limited separation distances between expansion joints make the pounding of the different parts of one building an expected incident, especially when these parts have dissimilar dynamic characteristics.

Several research studies have been directed to the local damage induced by pounding on the facades of the buildings facing each other, and the direct damage incurred by elements on these facades. This research is directed towards an investigation of the global effect of pounding on the overall behavior of the buildings, and its effect on all structural elements, shear walls, frames, etc, whether they are near or far away from the collision points.

II. Code requirements to avoid pounding

The main objective of code previsions is to prevent pounding through providing adequate separation between adjacent buildings. However codes generally permit smaller separation distances provided that pounding analysis is performed. In the following, the required separation distances specified by some codes are described:

- **American Society of Civil Engineers (ASCE 7-10) 2010**

The (ASCE 7-05) specifies that the minimum separation between the isolated structure and surrounding retaining walls or other fixed obstructions shall not be less than the total maximum displacement.

- **Provisions of Uniform Building Code (UBC 1997)**

UBC recommends that all structures shall be separated from adjoining structures. Separations shall allow for the displacement (Δ_M). Adjacent buildings on the same property shall be separated by at least (Δ_{MT}), where

$$\Delta_{MT} = \sqrt{(\Delta_{M1})^2 + (\Delta_{M2})^2} \quad (1)$$

$$\Delta_M = 0.7 \times R \times \Delta_S \quad (2)$$

Where,

Δ_M = Maximum inelastic response displacement from time history analysis, which is the total drift or the total story drift that occurs when the structure is subjected to the design basis ground motion, including estimated elastic and inelastic contributions to the total deformation.

Δ_S = Design level response displacement, which is the total drift or the total story drift that occurs when the structure is subjected to the design seismic forces.

R = Numerical coefficient representative of the inherent over strength and global ductility capacity of lateral-force-resisting systems.

It is worth mentioning that UBC does not address the case where the separation is less than Δ_M.

- **International Building Code (IBC) 2006**

It specifies that all structures shall be separated from adjoining structures. Separations shall allow for displacement Δm. adjacent buildings on the same possessions shall be separated by at least Δ_{mT}

Where:

$$\Delta_{mT} = \sqrt{\Delta_{m1}^2 + \Delta_{m2}^2} \quad (3)$$

Where, Δ_{m1} ,and Δ_{m2} are the lateral displacements of the adjacent buildings and they could be calculated as in (UBC 1997). On the other hand the code allows for smaller separations provided that rational analysis is preformed base on maximum expected ground motion. The method used here to calculate the gap distance (Δ_{mT}) is called square root of the sum of the squares (SRSS) rule which is often conservative in deducing the gap distance required to avoid pounding effect.

- **Egyptian Code (ECP) 201-2012**

It outlines that to avoid the pounding effect; the separation distance between adjacent structures must not be less than the SRSS of the maximum displacements of the two adjacent structures

$$\text{Gap} = \sqrt{S_1^2 + S_2^2} \quad (4)$$

Where S_1 and S_2 are the maximum horizontal displacements of the adjacent resulted from the designed base shear after multiplying it by force modification factor (R). If the adjacent buildings have the same storey heights the separation distance may be abridged by a factor equal to (Gap × 0.7). The code also allows to neglect the calculation of gap distance when there is at least two shear walls perpendicular to the line separating the two adjacent buildings provided that these shear walls must expand to the whole height of the building. In this case, the gap distance may be reduced to 4 cm only. On the other hand, the code allows for smaller separations provided that rational analysis is performed.

III. Literature Review

In modern decades, Pounding becomes an important phenomenon due to presence of large metropolitan areas subjected to many earthquakes. Different techniques had been used to simulate the pounding and to estimate the required gap distance to avoid it. Engineering community has been paid more attention into structural pounding formulas to improve and most likely prevent the damages of the pounding effects on the buildings.

First technique is using single degree of freedom (SDOF) models as discussed by **Lopez-Garcia, D. and Soong, T.T. (2009)**. They studied the accuracy of the Double Difference Combination (DDC) rule (also known simply as the CQC rule) in predicting the separation necessary to prevent seismic pounding between linear structural systems. Seismic excitations were modeled as modulated and filtered modulated Gaussian white noise random processes, and adjacent structures were modeled as 5%-damped SDOF systems having a wide range of values of natural periods. Modulated and filtered modulated Gaussian white noise random processes were considered as seismic excitations, and the response of the structural systems was evaluated through Monte Carlo simulations. It was found that the accuracy of the DDC rule depends not only on the ratio between the natural periods TA and TB of the adjacent structural systems A and B, as suggested in former studies, but also on the relationship between TA, TB and the period Tm associated with the main frequency of the excitation (ω_m). Further, it was also found that, qualitatively, the relationship between the accuracy of the DDC rule and the periods TA, TB and Tm is, for practical purposes, essentially invariant, i.e., it does not depend on whether the excitation has wide- or narrow-band characteristics, or on whether the value of Tm is relatively large or small.

Second technique used in simulating pounding is using multi degree of freedom (MDOF) models as previously studied by **Lin, J. (1997)**. Author proposed a theoretical solution to determine the required safe gap distance between adjacent buildings, under seismic pounding. Simulated by linear multi degree of freedom system, elastic response and, the stochastic method, the author reached two equations to calculate the mean values and standard deviations of separation distances to avoid seismic pounding of adjacent buildings. The simulation results agreed well with the theoretical results obtained from the application of the latter equations. However, this method is only applicable if the system response can indeed approach statistical stationary, well separated modal frequencies of buildings and, small modal damping.

Third Technique is the two dimensional frame idealization models as discussed before by **Goltabar, A.M., Kami R.S. and Ebadi, A. (2008)**, analyzed buildings with 2-15 stories and different heights were put together using GAP joint element and nonlinear time-history analyses were done for Tabas, Elcentro, and Sakaria earthquakes. The responses of both impact and non-impact cases were compared. The distance between two adjacent structures and the hardness of the two buildings were considered as the major factors. A model of 10 and 13 story buildings had been formed using the SAP2000 software. They found that maximum responses (lateral displacement and story shearing) caused by the impact of two adjacent buildings, decreases in the shorter building, whereas it increases in the taller one, which may lead to critical conditions, also maximum responses in the shorter building decreased throughout the whole height of building except for the impact point, On the other hand maximum responses in the taller building increased throughout the building. They also found that there are different dynamic responses and consequently different responses caused by impact depending on the earthquakes. Earthquakes with acceleration history of repeatedly changes in direction, which have higher acceleration maximums, lead to more effect that is intensive. Based on their study they proposed two ways in order to decrease impact effects, first is considering a proper distance between the two adjacent structures. This distance decreases the impact effects, as a result, the responses will be similar to those of non-impact case, Second is to harden the building. This change decreases the impact effects; as a result, the responses will be similar to those of non-impact case.

The last technique used previously to simulate the pounding phenomenon is using three dimensional models as done by **Jankowski, R. (2008),** conducted non-linear analysis for detailed investigation on pounding-involved response of two equal height buildings with substantially different dynamic properties. The structures had been modeled as inelastic multi-degree-of-freedom lumped mass systems and the non-linear viscoelastic model had been incorporated to model impact force during collisions. The study had been focused on three-dimensional pounding between two adjacent three-storey buildings. The results of the response analysis shows that structural pounding during earthquakes has a significant influence on the behavior of the lighter and more flexible building, especially in its longitudinal direction. It may cause substantial amplification of the response, which may finally result in a considerable permanent deformation of the structure due to yielding. On the other hand, the behavior of the heavier and stiffer building in the longitudinal, transverse and vertical direction is nearly unaffected by collisions between structures. The results of the parametric investigation prove that the peak displacement of the lighter and more flexible building is very sensitive, in all three directions, to a change of different structural parameters, such as gap size between structures, storey mass, structural stiffness and yield strength. On the other hand, the response of the heavier and stiffer building had been found to be influenced only negligibly and mainly in the longitudinal direction. The results of the study clearly indicates that special attention should be paid to appropriate design of a weaker building, for which earthquake-induced structural pounding can be catastrophic. In order to prevent destructive collisions, the natural vibration period of the structure should be tuned with the period of a stronger building, so as to induce in-phase vibrations during the earthquake, or a sufficiently large separation between both structures should be provided. If none of the solutions is possible, the application of a certain pounding mitigation technique should be considered at the design stage.

IV. Development of the “GAP” Contact element

A special element is needed to achieve the representation of the impact and the interaction between the adjacent buildings, during pounding. In the analysis, this element would start to develop an internal force once the contact points on the 2 buildings are in touch with each other, and the force is removed once the buildings start to separate from each other at this specific contact point. This element will be named henceforth the (GAP Element).

For each deformational degree of freedom, independent gap (“compression- only”) properties may be specified.All internal deformations are independent. The opening or closing of a gap for one deformation does not affect the behavior of the other deformations.

The non-linear force- deformation relationship is given by:

$$f = \begin{cases} k\,(d + \text{open}\,) & \text{if } (d + \text{open}\,) < 0 \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

Where (k) is the spring constant, (open)is the initial gap opening, which must be zero or positive, (d) is the displacement in the gap element which has negative value.

Using equation (5),example of two SDOF systems had been developed in order to study the effect of gap element representation on the gap element force and force-time integral. For the two systems ($m=12.75t.s^2/m$, C=0, and K=500t\m). The initial displacements and velocities for the two systems equal (zero), the time step used (Δt=0.001 sec), and the gap distance (d=2cm).

In order to study the effect of gap element stiffness on the resulting impulse, constant dynamic force equals (20 ton) had been applied to the first SDOF system. Three values for gap element stiffness (4000t\m, 40000t\m, and 900000t/m) are used here to cover the wide range for values which had been used previously in older researches. The choice of such a large range of variation is aimed at investigating whether this stiffness coefficient has a significant effect on the analysis results, or whether it has only a local effect on the impact force value at local points of contact.

Force in the gap element for each model has been plotted with time for the first 0.5 second as shown in Figures (01 and 02).

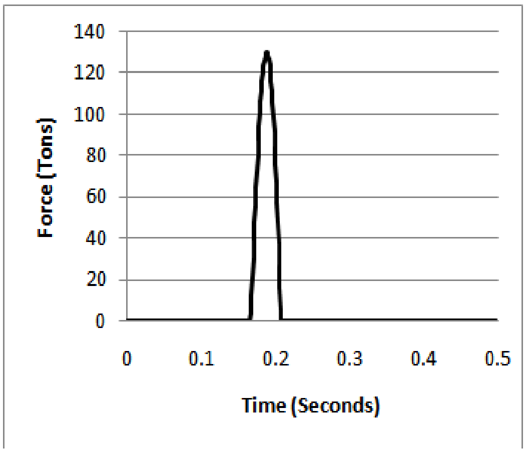

Figure 01 (Force in the gap element with k=40000t/m)

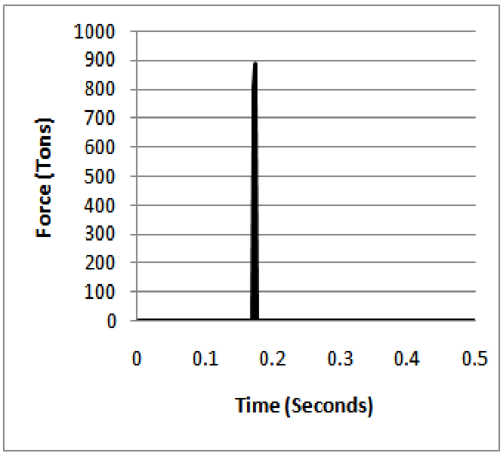

Figure 02 (Force in the gap element with k=900000t/m)

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The area under the curve (Force-time integral), which represents the impact, has been calculated for the each model in the excel program, and the results have been tabulated in Table (01).

	Area under the curve (Force-time integral) (ton.sec.)	**Percentage of difference in force-time integral**
Linear elastic (K=4000t\m)	3.359	-----
Linear elastic (K=40000t\m)	3.368	0.27%
Linear elastic (K=900000t\m)	3.497	4.11%

Table 01 (Comparison between force-time integral resulting from different models for the case of constant force)

As a conclusion from the previous table, it may be noted that while the actual value of the gap element stiffness affects the computed contact force, the impact (force-time integral) effect is not significantly changed, and hence that leads to the no significant effect on the structure behavior which is previously proved by **Anagnostopoulos S.A. (1988)**, and **Maison, B.F., Kasai, K., (1992)**.

For the finite element modeling purposes, it is highly favorable to assume a relatively low value for the gap element stiffness, in order to avoid the need to use a very small time step in analyses which could elongate the run time significantly. Therefore, in this research, a gap element stiffness equal to (4000 t/m) has been assumed in the buildings models.

Since the stiffness of the gap element in case of contact was found not to have a significant effect on the overall behavior of the buildings, a simple "linear stiffness in compression" type gap element was selected for the current analysis in order to facilitate performing a large number of analysis runs to be able to capture the pounding behavior more fully. SAP 2000 program was subsequently selected for performing the nonlinear analysis as it contains a GAP element of the selected type.

V. Modeling buildings under pounding effect

Two buildings which have regular arrangement of columns and shear walls, Spacing between columns is equal for both models together, the area of the two buildings and number of columns are different. Three models have been composed by changing the height of building (2).

- **Building (1)**

It consists of 13 floors with equal heights of 3 meters for each floor, except the first floor has a height of 5 meters. Area of the building is (31mx49m). Columns have spacing of 6 meters in X direction and Y direction. Two shear walls of 6 meters length had been used. Slab thickness is 20 cm for all floors.

- **Building (2)**

Number of floors for this building is changed for each model as will be presented later. All floors have equal heights of 3 meters for each floor, except the first floor has a height of 5 meters. Area of the building is (19mx49m). Columns have spacing of 6 meters in X direction and Y direction. Two shear walls of 6 meters length had been used. Slab thickness is 20 cm for all floors.

Columns of the two buildings had been designed according to the ECCS 203-2001 under vertical loads only, and the dimensions of shear walls had been assumed. Dimensions for column's cross section at each floor are shown in Table (02).

Floors	**Column Dimension (cm)**
1st to 4th floor	100x100
5th to 8th floor	80x80
9th to 13th floor	60x60

Table 02 (Dimension of columns for buildings (1&2))

The two buildings in have been placed next to each other inthe finite element model with a gap distance between them as shown in Figure (03).

The finite element models developed are used to perform a non-linear analysis on the previous described buildings. Columns have been modeled using frame elements, and shear walls have been modeled using shell elements. A four-point numerical integration formulation is used for the Shell stiffness. A separate horizontal diaphragm has been assigned to joints in each floor for each building, Horizontal non-linear gap element in X direction has been used to connect the two buildings at each floor. Each floor has 9 gap elements spaced by 6m as shown in Figure (04).

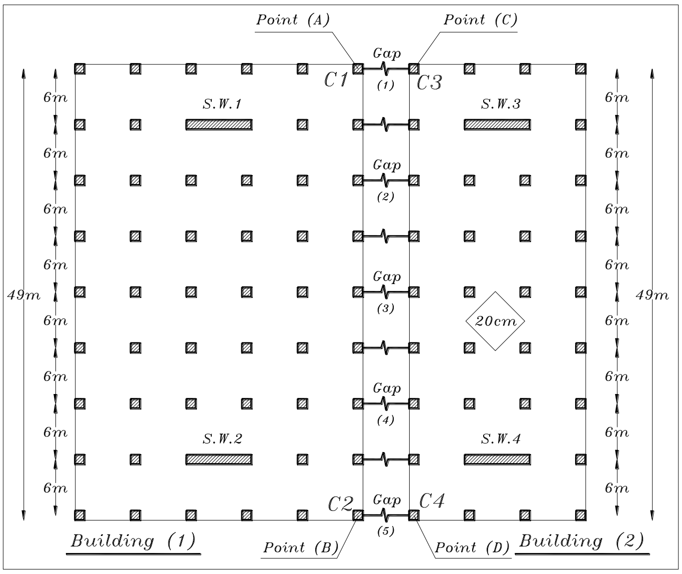


Figure 03 (The two studied buildings next to each other with location for gap elements)

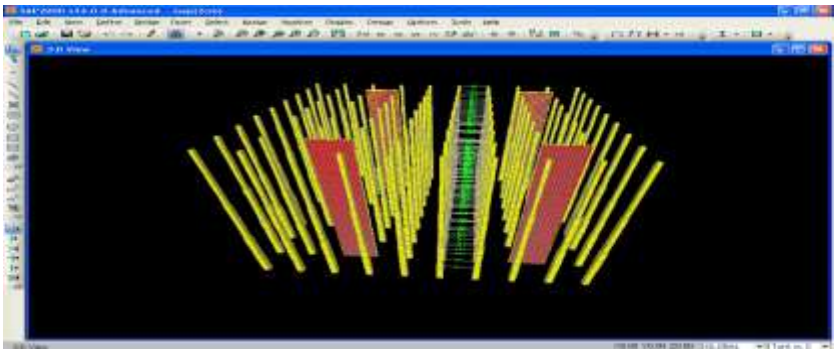
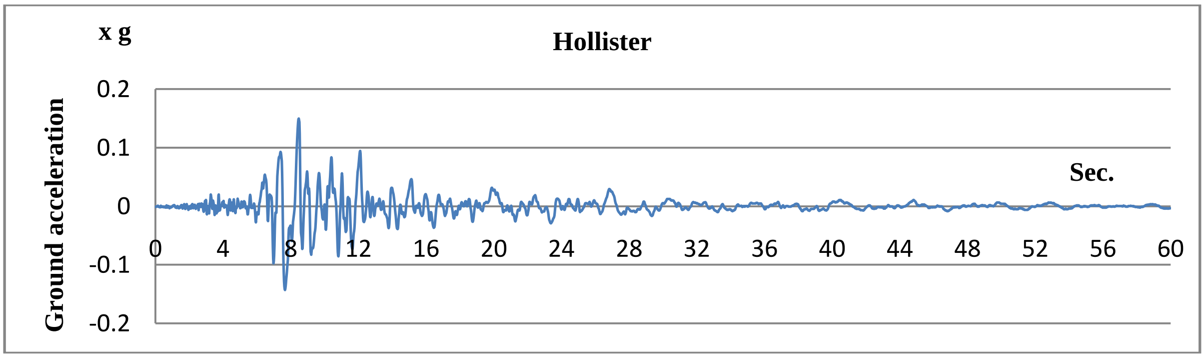


Figure 04 (Snapshot from SAP showing the gap elements connected the two buildings)

VI. Application of actual earthquake records to building analysis

Structural performance of buildings is estimated based on three natural ground motion records selected according to afore-mentioned criterion, namely Hollister, Newhall, and Sylmar. Peak accelerations of chosen earthquakes were normalized to 0.15g. This peak value was selected based on Egyptian Code recommendation that assigns such PGA value to Cairo zone. Figure (05) shows the three ground accelerations after scaling to 0.15g.



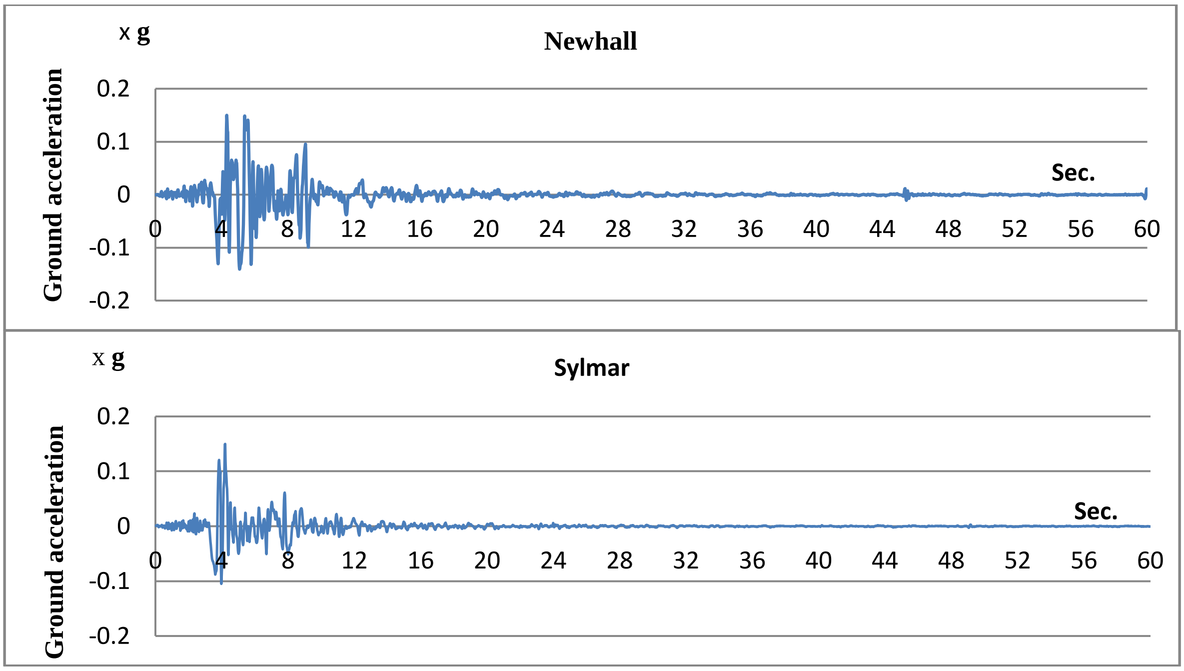


Figure 05 (Ground acceleration records for the three studied earthquakes)

Three models have been developed in order to study the effect of pounding under earthquake effect, by changing the height of building (2). The three models are as shown in Table (03).

Model	Building (1)		Building (2)		
	Number of floors	**Shear walls thickness**	**Number of floors**	**S.W.3 thickness**	**S.W.4 thickness**
1	13	30cm	13	60cm	60cm
2	13	30cm	9	60cm	60cm
3	13	30cm	6	60cm	60cm

Table 03(Describtion of the three proposed models)

Using the three earthquakes mentioned earlier, time history analysis has been performed on the three models in order to get the maximum displacement for the two buildings, and then the required gap distance to avoid pounding has been calculated using the Egyptian code (ECP 2012) for the four earthquakes and has been listed in Tables (04, 05, and 06).

Name of earthquake	**Maximum displacement of building (1)**	**Maximum displacement of building (2)**	**Required gap distance**
Hollister	0.25	0.25	0.25
Newhall	0.19	0.15	0.17
Sylmar	0.17	0.21	0.19

Table 04 (Maximum displacements in meters for the two buildings in model (1), and the required gap distance to avoid pounding)

Name of earthquake	**Maximum displacement of building (1) at the ninth floor**	**Maximum displacement of building (2)**	**Required gap distance**
Hollister	0.15	0.16	0.15
Newhall	0.11	0.17	0.14
Sylmar	0.10	0.12	0.11

Table 05 (Maximum displacements in meters for the two buildings in model (2), and the required gap distance to avoid pounding)

Name of earthquake	Maximum displacement of building (1) at the sixth floor	Maximum displacement of building (2)	Required gap distance
Hollister	0.08	0.08	0.08
Newhall	0.07	0.09	0.08
Sylmar	0.05	0.04	0.05

Table 06 (Maximum displacements in meters for the two buildings in model (3), and the required gap distance to avoid pounding)

Taking into considerations the results in tables 2-5 to 2-7, eight values of gap distances have been chosen for the analysis, namely, zero gap, 2cm, 5cm, 10cm, 15cm, 20cm, 25cm, and 30cm gaps.

VII. Results And Discussion

VII.1 Analysis Results for selected model [1] under the effect of different earthquake records

For Model [1], Pseudo spectral acceleration response, assuming 5% damping, for each of the selected ground motions has been developed using SAP for a point at the top of building (1) and another point at the top of building (2). Pseudo acceleration is a good representative for the energy gained by each building from the ground motion. Values are shown in Table (07).

First mode fundamental period (Seconds)	Pseudo Acceleration Response (m/sec^2) at the 13^{th} floor		
	Hollister	Newhall	Sylmar
Building (1) = 3.41	4.70	3.50	3.00
Building (2) = 2.76	5.25	2.50	5.35

Table 07 Pseudo Acceleration Response (m/sec^2) at the 13^{th} floor

As this research concentrates on the case of zero gap distance between buildings so, the maximum lateral displacements at each floor for points A and B of building (1) have been plotted for all studied ground motions in Figures (05, 06, and 07), These figures show that for three studied ground motions, the lateral displacements in positive direction which means right almost have not been changed and in negative direction which means left have been increased due to pounding with zero gap.

In addition, maximum lateral displacements at each floor for points C and D of building (2) have been plotted for all studied ground motions in Figures (08, 09, and 10), these figures show that for Hollister, the lateral displacements in positive and negative direction almost have not been changed due to pounding with zero gap. For Newhall, and Sylmar, the lateral displacements in positive direction almost have not been changed but in negative direction they have been decreased due to pounding compared to the no pounding case.

Curves clarify that in case of pounding with zero gap distances, the lateral displacements for building (1) remained almost constant or increased compared to the no pounding case. On the contrary the lateral displacements for building (2) remained almost constant or have been suppressed relative to no pounding case.
A reasonable explanation of such pattern of behavior may be found by referring to Table (07) where magnitude of pseudo acceleration response corresponding to fundamental period of building (2) is bigger than building (1). Thus, imparted energy to building (2) from selected earthquakes is higher than that of building (1), which magnified the displacements of building (1). In turn, building (1), which possesses higher mass, restrained the motion of building (2).

In the same context, Table (08) reports maximum roof displacements, either to right or left, of both buildings for no-pounding and pounding cases with different gap distances. The change in displacement, either it is increase or decrease, is a small value as it ranges from 1% to 19% in case of increasing and from 1.6% to 4.8% in case of decreasing, from the maximum roof displacements for the no pounding case.

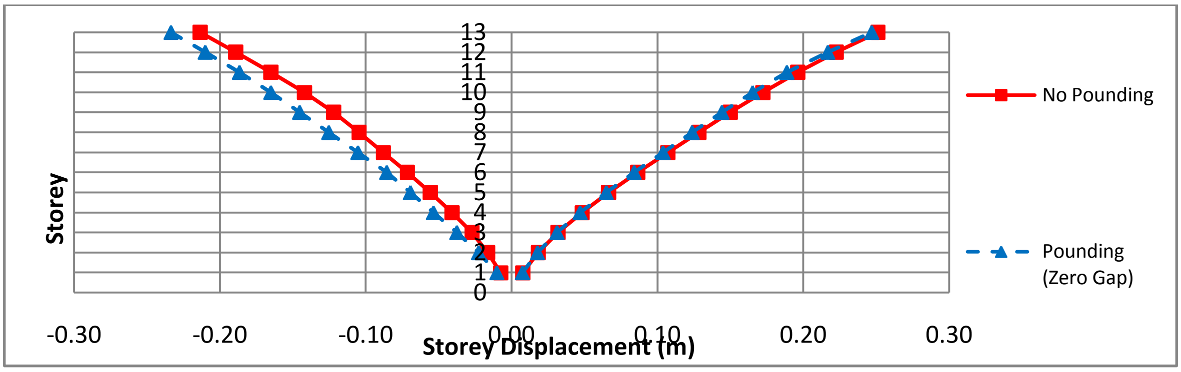


Figure (05) (Lateral displacements for all storeys under Hollister earthquake for building (1) in model (1))

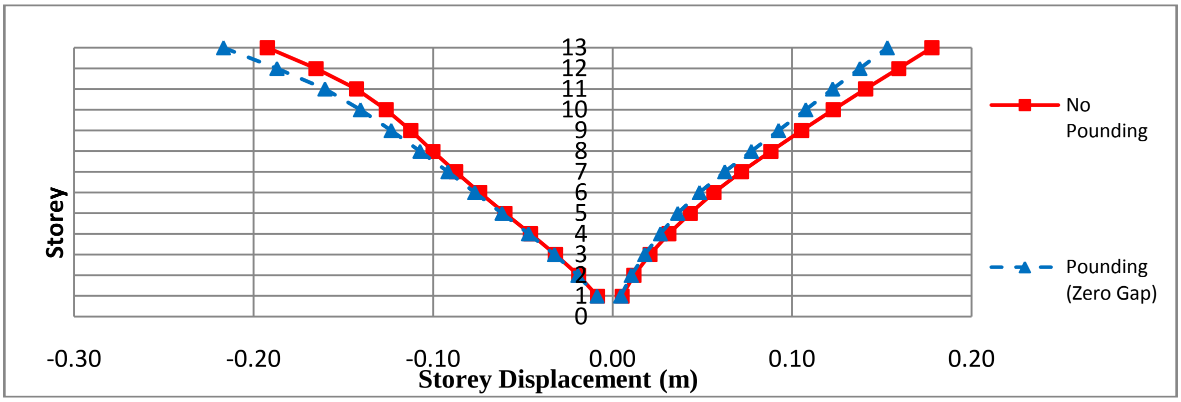


Figure (06) (Lateral displacements for all stories under Newhall earthquake for building (1) in model (1))

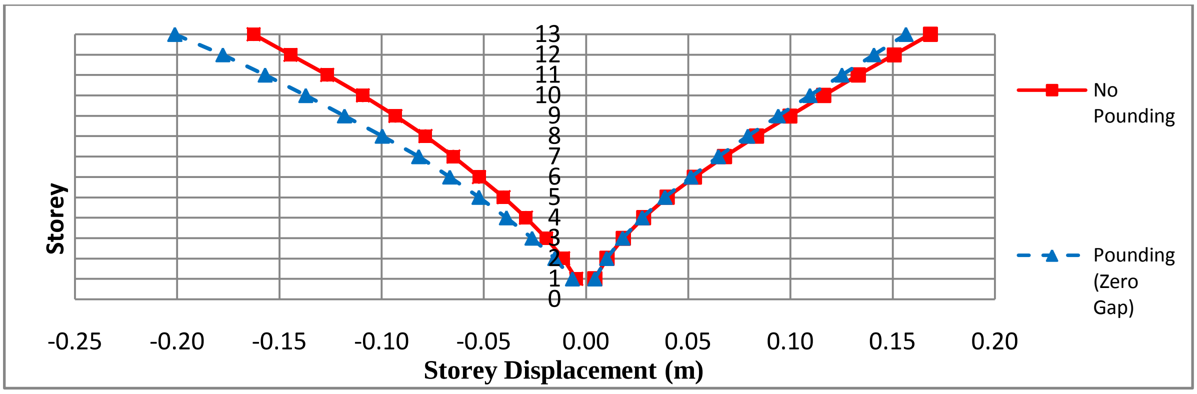


Figure (07) (Lateral displacements for all stories under Sylmar earthquake for building (1) in model (1))

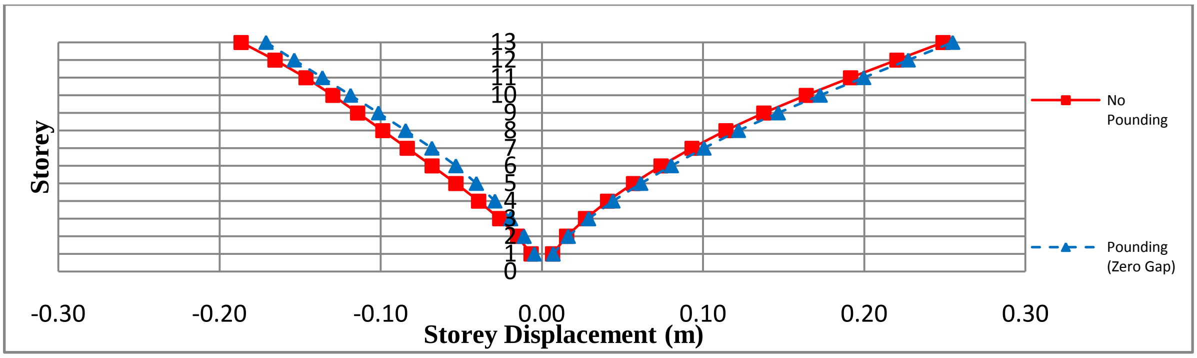


Figure (08) (Lateral displacements for all stories under Hollister earthquake for building (2) in model (1))

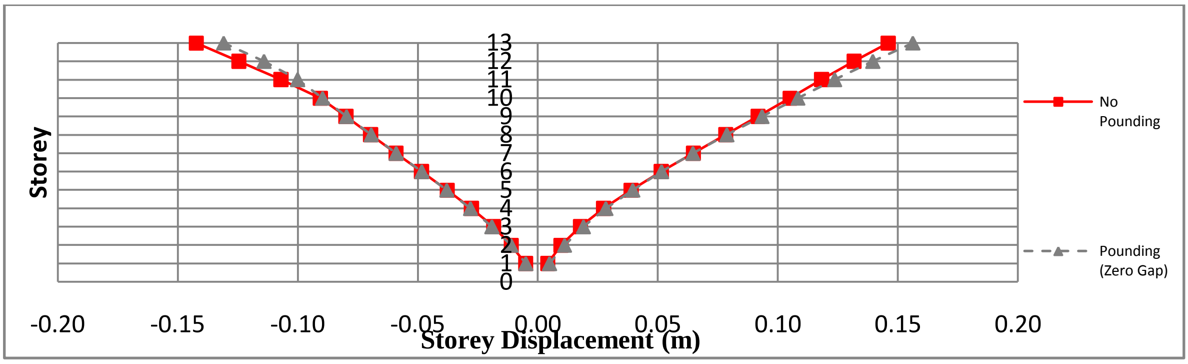


Figure (09) (Lateral displacements for all stories under Newhall earthquake for building (2) in model (1))

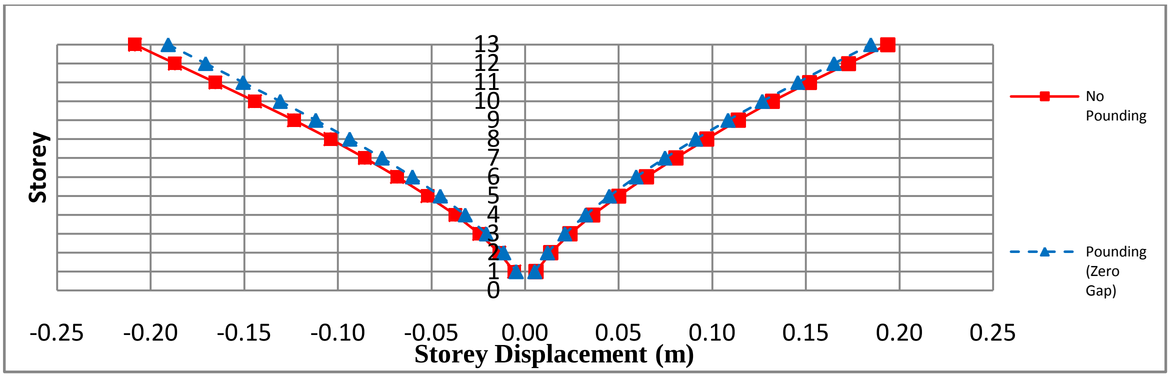


Figure (10) (Lateral displacements for all stories under Sylmar earthquake for building (2) in model (1))

Additional runs are performed on model 1, using different values for the gap distance. The results obtained are summarized in Table (08).

Building	Point	Gap distance	Hollister	Newhall	Sylmar
1	A&B	No pounding	0.2510	0.1923	0.1684
		Zero	0.2469	0.2168	0.2012
		2 cm	0.2561	0.2247	0.2177
		5 cm	0.2534	0.2176	0.2138
		10 cm	0.2618	0.1923	0.2197
		15 cm	0.2510	0.197	0.1945
		20 cm	0.2510	N.P	0.1684
		25 cm	0.2510	N.P	N.P
		30 cm	N.P	N.P	N.P
2	C&D	No pounding	0.2489	0.1460	0.2085
		Zero	0.2447	0.1562	0.1907
		2 cm	0.24539	0.1460	0.1726
		5 cm	0.2489	0.1460	0.1494
		10 cm	0.2489	0.1460	0.1832
		15 cm	0.2489	0.1460	0.1832
		20 cm	0.2489	N.P	0.2085
		25 cm	0.2489	N.P	N.P
		30 cm	N.P	N.P	N.P

Table 08 (Maximum roof displacements of buildings 1&2 in model (1))

To study the effect of pounding on straining actions of the structural elements, moment on shear wall (1) and (3) have been plotted with different gap distances in Figures from (11) to (13). These figures show that in case of pounding with zero gap the straining actions on S.W.1 of building (1) almost have not been changed or have been magnified compared to the no pounding case, on contrary, straining actions of S.W.3 of building (2) almost have not been changed or have been suppressed relative to the no pounding case. These observations explain the high imparted energy by building (2) than building (1). Also, an important finding can be captured that the bending moment on S.W1 and S.W3 at "Zero Gap" case is less than the case of 2 or 5 cm for most of cases.

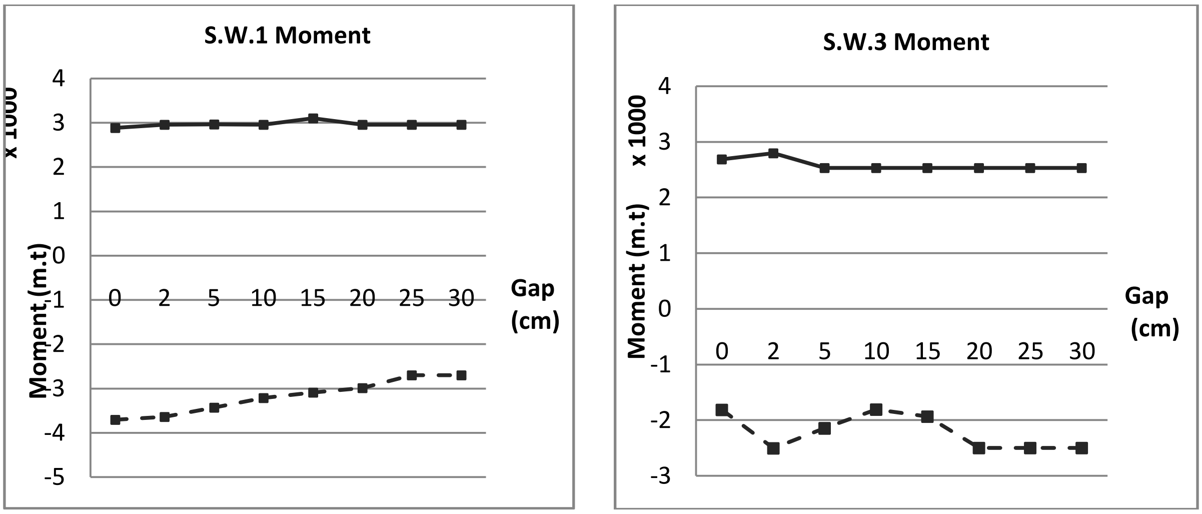


Figure (11) (Shear walls bending moments under Hollister earthquake)

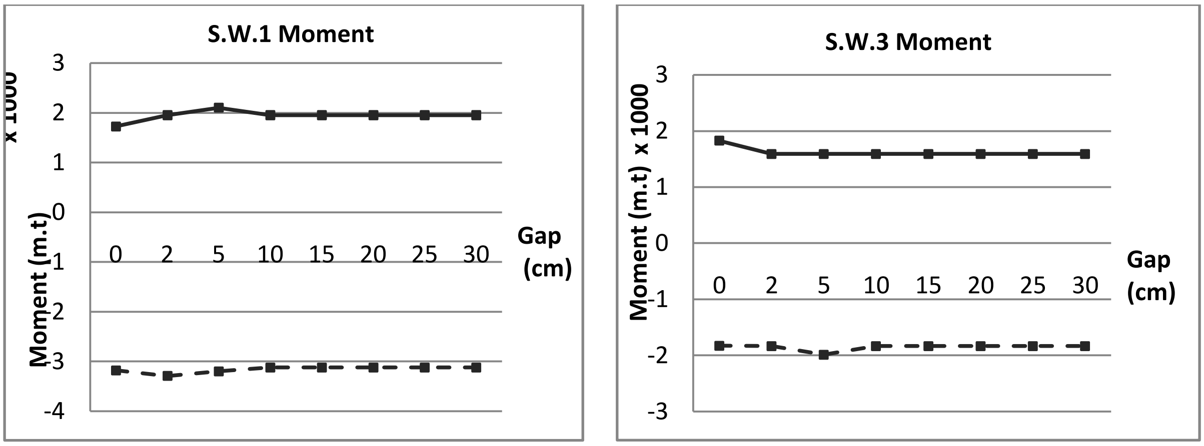


Figure (12) (Shear walls bending moments under Newhall earthquake)

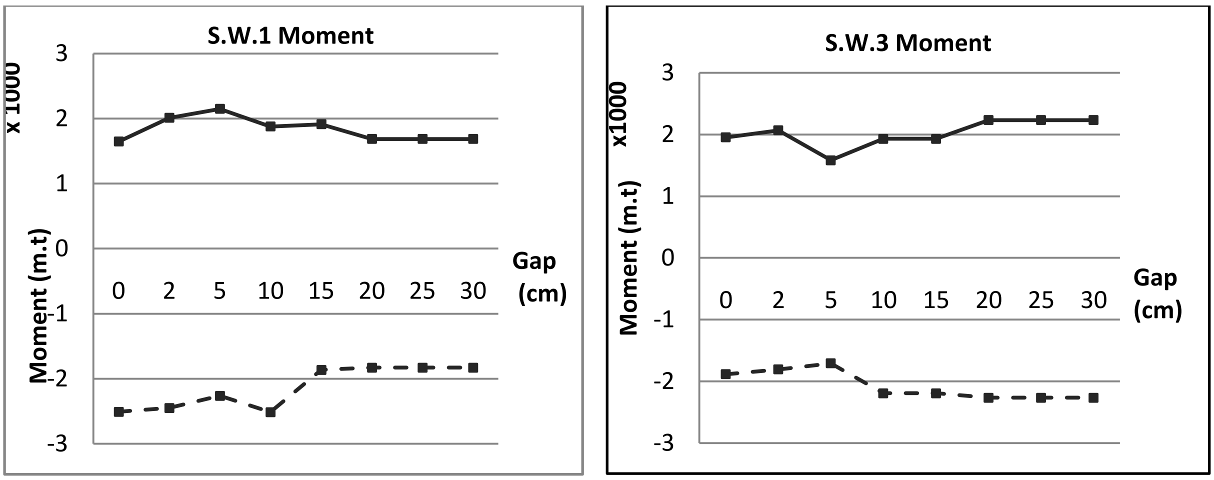


Figure (13) (Shear walls bending moments under Sylmar earthquake)

By another way, the maximum moments, whether they are positive or negative, of shear walls in case of no pounding and case of pounding with zero gap distance are tabulated in Table (09).

		Hollister	Newhall	Sylmar
Maximum moment on S.W.1	No pounding	2952m.t	3121m.t	1829m.t
	Pounding (gap=0)	3704m.t	3177m.t	2511m.t
Maximum moment on S.W.3	No pounding	2529m.t	1821m.t	2267m.t
	Pounding (gap=0)	2686m.t	1818m.t	1851m.t

Table 09 (Bending moment of shear walls in model (1) under different ground motions)

The maximum magnification in moments for pounding case with zero gap distance is obtained in building (1) from Sylmar earthquake and equals 37.28% relative to no pounding case, and the maximum reduction in straining actions is obtained in building (2) from Sylmar earthquake and equals 18.54% relative to no pounding case.

Similarly, moments on column (1) and (3) have been studied, and the same findings of shear walls results have been captured. Also a comparison between "no pounding case and pounding with zero gap" is shown in Table (10) with a magnification reaches 42% for building (1) and a reduction up to 18% for building (2). Also, bending moment on C1 and C3 at "Zero Gap" case is less than the case of 2 or 5 cm.

		Hollister	Newhall	Sylmar
Maximum moment on C1	No pounding	29.04m.t	33.32m.t	17.66m.t
	Pounding (gap=0)	40.50m.t	33.76m.t	25.18m.t
Maximum moment on C3	No pounding	25.16m.t	20.53m.t	22.04m.t
	Pounding (gap=0)	24.82m.t	18.67m.t	18.14m.t

Table 10 (Bending moment of columns in model (1) under different ground motions)

Maximum impact force in gap elements 1,2,3,4, and 5 have been plotted with different gap distances at three selected levels; first floor, sixth floor, and 13th floor for all ground motions in Figures from (14) to (16).

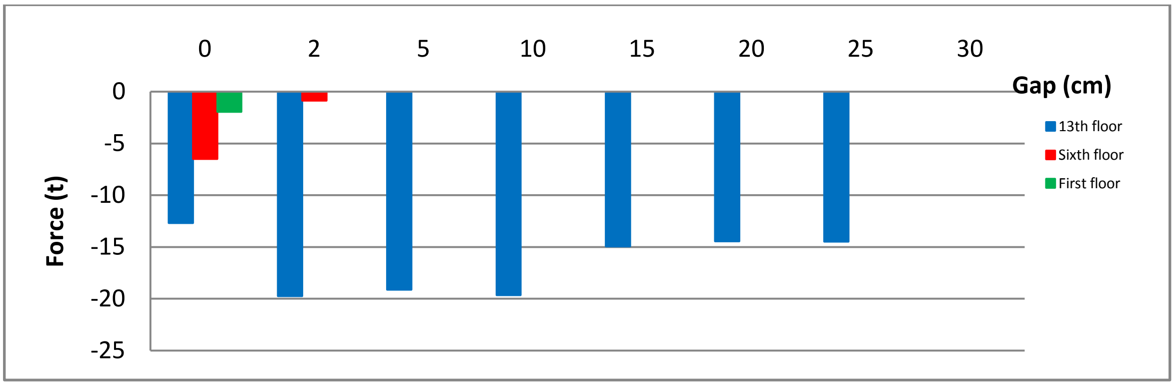


Figure 14 (Forces in gap elements 1,2,3,4, and 5 in model (1) with different gap distances under Hollister earthquake)

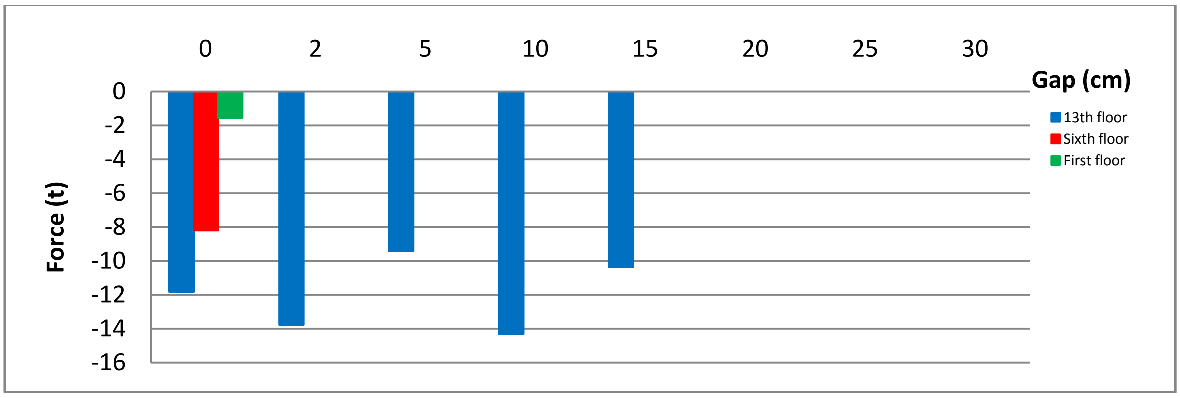


Figure 15 (Forces in gap elements 1,2,3,4, and 5 in model (1) with different gap distances under Newhall earthquake)

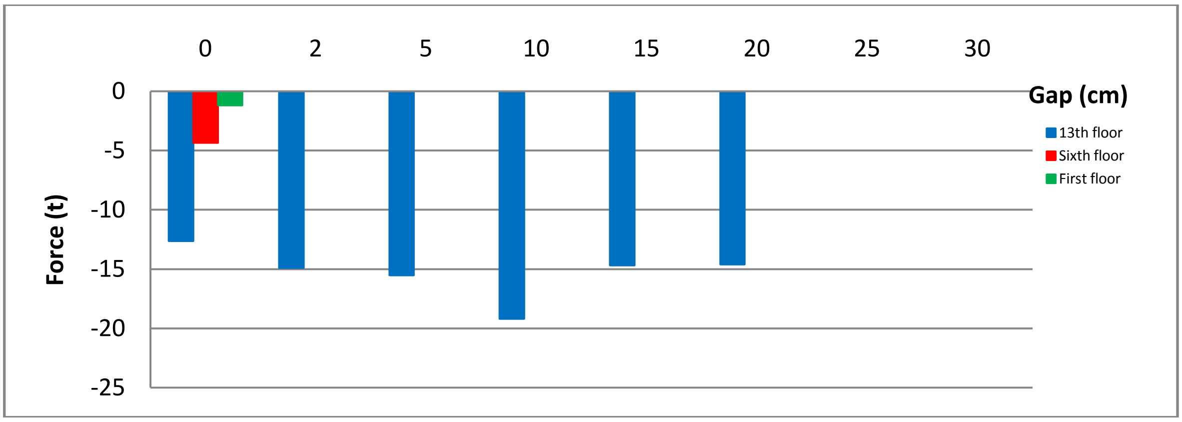


Figure 16 (Forces in gap elements 1,2,3,4, and 5 in model (1) with different gap distances under Sylmar earthquake)

From previous figures, It is clear that for Hollister, pounding still occurs until gap equals 25 cm which is required by ECP. For Sylmar, pounding still occurs until gap equals 20 cm, however ECP requires a smaller value to prevent pounding. Also it can be noticed that the force obtained in gap elements at zero gap distance is almost smaller than at other gap distances when pounding occurs, specially 2 cm. Reasonable explanation for that is in case of zero gap distance, each building highly resists the other one which leads to light collision.

VII.2 Analysis Results for selected Models (2) and (3)under the effect of different earthquake records

pseudo spectral acceleration response, assuming 5% damping, for each of the selected ground motions has been developed by SAP for a point in the ninth floor of building (2) and another point at the top of building (1). Results are shown in Tables (11 & 12)

First mode fundamental period (Seconds)	**Pseudo Acceleration Response (m/sec^2) at the ninth floor**		
	Hollister	Newhall	Sylmar
Building (1) = 3.41	2.91	1.80	1.83
Building (2) = 1.44	12.9	15.6	12.0

Table 11 (Pseudo Acceleration Response (m/sec^2) at the ninth floor for buildings in mode (2))

First mode fundamental period (Seconds)	**Pseudo Acceleration Response (m/sec^2) at the sixth floor**		
	Hollister	Newhall	Sylmar
Building (1) = 3.41	1.67	1.04	0.98
Building (2) = 0.73	30.4	38.9	7.24

Table 12 (Pseudo Acceleration Response (m/sec2) at the sixth floor for buildings in model (3))

Results which had been captured from models 2 and 3 are similar to those of model 1 which clarify that in case of pounding with zero gap distances, the lateral displacements for building (1) remained almost constant or increased compared to the no pounding case for all ground motions. On the contrary the lateral displacements for building (2) have been suppressed with big values relative to no pounding case for all ground motions. The captured behavior is due to that imparted energy to building (2) from selected earthquakes is much higher than

that of building (1), which magnified the displacements of building (1) due to the strong shock resulted from pounding. In turn, building (1), which possesses higher mass, restrained the motion of building (2).
In the same context, Tables (13 and 14)report maximum roof displacements, either to right or left, of both buildings for no-pounding and pounding cases with different gap distances. Moreover, it is clear that the change in displacement ranges from 16% to 40% (in case of increasing) and ranges from 3% to 47% (in case of decreasing) from the maximum roof displacements for the no pounding case for all ground motions.

Building	**Point**	**Gap distance**	**Hollister**	**Newhall**	**Sylmar**
1	A&B	No pounding	0.2510	0.1923	0.1684
		Zero	0.2829	0.2409	0.2314
		2 cm	0.2866	0.2238	0.2346
		5 cm	0.2450	0.2297	0.2356
		10 cm	0.2510	0.2249	0.2116
		15 cm	0.2510	0.2104	N.P
		20 cm	0.2510	N.P	N.P
		25 cm	N.P	N.P	N.P
		30 cm	N.P	N.P	N.P
2	C&D	No pounding	0.1614	0.1683	0.1164
		Zero	0.1390	0.1021	0.0973
		2 cm	0.1086	0.0898	0.0905
		5 cm	0.1002	0.1060	0.0796
		10 cm	0.0888	0.1240	0.0901
		15 cm	0.0888	0.1557	N.P
		20 cm	0.1295	N.P	N.P
		25 cm	N.P	N.P	N.P
		30 cm	N.P	N.P	N.P

Table 13 (Maximum roof displacements of buildings 1&2 in model (2))

Building	**Point**	**Gap distance**	**Hollister**	**Newhall**	**Sylmar**
1	A	No pounding	0.2510	0.1923	0.1684
		Zero	0.2382	0.2259	0.2382
		2 cm	0.2178	0.2084	0.2127
		5 cm	0.2310	0.1976	0.1749
		10 cm	0.2480	N.P	N.P
		15 cm	N.P	N.P	N.P
		20 cm	N.P	N.P	N.P
		25 cm	N.P	N.P	N.P
		30 cm	N.P	N.P	N.P
	B	No pounding	0.2510	0.1923	0.1684
		Zero	0.2382	0.2259	0.2382
		2 cm	0.2178	0.2084	0.2127
		5 cm	0.2310	0.1976	0.1749
		10 cm	0.2480	N.P	N.P
		15 cm	N.P	N.P	N.P
		20 cm	N.P	N.P	N.P
		25 cm	N.P	N.P	N.P
		30 cm	N.P	N.P	N.P
2	C	No pounding	0.0775	0.0970	0.043
		Zero	0.0749	0.0887	0.0404
		2 cm	0.0775	0.0948	0.0304
		5 cm	0.0775	0.1067	0.0403
		10 cm	0.0775	N.P	N.P
		15 cm	N.P	N.P	N.P
		20 cm	N.P	N.P	N.P
		25 cm	N.P	N.P	N.P
		30 cm	N.P	N.P	N.P
	D	No pounding	0.0775	0.0970	0.043
		Zero	0.0749	0.0887	0.0404
		2 cm	0.0775	0.0948	0.0304
		5 cm	0.0775	0.1067	0.0403
		10 cm	0.0775	N.P	N.P
		15 cm	N.P	N.P	N.P
		20 cm	N.P	N.P	N.P
		25 cm	N.P	N.P	N.P
		30 cm	N.P	N.P	N.P

Table 14 (Maximum roof displacements of buildings 1&2 in model (3))

To study the effect of pounding on straining actions of the structural elements in models 2 and 3, moment on shear wall (1) and (3) has been compared with different gap distances, show that in case of pounding with zero gap distance the moments on S.W.1 of building (1) almost have been magnified compared to the no pounding case for most of the ground motions, on contrary, moments of S.W.3 of building (2) almost have been suppressed relative to the no pounding case for all ground motions. These observations explain the high imparted energy by building (2) than building (1). Also, an important finding can be captured that the bending moment on S.W1 and S.W3 at "Zero Gap" case is less than the case of 2 or 5 cm.
By another way, the maximum moments, whether they are positive or negative, of shear walls in case of no pounding and case of pounding with zero gap distance are tabulated in Tables (15& 16).

		Hollister	**Newhall**	**Sylmar**
Maximum moment on S.W.1	No pounding	2952m.t	3121m.t	1829m.t
	Pounding (gap=0)	4273m.t	3860m.t	2562m.t
Maximum moment on S.W.3	No pounding	3076m.t	3023m.t	2462m.t
	Pounding (gap=0)	2685m.t	2323m.t	2080m.t

Table 15 (Moments on shear walls (1) and (3) in model (2))

		Hollister	**Newhall**	**Sylmar**
Maximum moment on S.W.1	No pounding	2952m.t	3121m.t	1829m.t
	Pounding (gap=0)	3143m.t	3140m.t	2374m.t
Maximum moment on S.W.3	No pounding	3106m.t	3851m.t	1570m.t
	Pounding (gap=0)	3017m.t	3546m.t	1410m.t

Table 16 (Moments on shear walls (1) and (3) in model (3))

The maximum magnification in moments for pounding case with zero gap distance is obtained in building (1) from Hollister earthquake and equals 54% relative to no pounding case, and the maximum reduction in straining actions is obtained in building (2) from Newhall earthquake and equals 21% relative to no pounding case.

Maximum force in gap elements 1,2,3,4, and 5 have been plotted with different gap distances at three selected levels; first floor, sixth floor, and ninth floor for Hollister ground motions as an example in Figures (17 & 18)

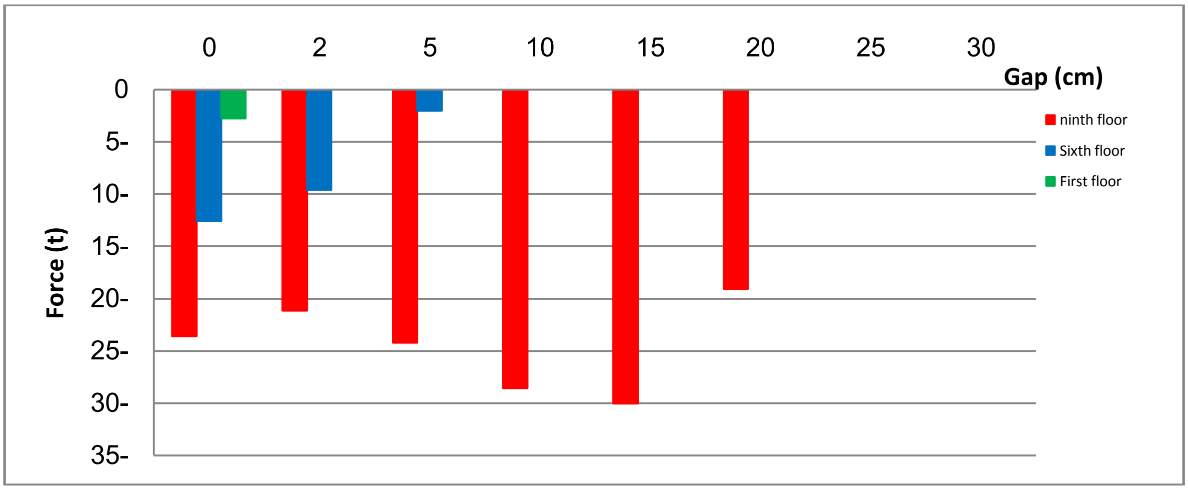


Figure 17 (Forces in gap elements 1,2,3,4, and 5 in model (2) with different gap distances under Hollister earthquake)

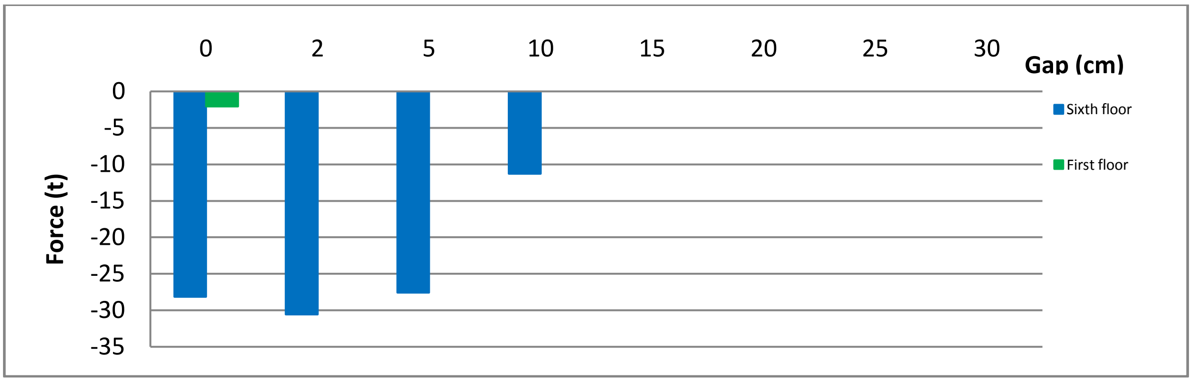


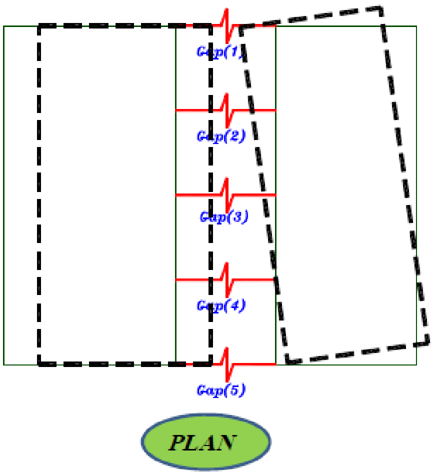
Figure 20 (Forces in gap elements 1,2,3,4, and 5 in model (3) with different gap distances under Hollister earthquake)

Previous figures reveal that models 2 and 3 exhibit pounding at values higher than those calculated by ECP-2012. So it can be noticed that gap distance calculated by ECP-2012 is not sufficient to prevent pounding. Also the force obtained in gap elements at zero gap distance is almost smaller than at other gap distances when pounding occurs. Reasonable explanation for that is in case of zero gap distance, each building highly resists the other one which leads to light collision.

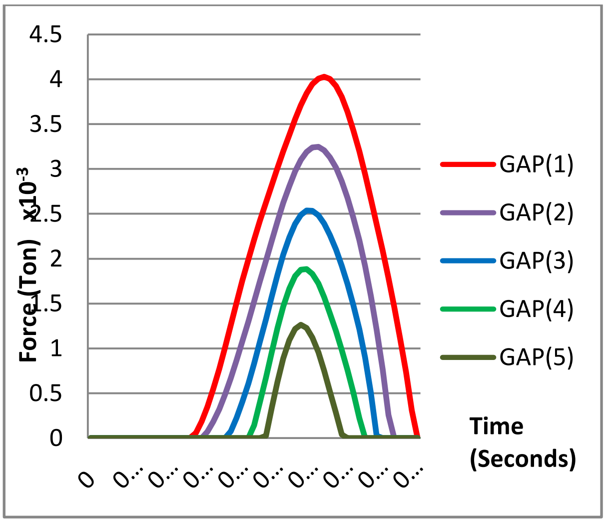
VII.3 Effect of Torsional Building Movements on pounding behavior

To investigate the effect of torsional movement on pounding phenomenon, model (4) had been developed shifting strong structural elements in building (2) to one side so as to cause high torsional movements by increasing the thickness of shear wall (4) to 75 cm and decreasing the thickness of shear wall (3) to 45 cm. Modifications resulted in torsional movement for building (2) while no change occurred to building (1). Sylmar earthquake had been selected to be applied on model (4).

Time history analysis had been executed, and successive pounding had been noticed starting from one end of the building toward the other one. Force resulting from the first collision had been plotted with time at Figure (21) which illustrates that the collision force started with a big value at one end. Due to the successive pounding, force in gap elements toward the other side of building was found to have smaller values. That means the longer distance which gap element has from the first point of collision, the smaller force that it will gain from collision.



a) Schematic plan illustrates location of gap elements and torsional movement



b) Force-Time relation for the first collision at each gap element

Figure 21 (Effect of torsional movement on successive pounding)

In addition, a comparison had been held between the force-time integral (area under the curve between force and time) for the first collision at the five gap elements in case of pounding with no torsional movement and case pounding with torsional movement. Results are tabulate at Table (17) which illustrates that two cases have approximately the same summation of force time integral for the five gap elements. While the difference in value of gap element force for pounding and no pounding cases reaches 96% which show the high effect of torsion on forces resulting from pounding.

Gap element	1	2	3	4	5
Force-Time integral (N.S) (No torsional movement)	11.5	11.5	11.5	11.5	11.5
Force-Time integral (N.S) (with torsional movement)	22.5	15.4	9.9	5.6	2.7

Table 17 (Force-Time integral of five selected gap elements for pounding with and without torsional movement)

Maximum lateral displacements at each floor for points (A) and (B) of building (1) have been plotted in Figures (22&23). An increase in lateral displacements of point (A) at all floors can be captured. Also lateral displacements of point (B) have been increased at one direction while had been decreased at the other one, butfinally the maximum displacements had been magnified. In addition, maximum lateral displacements for points (C) and (D) at each floor had been plotted in Figures (24&25). Reduction at displacementvalues of point (C) can be clearly captured at all floors, however magnification in displacement values of point (D) had been occurred. Behaviour of points (A) and (B) can be explained by the high energy imparted to building (2) which resulted in magnification of displacements of building (1). On the other hand, Torsional behavior of building (2) is resisted by building (1) by reducing displacements at the weaker side where point (C) is located and increasing the displacements on the other stronger side where point (D) is located. Previous observations and explanations lead to the fact that torsional behavior of buildings is supposed to be resisted by pounding effect.

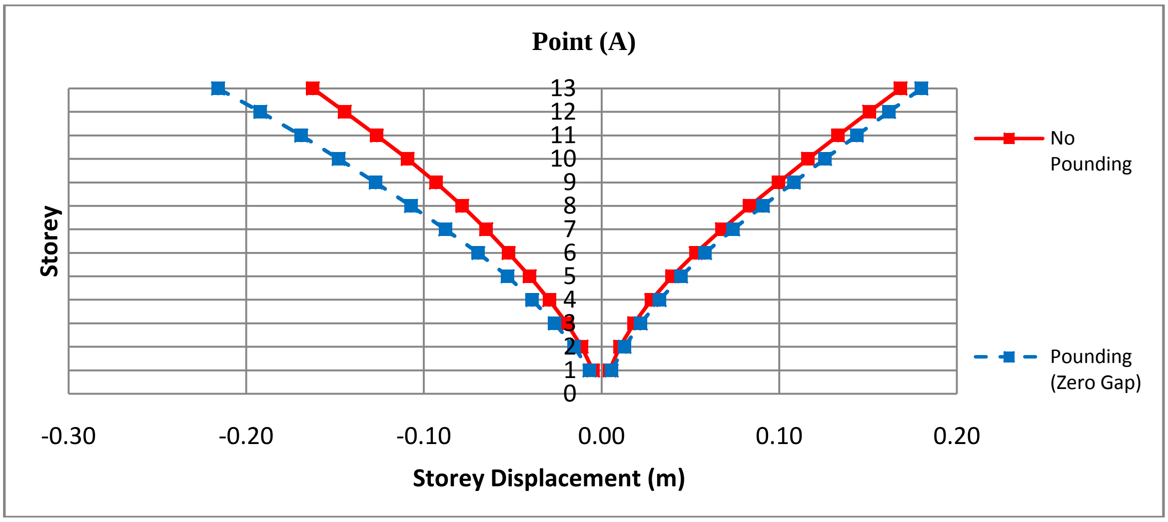


Figure 22 (Maximum lateral displacements for all stories under Sylmar earthquake for point (A) in model (4))

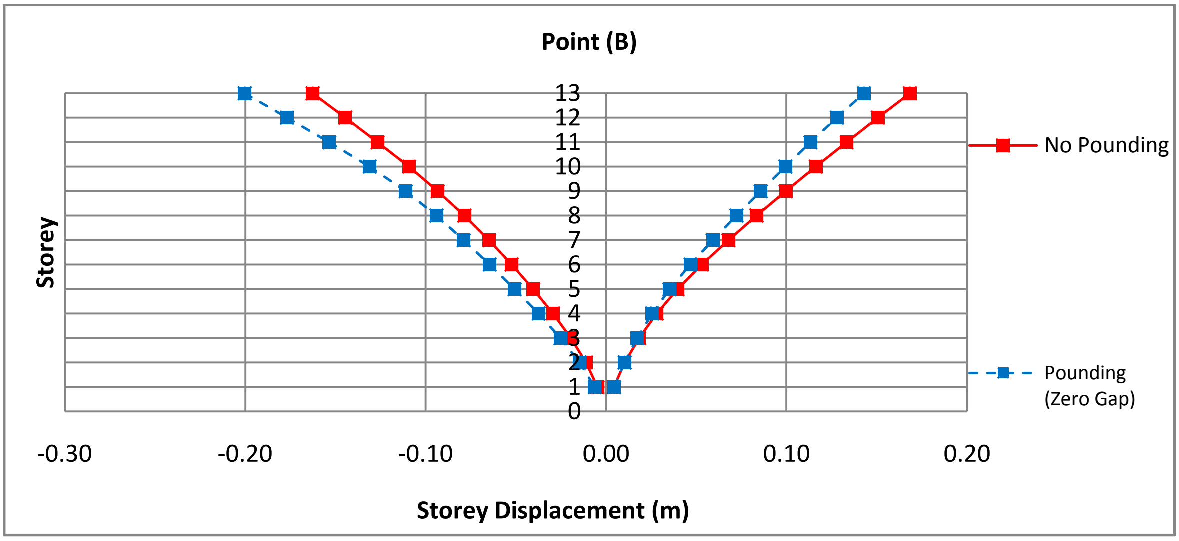


Figure 23 (Maximum lateral displacements for all stories under Sylmar earthquake for point (B) in model (4))

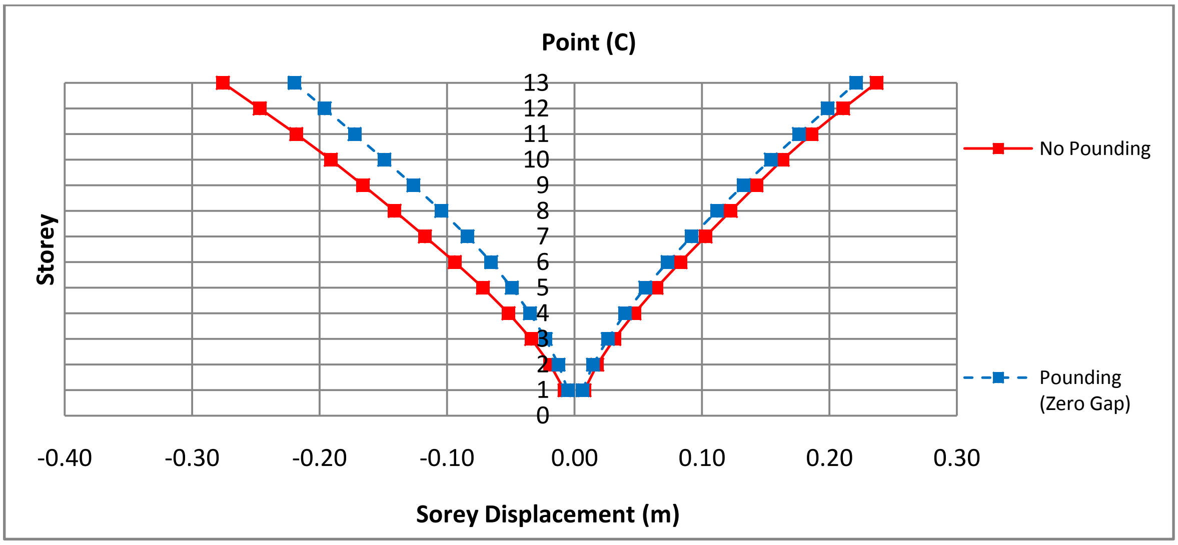


Figure 24 (Maximum lateral displacements for all stories under Sylmar earthquake for point (C) in model (4))

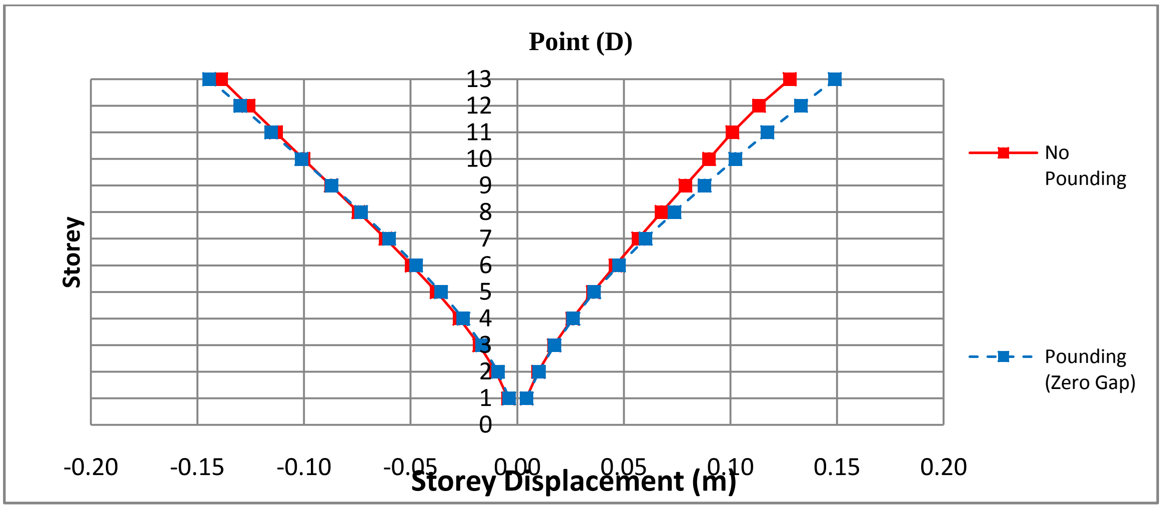


Figure 25 (Maximum lateral displacements for all stories under Sylmar earthquake for point (D) in model (4))

Bending moments on shear walls (1, 2, 3, and 4) had been plotted in Figures (26, 27, 28, and 29). Values confirm the captures behavior as moments on shear walls (1, and 2) had been increased with pounding compared to no pounding case. As a result of restricting torsional behavior of building (2), moments on shear wall (3) which located at the weaker side of building had been decreased while moments on shear wall (4) had been increased. Table (18) is showing the bending moments on shear walls without pounding compared to pounding with zero gap.Results of bending moments confirm that torsional behavior of the building is improved by pounding effect, as moments at the weaker side of the building which are with big values are decreased due to pounding while moments at the stronger side are increased.

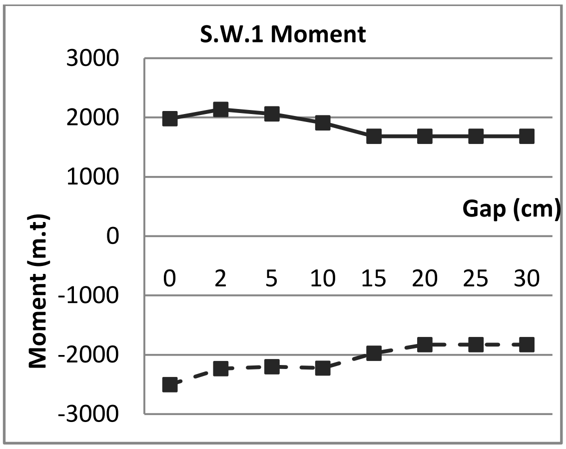


Figure (26) (Shear wall (1) bending moments under Sylmar earthquake in model (4))

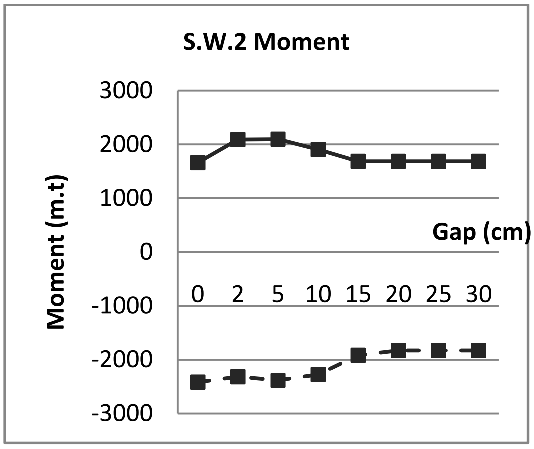


Figure (27) (Shear wall (2) bending moments under Sylmar earthquake in model (4))

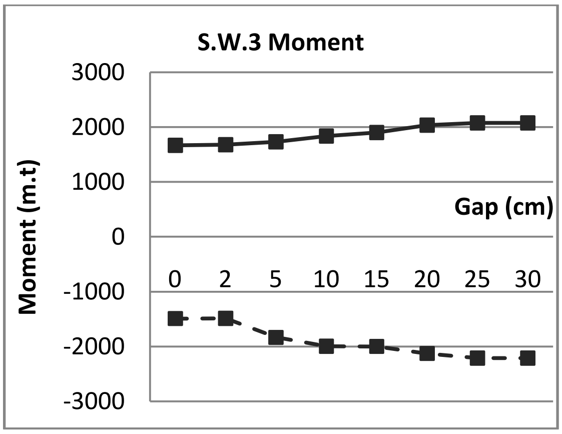


Figure (28) (Shear wall (3) bending moments under Sylmar earthquake in model (4))

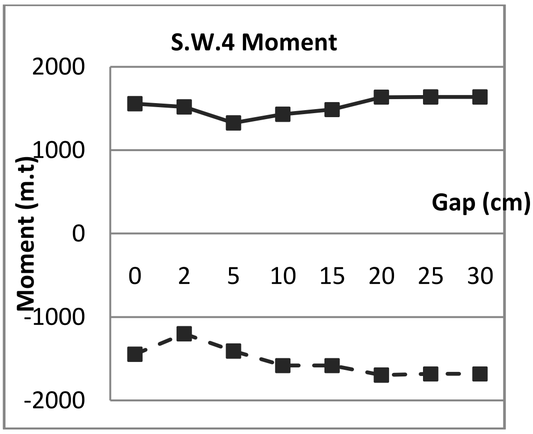


Figure (29) (Shear wall (4) bending moments under Sylmar earthquake in model (4))

		Hollister	Newhall	Sylmar
Maximum moment on S.W.1	No pounding	2952m.t	3121m.t	1829m.t
	Pounding (gap=0)	3695m.t	3462m.t	2501m.t
Maximum moment on S.W.2	No pounding	2952m.t	3121m.t	1829m.t
	Pounding (gap=0)	3574m.t	3005m.t	2418m.t
Maximum moment on S.W.3	No pounding	2525m.t	1892m.t	2212m.t
	Pounding (gap=0)	2391m.t	1753m.t	1667m.t
Maximum moment on S.W.4	No pounding	1792m.t	1387m.t	1680m.t
	Pounding (gap=0)	2104m.t	1330m.t	1557m.t

Table 18 (Moments on shear walls (1), (2), (3) and (4) in model (4) in model (4))

Force in three gap elements had been plotted at Figures. One of them (Gap element 1) is located at the weaker side of building, another one (Gap element 2) is located at the middle of building, and the last one (Gap element 5) is at the stronger side. Results show that the resulting gap forces are high at the two ends of building (Gap elements 1 and 5) while they are small at the middle of building which illustrates the high effect of torsional movement of building 2 on the resulting gap forces, and accordingly the resulting displacement and straining actions.

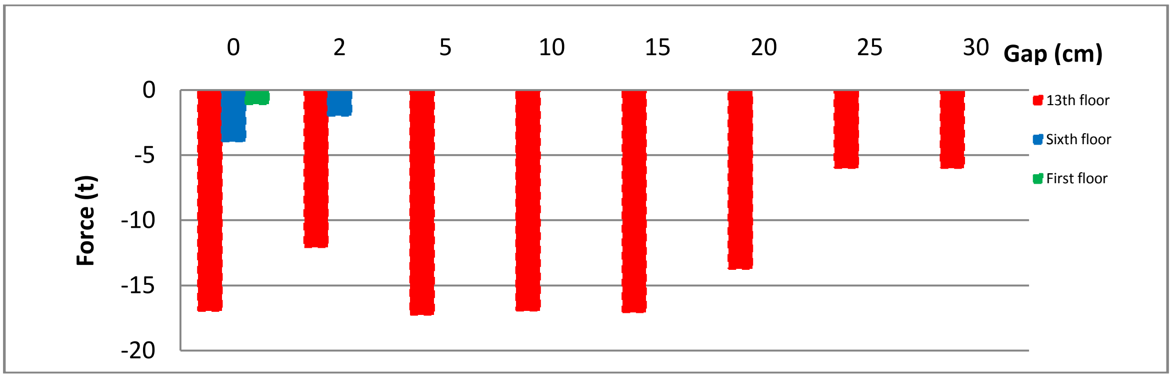


Figure 30 (Forces in gap elements (1) in model (4) with different gap distances)

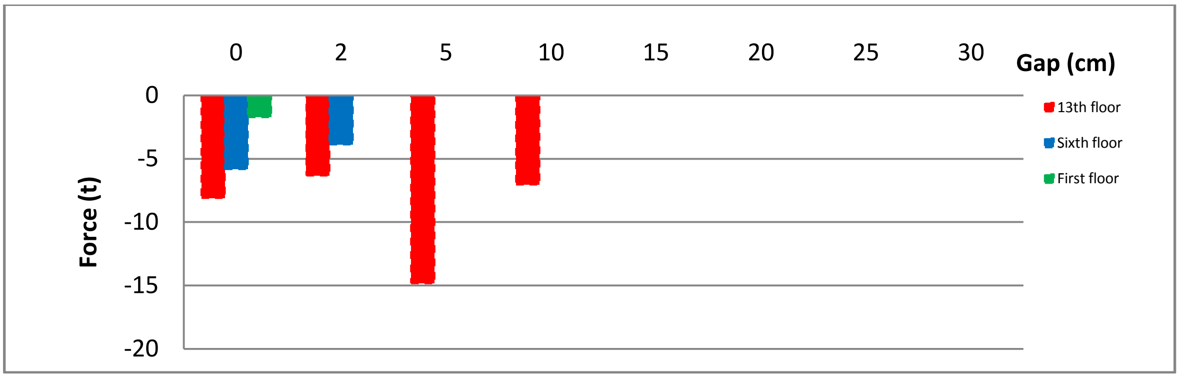


Figure 31 (Forces in gap elements (3) in model (4) with different gap distances)

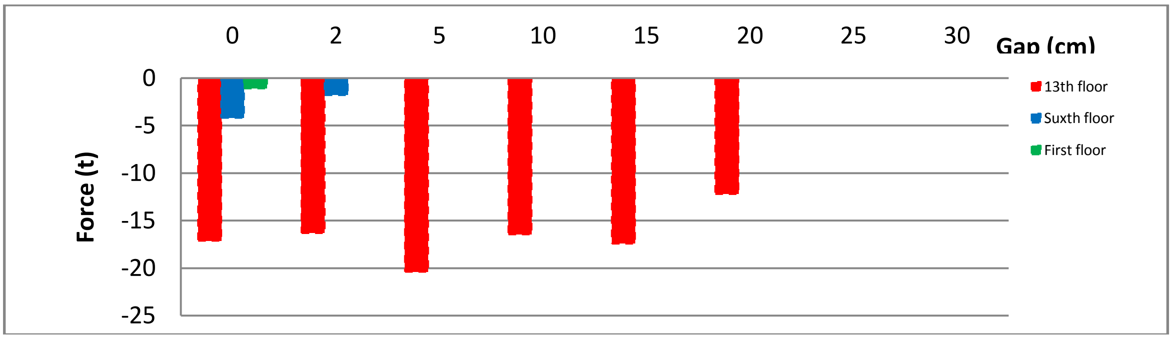


Figure 32 (Forces in gap elements (5) in model (4) with different gap distances)

VIII. Summary And Conclusions

The research work presented in this thesis deals with the structural behavior of adjacent buildings that suffer from "pounding" during earthquakes. The simulation of this "pounding" phenomenon is addressed in this study, and an extensive parametric study is performed to investigate the behavior patterns of adjacent buildings under "pounding" effect.

3-D finite element modeling was used to model the adjacent buildings and to perform time history analysis using four actual earthquake records. Gap element from the finite element program library was used to simulate the interaction between the adjacent buildings during pounding. Verification of time history analysis and gap element had been performed and illustrated in this thesis.

Parametric study was developed to simulate pounding between adjacent buildings with different gap distances, different heights, and different distribution for structural elements using 3-D models with a special emphasis on the case of zero gap distance. The effect of pounding on displacements and straining actions of colliding buildings was investigated.

Concentrating on practical application of pounding of two actual designed buildings located in Cairo, another parametric study was developed to investigate the effect of pounding on those buildings using 3-D models.

A discussion of the results of the parametric study was presented, and comparison was made between the analysis results and the Egyptian code of practice. The findings of the study were used to develop the following general conclusions, and recommendations.

General pounding behavior

1. The analytical model developed in this thesis is capable of accurate prediction of three-dimensional dynamic response of structures under pounding effect.
2. The fundamental natural period of the building controls the magnitude of imparted energy to this building which in turn has a highly significant effect on the interaction between the adjacent buildings.
3. From the analysis results, it was found that Pseudo acceleration for a building is a good representative for the magnitude of imparted energy to that building.
4. The building which has higher energy gives a stronger shock to the other building resulting in increasing displacements and straining actions for elements of the shocked building.
5. Buildings with heavy masses resist the motion of the adjacent lighter buildings, which results in mitigating displacements and straining actions of those lighter buildings.
6. Designed strong lateral resisting elements will suppress the displacements and straining actions resulted from pounding in the building at which they are located.
7. Loose building which have not enough lateral resisting elements will suffer from pounding, the displacements and straining actions of it will be increased due to pounding significantly.

Effect of building torsional movement on pounding behavior

8. The effect of building torsional movement was found to have a highly significant effect on the pounding response of the adjacent buildings.
9. Buildings subjected to torsional movement were found to undergo a “successive pounding” behavior, where pounding starts at one edge of the contact boundary and progresses towards the other end, as the buildings come in contact together. The resulting forces and impact effect was found to be highest at the starting point.
10. Maximum contact force (and impact effect) were found to be significantly higher in case of buildings subject to torsion, than for the case of NO-torsion behavior. 3-D analysis of the pounding phenomenon is essential for prediction of this type of behavior.

Effect of gap distance variation

11. Effect of the gap distance between adjacent buildings on their pounding behavior was found to be highly significant.
12. In general, gap distances in the range of 2 to 5 cm (very common expansion joint distanced in practice in Egypt) was found to produce very high pounding effect, and in most cases producing the maximum pounding effect.
13. The case of “ZERO gap distance” between adjacent buildings, (very common practice in OLD CAIRO districts) was found to produce high pounding effect. However, in most cases, this effect was less than the case of (2 to 5 cm gap).
14. Higher gap distances, specified by the Egyptian code of practice produced a significant reduction in the pounding effect, and in some cases avoided pounding altogether. However, these distances are specified for the case of expansion joints separating 2 parts of the same building. This does not apply to 2 different buildings where licence procedures in old Cairo districts allow building owners to erect buildings with zero gap between them.
15. Based on the results of this study, it is highly recommended that the specifications of the Egyptain code of practice regarding “separation distance” be extended to the licence procedures in order to make it imperative for building owners to leave this separation distance between any newly built building, and the adjacent existing buildings.

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