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Seismic Pounding Analysis of Adjacent RC Structures with Eccentric Alignment

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Abstract
One of the main hazards during an earthquake is the collision between structures caused by earthquake excitations, due to the constrained separation gap between adjacent buildings. The seismic lateral oscillation of adjacent buildings with eccentric alignment is partly restrained, and therefore a torsional response is induced in the building under earthquake excitation. Due to this, a significant increase in collisions, building displacements, torsion demands are seen. This paper studies the effect of pounding on adjacent RCC buildings with eccentric alignments. The study focuses on two adjacent buildings that have different storey heights, but same floor heights and compare two different in-plan alignment configurations, namely one-bay setback and two-bay setback, with the case that has no setback. The buildings are modelled in Etabs software and time history analysis has been carried out. Results in terms of pounding force, maximum storey displacements and maximum storey rotations are presented and commented. The results show that the magnitude of pounding force increases with increase in the setback distance. Overall displacement is significantly impacted by setbacks, and larger setback distances result in increased displacements in the structures. Eccentric pounding causes significant increase in torsional movement of the building although the plan views are symmetrical.

Keywords
Eccentric Pounding, Gap Element, Time History Analysis, Pounding force

1. Introduction

1.1 Background

During an earthquake, the collision of surrounding buildings or structures may cause significant local damage or structural collapse. When the inherent frequencies of adjacent structures differ, they can undergo Seismic Pounding and vibrate out of phase. The concern of seismic pounding is particularly prominent in earthquake-prone areas, particularly those with a dense concentration of multi-story buildings. Many earthquakes have demonstrated the occurrence of structural pounding. The 1944 Elcentro earthquake, the 1985 Mexico earthquake, the 1994 Northridge earthquake, and the 1995 Kobe earthquake all had pounding damage assessed. The Mexico earthquake (1985) produced the greatest documented damage, with around 40 of the impacted structures undergoing pounding and structural collapse. During the 1989 Loma Prieta earthquake, over 500 buildings indicated more than 200 pounding occurrences [1]. Recent earthquakes in Wenchuan, Sichuan Province, China (2008), Christchurch (2011), Gorkha, Nepal (2015)and Mexico city, Mexico (2017) all demonstrated pounding between nearby structures. Extensive structural pounding was observed in buildings and houses within Mexico City during 2017 earthquake.The majority of structural pounding occurred in soft soils with 53% of them experiencing tilting and 50.3% exhibiting soil settlements as a result [2]. Pounding events were reported in masonry structures in mountainous urban communities during the Gorkha earthquake. In the Kathmandu city center, however, pounding between adjacent buildings was rare. This finding could be attributed to the ground motion being rich in long period motions with little effect on short period structures. Yet the same ground motion had a substantial impact on high-rise apartment buildings more than ten stories high [3].

1.2 Types of Pounding

Structural Pounding can be classified into five categories: [4]

1. Floor to column pounding
2. Pounding of heavier building with adjacent lighter building
3. Pounding of taller building with adjacent shorter building
4. End building pounding
5. Eccentric pounding

1.3 Eccentric Pounding

Eccentric pounding can occur if either of the colliding structures or the contact region is asymmetric. The first instance occurs when the centers of mass (C.M.) and gravity (C.G.) are eccentrically aligned (ex or ey), whereas the second case occurs when the colliding structures are not in the same row. During an earthquake, nearby structures with eccentric alignment experience partially restricted seismic lateral oscillation, inducing torsional movement in the surrounding buildings. Because of the torque produced by colliding buildings, eccentric pounding is more critical than symmetric pounding. Because to eccentric pounding, the number of collisions, building displacements, shear demands and torsion demands of the structure increase significantly [5].The pounding force increases as the setback distance increases [6]. There is substantial torsional movement and higher value torsional movements observed during eccentric pounding [7, 8]. The shear demands of columns impacted from another structure is notably exceeds their capacity multiple times during seismic analysis, indicating that neglecting to consider asymmetric pounding in building design could lead to insecure or critical situations under certain conditions [9].

1.4 Research Objectives

The main objective of this research is to evaluate the effects of pounding on the adjacent RCC buildings with eccentric alignments.

1.5 Limitation of Study

1. No soil interaction is considered.
2. Only bare frame is considered. The effect of infill walls are not considered in the study.
3. The frames considered are regular both in plan and elevation.
4. Pounding is considered to occur between floors so the case of floor-column pounding is not studied.

2. Methodology

2.1 Model of Interacting Adjacent buildings

In order to observe pounding between adjacent buildings, two RC buildings are selected with heights ranging from 3-, 5-, and 7-floors. The story height is 3.0m for all building. The structure has a three-bay layout with bay widths of 4m in both directions. The seismic separation between the adjacent buildings is taken as 1cm for all the cases.

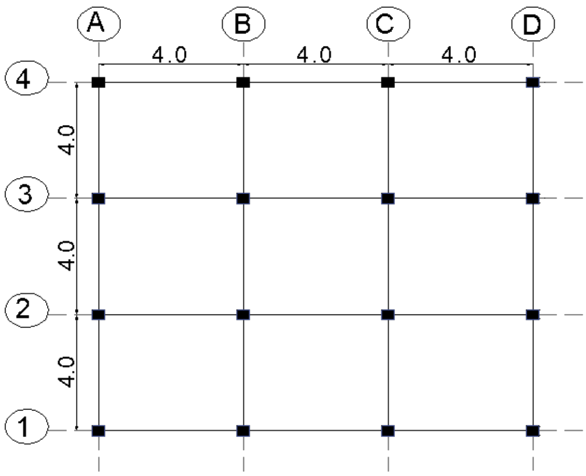

Figure 1: Plan of building

Table 1: Geometry of building

Story Number	Column Size	Beam Size	Slab Thickness
3	350x350	230x350	125mm
5	400x400	300x450	125mm
7	450x450	350x500	125mm

Compressive strength of the reinforced concrete is $fc = 25MPa$ (M25), and its unit weight is $25KN/m^3$. The reinforced steel has a yield strength of Fe500, elastic modulus of a $200GPa$, and Poisson's ratio 0.2. The unit weight of a brick is $20KN/m^3$. The dead load and living load are taken into account as gravity loads for the design of building. Live load is assumed to be $2KN/m^2$ on the floor, $3KN/m^2$ on the stairs, and $1.5KN/m^2$ on the roof. The weight of floor finish is taken as $2KN/m^2$.

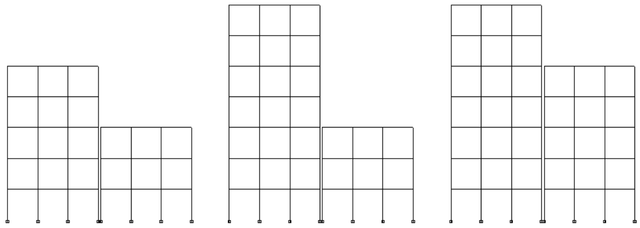

Figure 2: Configuration of Adjacent building

The structures are first analyzed separately using the linear static equivalent force method to ensure that all members are safe in accordance with the NBC code. According to the NBC 105:2020 code, Kathmandu's seismic zone factor (Z) is taken as 0.35 and for residential building, importance factor is taken as 1. For reinforced concrete moment resisting frame, the response reduction factor (Rμ) is taken as 4 and the over strength factor is taken as 1.5.The soil type is taken as very soft soil (Type D). The damping for all cases is taken as 5 percent of critical. Then, the structures are analysed by non linear modal Time History analysis method for seven earthquake records. The analysis is carried out in Finite Element software Etabs2020. Fast nonlinear analysis method is used for time history analysis [10]. The non-linearity is considered for the gap elements in this method. Geometric non linearity is considered using P-delta effects. P-Delta load combination of 1.2DL+0.5LL is taken.

2.2 Pounding Gap Model

In this study, pounding force is simulated by the use of gap elements. These are compression-only two-node link elements. They are activated when adjacent buildings come into contact with one another and sum of displacements is more than the gap between the buildings. Conversely, when the distance between two buildings is less than the sum of the displacements of the nearby buildings, they stay inactive.

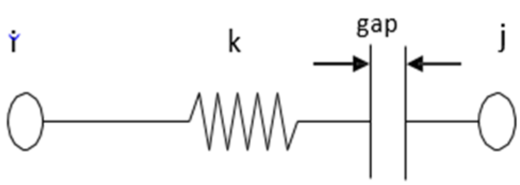

Figure 3: Gap Model

The pounding force F(t) is calculated as:

$$F(t) = \begin{cases} k\delta(t), & \delta(t) > 0 \\ 0, & \delta(t) \le 0 \end{cases} \tag{1}$$
$$\delta(t) = u_1(t) - u_2(t) - d$$

where,
k is the stiffness of the spring (impact element stiffness at the contact location),
$\delta(t)$ is the interpenetration depth,
$u_1(t)$ is the displacement of the first structure,
$u_2(t)$ is the displacement of the second structure, and
d is the initial separating distance.

The gap elements in this study are located at each storey of the shorter building every 3 meters along the collision length. Each gap element is activated in the numerical model with the assistance of a spring with a relatively high stiffness. The spring stiffness in this study is computed using equation (2) [11, 12].

$$k = \left[\frac{1-\nu_1^2}{E_{\text{Dyn},1}} + \frac{1-\nu_2^2}{E_{\text{Dyn},2}} \right]^{-1} \tag{2}$$

Where,

$$\begin{aligned} \nu &= \text{Poisson's ratio} \\ E_{\text{Dyn}} &= \text{Dynamic modulus of elasticity,} \\ &= 5.82(E_{\text{static}})^{0.63} \text{ in GPa} \\ E_{\text{static}} &= \text{Static modulus of elasticity,} \\ &= 5000\sqrt{f_{ck}} \text{ in MPa} \end{aligned}$$

Poisson's ratio for concrete is taken as 0.2 and f_{ck} is taken as 25 MPa. From equation (2),the value of k is found to be equal to $6.4x10^7$ KN/m.

2.3 Time History Analysis

For the time history analysis, the actual earthquake ground motion data is necessary as input. These ground motion time history is obtained from Pacific Earthquake Engineering Research Centre (PEER) NGA West database. The selected ground motions should correspond to the seismic hazard level of the site which in our case is defined by the design response spectrum provided in NBC 105-2020 modified for Kathmandu Valley. The response spectrum is defined as target spectrum in PEER search engine. Other parameters such as magnitude range (Mw 6.5-8), source to site distance (0-150km) and shear velocity (50-200 m/s) are also specified. [13].

Choosing the ground motions with similarity in shape of response spectrum with that of target spectrum, scale factor ranging between 0.33 to 3, seven ground motions presented in table 2 are selected.

The response spectrum graph of seven earthquakes is displayed in Figure 4. It is necessary for these ground motion time histories to match the site's target spectra. The ground motions in this study are scaled in accordance with NBC 105:2020 code to the target spectrum of the Kathmandu Valley. Spectral matching is carried out using the Seismomatch 2022 software over a range of time intervals from 0.05 to 4.0 seconds. As seen in Fig. 5, the matched ground motion spectra are plotted against the design response spectrum.

Table 2: Selected Ground Motions for Time History Analysis

Date	Location	Station	Magnitude
1970	Imperial Valley	El Centro Center FF	6.53
1989	Loma Prieta	APEEL, Redwood City	6.93
1995	Kocaeli	Ambarli	7.51
1995	Kobe	Port City	6.9
1999	Chi-Chi	CHY047	7.62
2010	Darfield	Christchurch Botanical Garden	7.0
2015	Gorkha	Patan	7.8

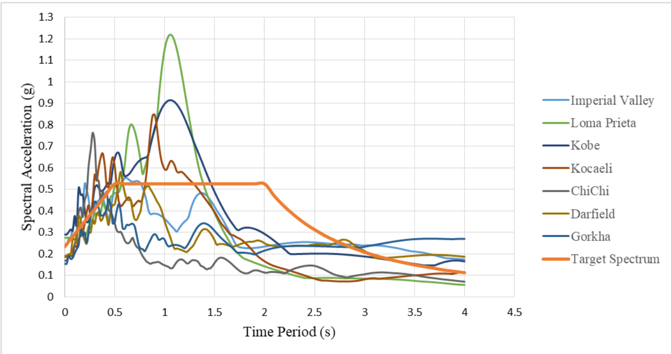

Figure 4: Response Spectrum before spectral matching

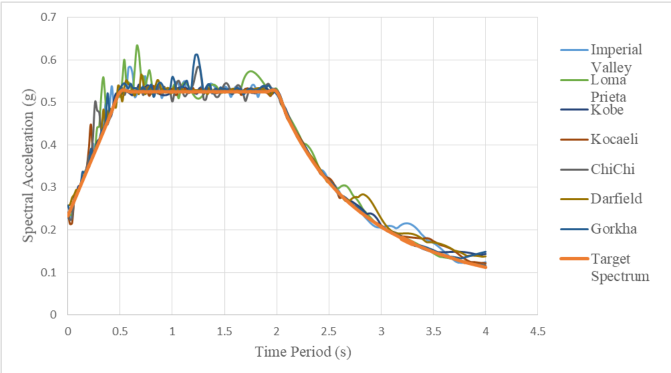

Figure 5: Response Spectrum of matched time histories

3. Results and Discussions

Two buildings of different story height are taken at a time with gap element connected between them. The gap between the adjacent building is taken as 1cm for all cases. The combinations 7-3, 5-3 and 7-5 are made where the numbers represent the storey height of the building. Similarly, by keeping the shorter building on left side, 3-7, 3-5 and 5-7 combinations are made. To study the effect of torsional pounding of adjacent symmetric buildings, two different setbacks are considered:one bay setback and two bay setback and compared with the case of no setback.

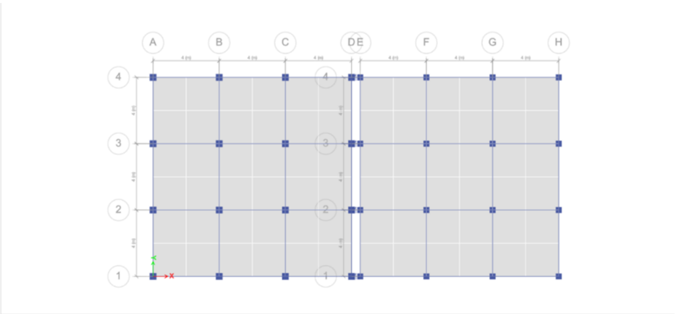

Figure 6: Case I:No setback

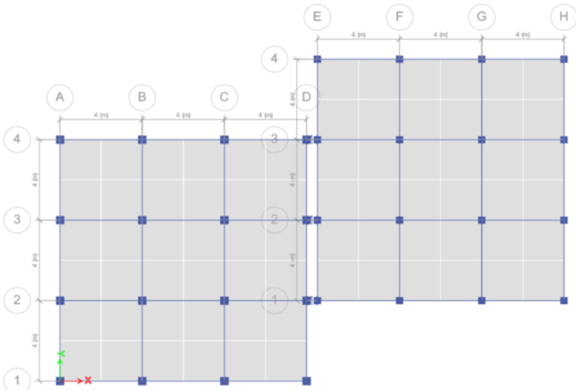

Figure 7: Case II:One bay setback

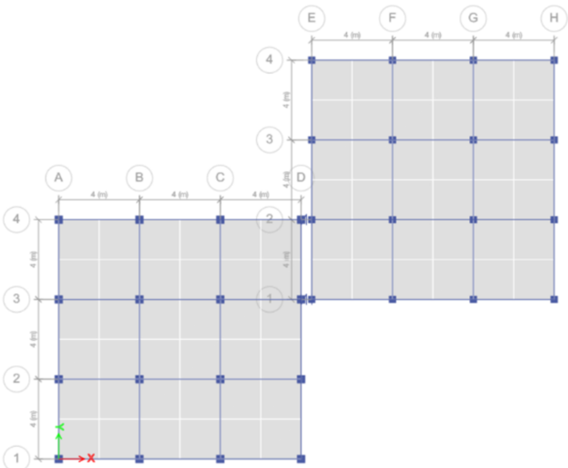

Figure 8: Case III:Two bay setback

Eighteen pounding cases have been studied. Each one is subjected to seven different earthquake excitation and responses are observed. The responses are observed along x direction for all the two adjacent buildings with reference to the corners of the adjacent buildings.

3.1 Pounding Force

The relative displacements of the two adjacent edges of the buildings at the roof level of the shorter building are checked at every integration step to determine whether pounding occurs or not. When pounding occurs, the locations of the impact point and consequently the overlapping distances are determined and pounding force is calculated based on equation (1).

Figures 9 and 10 illustrate the time displacement graph of 7-3 building at third floor level for two setback cases under Gorkha earthquake. The maximum out of phase displacement of two buildings at any time is calculated. In figure 9, the maximum out of phase displacement occurs at 46.75s, and corresponding maximum pounding force is 3200KN for one bay setback case and in figure 10, the maximum out of phase displacement occurs at time 58.08s and the maximum impact force is 5184KN. The maximum pounding forces for all seven earthquakes are calculated and their average value is taken as shown in table 3 and 4.

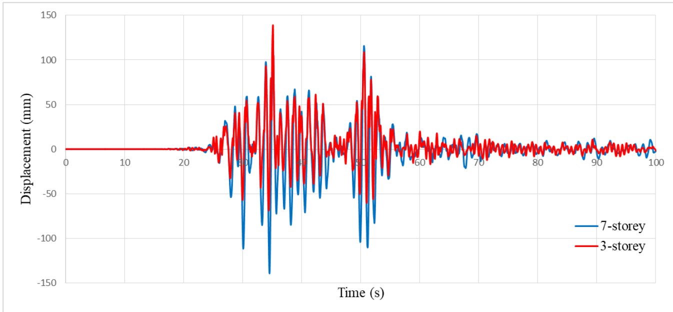

Figure 9: Displacement Time history for one-bay setback case under Gorkha earthquake

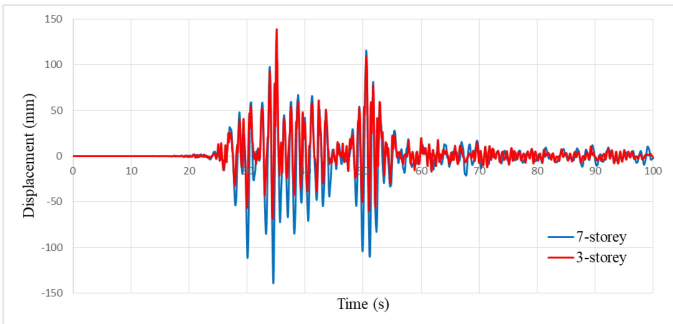

Figure 10: Displacement Time history for two-bay setback case under Gorkha earthquake

Table 3: Pounding Force in KN

Case	No setback	One bay setback	Two bay setback
5-3	3136	4791	6720
7-3	4224	5403	5467
7-5	2414	2514	3493

Table 4: Pounding Force in kN

Case	No setback	One bay setback	Two bay setback
3-5	2959	4571	6232
3-7	4161	5223	5427
5-7	2238	2440	3418

From table 3 and 4, it is observed that the pounding forces increase with increase in setback distances. The pounding force in 7-3 case is increased by 28% in one bay setback and 30% in two bay setback case as compared to no setback case.

Similarly, for 3-7 case, the pounding force is increased by 26% in one bay setback and 30% in two bay setback as compared to no setback case. This increase in pounding force along with the torsional effects can cause severe structural damage to the buildings. From the table 3 and 4, it is found that pounding force increases as the difference in height between the adjacent building increases. The pounding force for 7-3 case is higher than 5-3 and 7-5 case. It is a result of the building's time periods. The buildings will vibrate nearly in phase for smaller time period difference between the buildings, which will reduce the pounding force. The pounding forces when taller building is left to the shorter building is larger when compared to when the shorter building is on the left. Numerous factors, including mass distribution, dynamic characteristics, and earthquake motion, could be responsible for this. The taller building in each configuration will have more mass in the upper stories compared to the shorter building. This difference in mass distribution can affect the response of the buildings to seismic ground motion and how they interact with each other. The specific contact areas and points of contact between the buildings can vary depending on their relative positions. This can result in different interaction forces and pounding effects.

3.2 Maximum Storey Displacement

The effect of pounding on storey displacements of adjacent buildings for all combinations are studied. The graphs of storey displacement of 7-storey and 3-storey for 7-3 and 3-7 case are shown in the figures 11 to 14.

Figures 11 and 12 present the maximum displacement responses envelopes of 7 storey building for different setback cases. For 7-3 building configuration, the maximum storey displacement at third level of 7-storey building is 108mm for no setback case. With one way setback, the displacement increases to 125mm resulting in 16% increase compared to no setback case. Similarly, with two bay setback, the displacement further increases to 134mm showing 24% increase compared to no setback case. The maximum storey displacement at the third level of a 7-story building for 3-7 configuration is 125mm for no setback case, increasing by 6% to 133mm for one bay setback case. The maximum displacement increases to 139mm with two bay setback, indicating an 11% increase over no setback.

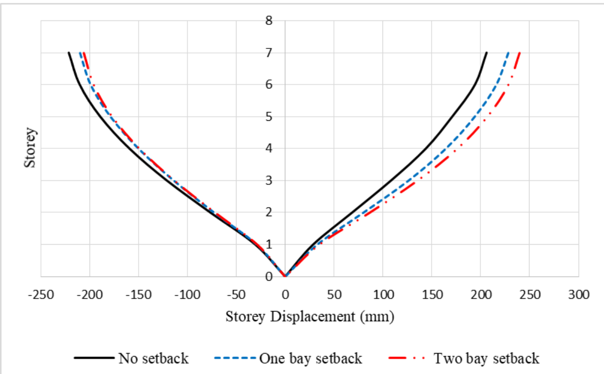

Figure 11: Maximum Storey Displacement of 7-storey building (7-3 case)

Figure 12: Maximum Storey Displacement of 7-storey building (3-7 case)

Figures 13 and 14 depict the maximum storey displacement of 3-storey building for different setback cases.For 7-3 building configuration, the maximum storey displacement at top level of 3-storey building is 104mm for no setback case. The displacement rises to 111 mm with a one-way setback, which is 7% more than in the case of no setback. Likewise, in the case of two bay setback, the displacement rises to 116mm, indicating an 11% increase over the no setback scenario.

For 3-7 configuration, the maximum storey displacement at top level of 3-storey building is 74mm for no setback case, which increases by 2% to 75mm for one bay setback case. With two bay setback, the maximum displacement increases to 76mm showing 3% increase as compared to no setback.

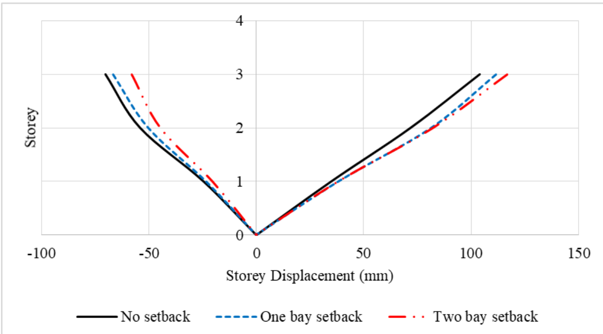

Figure 13: Maximum Storey Displacement of 3-storey building (7-3 case)

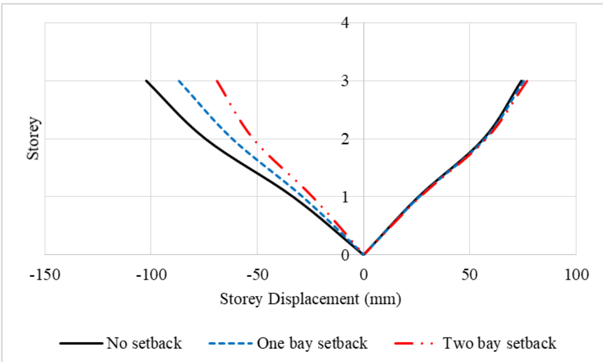

Figure 14: Maximum Storey Displacement of 3-storey building (3-7 case)

When a seven-story building is positioned to the right of a three-story building (3-7 case), its maximum positive storey displacement is greater than when it is positioned to the left of the three-story building (7-3 instance). Similar to this, when a 3-story building is located left to a 7-story building, the maximum storey displacement increases. The reason for this might be that the seismic pounding causes displacement retrains on the impacting side, but it may also increase displacement responses on the other side. Thus, it can be concluded that the building alignment affects the peak storey displacement response.

3.3 Maximum Storey Rotation

Figures 15 and 16 depict the maximum storey rotations of 7-storey building for 7-3 and 3-7 case. From figures, it is clear that introducing setbacks leads to higher storey rotation. The maximum storey rotation at seventh level of 7-storey building in one bay setback case is significantly higher, about 9 times compared to the no setback case. For two bay setback case, the storey rotation further increase which is about 12 times higher as compared to the no setback case.

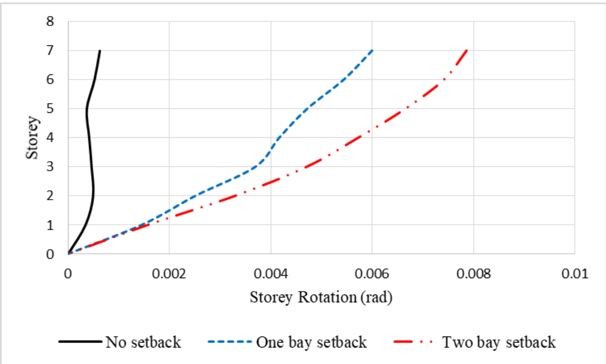

Figure 15: Maximum Storey rotation of 7-storey building (7-3 case)

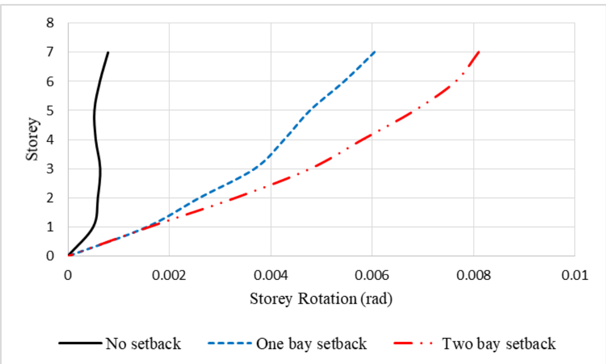

Figure 16: Storey rotation of 7-storey building (3-7 case)

In 3-storey building, the maximum storey rotation value at top level with one bay setback is about 5 times greater than with no setback, indicating a significant increase in torsional behavior of the building as shown in figures 17 and 18.

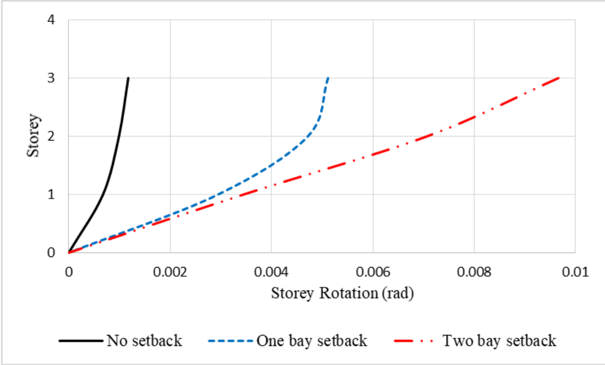

Figure 17: Maximum Storey rotation of 3-storey building (7-3 case)

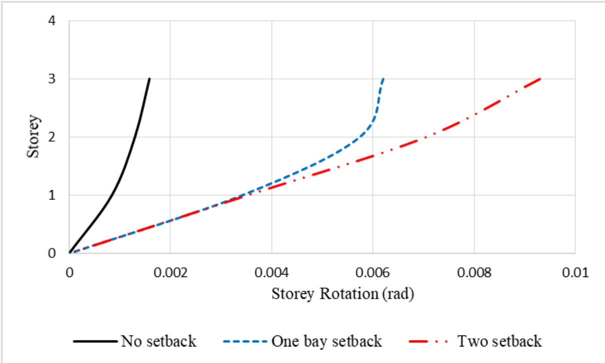

Figure 18: Maximum Storey rotation of 3-storey building (3-7 case)

When comparing the two-bay setback case to the no-setback case, the rotation values increase by 9 times. The results show that eccentric pounding induces significant rotational values even though the plan of the building is symmetrical. The storey rotations increase as the setback distance increases, which shows that the torsional movement depends on the impact interaction area of the collided buildings. These rotational responses lead to unequal displacement demands on the floor diaphragm and induce torsional movement in the buildings, which can lead to structure collapse.

4. Conclusion

In this paper, the seismic pounding analysis of adjacent symmetric buildings with eccentric alignment have been studied. The two adjacent buildings with different heights of 3-, 5-, and 7-stories with different setback distances are modelled using the finite element software ETABS. Numerical investigation has been conducted to find pounding force, maximum storey displacement and maximum storey rotations of adjacent buildings. Following conclusion are drawn from the study:

The pounding forces increase with increase in setback distances. This implies that structures with greater differences in setback configurations are more susceptible to experiencing larger pounding forces during earthquakes.

The setbacks have a significant impact on the overall displacement of the buildings. By increasing the setback distance, the displacement of adjacent buildings also increases.

The storey rotation values increase with increase in setback distances. This emphasizes that a larger setback leads to a substantial increase in torsional behavior of the building although the plan view is symmetrical.

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