Evaluation of Seismic Pounding between Adjacent RC Building

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Abstract

Pounding between adjacent structures is commonly observed phenomenon during major earthquakes which may cause both architectural and structural damages. To satisfy the functional requirements, the adjacent buildings are constructed with equal and unequal heights, which may cause great damage to structures during earthquakes. During earthquake, the buildings vibrate out of phase and at rest separation is deficient to accommodate their relative motions. Such buildings are usually separated by expansion joint which is insufficient to provide the lateral movements of the buildings during earthquakes. It can be prevented by providing safe separation distances, sometimes getting of required safe separations is not possible in metropolitan areas due to high land value and limited availability of land space. If building separations is found to be deficient to prevent pounding, then there should be some secure and cost effective methods to prevent structural pounding between adjacent buildings. There are many buildings which are constructed very nearly to one another in Metropolitan cities, because everyone wants to construct up to their property line due to high cost of land. This study compare the seismic pounding of framed RC as well as soft story RC buildings, and evaluates the prevention techniques of pounding between adjacent buildings during earthquakes. Constructing new RC walls, cross bracing system and combined RC wall & bracing, with proper placement are proposed as possible prevention techniques for pounding between adjacent buildings. ETABS software is used for modeling and analysis of buildings. After analysis results shows that seismic pounding is more severe in the case of adjacent soft-storey building compared to framed buildings, that is displacement of soft-storey buildings are larger than framed buildings, and also displacement of buildings with different floor level is less than that of buildings with same floor level. The mitigation methods such as use of shear wall, bracings and combination of shear wall & bracings are proved to be effective in all cases.

Keywords: Soft-Storey Building, Seismic Pounding, Shear Wall, Bracing

I. INTRODUCTION

Structures are built very close to each other in metropolitan areas where the cost of land is very high. When structural engineers undertake a seismic design for a building, assumptions are made by necessity. As a design advances, the engineer progressively challenges these assumptions to ensure they are valid for the situation under consideration. Nevertheless, assumptions can be and have been overlooked by both individuals and the wider engineering community over considerable periods of time. Historically, engineers usually assumed that buildings would respond to earthquake ground motions without interference from surrounding objects. Unfortunately, in reality this assumption has frequently been invalid at the time of construction, or has become invalid as the surrounding land was developed. During earthquakes buildings make displacements and deformations for damping earthquake forces. As a reason of this, structural elements can be damaged or whole structure can be collapsed. Character of these displacements and deformations is very complex and it is a function of many variables from ground acceleration to rigidity center of the structure. If adjacent buildings are not separated properly from each other, a pounding case can be possible on an earthquake and buildings can be damaged even if they are well designed and constructed.

Today, many buildings face the risk of collision with other neighboring buildings during a seismic event. These collisions cause additional loadings to all involved buildings in ways that were never considered during design. This phenomenon is known as ‘inter building pounding’. This may happen not only in buildings but also in bridges and towers which are constructed close to each other. Although some modern codes have included seismic separation requirement for adjacent structures, large areas of cities in seismically active regions were built before such requirements were introduced. Many investigations have been carried out on pounding damage caused by previous earthquakes.

Due to increasing population since the past few years car parking space for residential apartments in populated cities is a matter of major concern. Hence the trend has been to utilize the ground storey of the building itself for parking. These types of buildings having no infill masonry walls in ground storey, but in filled in all upper storeys, are called Open Ground Storey (OGS) buildings. They are also known as ‘open first storey building’ (when the storey numbering starts with one from the ground storey itself), ‘pilots’, or ‘stilted buildings’.

The objective of this research work is to study the pounding of both framed and soft-story buildings with different floor level and compare the result obtained and also explore the effectiveness of pounding mitigation strategies for closely spaced buildings to reduce the possible damage due to seismic pounding, while minimizing the alteration to the existing structural
system. This research work presents the techniques to mitigate pounding between adjacent buildings exposed to natural hazards. Techniques like safe clear distance between buildings, increasing the stiffness of both building by using shear wall, bracing system are used as effective mitigation techniques to avoid pounding between adjacent building structures during an earthquake.

II. LITERATURE REVIEW

Impact between adjacent structures during an earthquake is a phenomenon that has attracted considerable research interest in the recent past. Pounding is a non-linear problem due to its impact. Most of the numerical studies utilize single-degree-of-freedom (SDOF) and multi-degree-of-freedom (MDOF) systems in order to simplify the problem and concentrate on the non-linear aspects. Structural pounding is a complex phenomenon which involves local damage to structures. The only method proposed in codes to prevent pounding is by providing sufficient separation between structures. An alternative to seismic separation gap is to decrease lateral motion. If buildings are old and not in a stage to provide safe gap then prevention measure should be taken. Extensive literature review is carried out to study the pounding of building under 3 categories such as study of seismic pounding of buildings, study of mitigation methods, study of behaviour of soft-storey buildings etc. Brief review on various aspects is summarized below.

III. MODELING OF ADJACENT RC BUILDINGS

Accurate modeling of the nonlinear properties of various structural elements is very important in nonlinear analysis. Nonlinear modeling of gap element is also very important. Modeling is done by using the software ETABS.

A. Modeling of Framed Buildings

In order to observe pounding between adjacent buildings, two buildings are selected having different dynamic properties. These buildings are separated by an expansion joint of 80mm and are subjected to gravity and dynamic loading. Both buildings are analyzed in ETABS and designed as per IS 456-2000. The buildings consist of eight storey (G+8A) and five storey (G+5A) buildings. All columns models in all the models are assumed to be fixed at the base for simplicity. The height of ground floor and upper floor is 3.2 m. Slab of eight stories and five stories is modeled as rigid diaphragm element of 0.14m and 0.13m thickness respectively, for all stories considered. Wall thickness is of 230mm on all the beams. The grade of concrete for column is M-25 and for beam and slab M-20. Beams and column members have been defined as ‘frame elements’ with the appropriate dimensions and reinforcement. Soil structure interaction has not been considered. Slabs are defined as area elements having the properties of shell elements with the required thickness.

B. Modeling of Soft-Storey Buildings

Modeling of soft storey buildings are carried out by using the software ETABS. Ground storey is taken as soft storey and infill walls are provided in all upper stories. Infill walls are two dimensional elements that can be modelled with orthotropic plate element for linear analysis of buildings with infill wall. But the nonlinear modelling of a two dimensional plate element is not understood well. Therefore infill wall has to be modelled with a one-dimensional line element for nonlinear analysis of the buildings. All of these buildings model with infill walls modelled as one-dimensional line element is used in the present study for nonlinear analysis. Infill walls are modelled here as equivalent diagonal strut elements.

C. Modeling of Equivalent Strut

For an infill wall located in a lateral load-resisting frame, the stiffness and strength contribution of the infill has to be considered. Non-integral infill walls subjected to lateral load behave like diagonal struts. Thus an infill wall can be modelled as an equivalent ‘compression only’ strut in the building model. Rigid joints connect the beams and columns, but pin joints connect the equivalent struts to the beam-to-column junctions.

In a linear structural analysis, the required properties of an equivalent strut are the effective width, thickness, length and elastic modulus. The thickness (t) is assumed to be same as that of the infill wall. The length (d) is the diagonal length of the frame. The remaining properties to be determined are the effective width (w) and elastic modulus (Es) of the equivalent strut. The strength of the equivalent strut is required to check its capacity with the axial load demand in the strut. The simplest form w and Es are taken equal to d/4 and Em (modulus of masonry), respectively. The elastic modulus of the equivalent strut Es can be equated to Em, the elastic modulus of the masonry. Following range of values for Em were obtained. Em= 350 to 800 MPa for table moulded bricks Em= 2500 to 5000 MPa for wire cut bricks.

D. Modeling of Adjacent Buildings

Five storey building is located on right hand side of eight storey building. Both buildings are separated by an expansion joint of 80 mm. Connection between two adjacent building blocks is modelled by using a GAP element, which has two nodes connected to either end of building blocks without which the buildings behave independent of each other.

Figure 2 & 3 shows model of framed and soft-storey building.


**E. Gap Element**

Gap has been defined as link elements in ETABS. A Link element is a two-joint connecting link. It has only compression properties i.e. when two blocks come in contact with each other impact force is transmitted otherwise it is zero. It is a compression-only element required to assess the force of pounding and simulate the effect of pounding. This is activated when structures come closer and deactivate when they go far away. From Fig. 1, it is shown that, the gap element will activate if ‘open’ is equal to zero. The purpose to modeling ‘gap joint element’ is to program the software that the two structures are apart by that much distance and it model the contact between buildings when they comes closer. Without this element software will not assume the contact between structures and structure will behave independently. Figure 2 & 3 shows adjacent G+8A & G+5A framed and soft-storey buildings respectively.

![Fig. 1: Gap Joint Elements from ETABS](image1.png)

Fig. 1: Gap Joint Elements from ETABS

![Fig. 2: G+8A & G+5A framed building](image2.png)

Fig. 2: G+8A & G+5A framed building

![Fig. 3: G+8A &G+5A soft-storey building](image3.png)

Fig. 3: G+8A &G+5A soft-storey building

### IV. Analysis Results

Seismic time history function is selected as the ground excitation data of El Centro earthquake (magnitude 7.1, total duration 31.18sec) at Imperial Valley USA in year 1940 is used. It has a peak pounding acceleration of 0.319g at time 2.006 seconds. The predominant frequencies range present in the ground motion is 1.15-2.22 Hz (0.45-0.87 sec). It is applied in the longitudinal X direction. Damping of 5 % is taken for earthquake ground motion. The graph of the functions is illustrated in Figure. Each record is divided into 5000 points of acceleration data equally spaced at .002 sec. Figure 4 shows time history function of El Centro earthquake.

![Fig. 4: Time History function of El Centro earthquake 1940](image4.png)

Fig. 4: Time History function of El Centro earthquake 1940

### A. Dynamic Response of Framed Building without Additional Stiffness

Time history analysis has been carried out by using Elcentro earthquake ground motion data to evaluate the pounding of framed buildings. Time history plot of each buildings at same floor level is used to find out the maximum out of phase movement, and compare the maximum out of phase movement with provided gap between the buildings to evaluate the chance of pounding.
B. G+8A and G+5A Buildings with Different Floor Level

After analyzing the two buildings with different floor level in ETABS under Time History data of Elcentro which is to be known as above average earthquake, the buildings were observed displacement with respect to time. For pounding observance the worst condition is considered by taking positive displacement of G+8A story and negative displacement of G+5A storey building due to different dynamic characteristics. Figure 5 and 6 shows the time history plot of 5th floor of both buildings with different floor level.

![Fig. 5: Displacement time history plot of 5th floor of G+8A](image1)

![Fig. 6: Displacement time history plot of 5th floor G+5A](image2)

Maximum out-of-phase movement is = (89.02 + 108.3)-80 = 117.32mm. Which is greater than expansion joint. Hence the separation joint between the buildings is unable to accommodate this out of phase movement, and adjacent buildings will strike or collide.

C. Dynamic Response of Soft-Storey Buildings without Additional Stiffness

ETABS is used to compute the response of adjacent soft-storey buildings. Time history analysis has been carried out by using Elcentro earthquake ground motion data to evaluate the pounding of soft-storey buildings. Time history plot of each buildings at same floor level is used to find out the maximum out of phase movement, and compare the maximum out of phase movement with provided gap between the buildings to evaluate the chance of pounding.

D. G+8A and G+5A Buildings with Different Floor Level

For pounding observance the worst condition is considered by taking positive displacement of G+8A story and negative displacement of G+5A story due to different dynamic characteristics. Figure 7 and 8 shows the time history plot of both buildings at 5th floor level.

![Fig. 7: Displacement time history plot of 5th floor of G+8A](image3)

![Fig. 8: Displacement time history plot of 5th floor of G+5A](image4)

Maximum out-of-phase movement is = (213.3 + 245.8)-80 = 388.1mm. Which is greater than expansion joint. Hence the separation joint between the buildings is unable to accommodate this out of phase movement, and adjacent buildings will strike or collide.


E. Dynamic Response of Framed Building with Additional Stiffness

Stiffness of buildings is increased by using Shear wall, bracings and combined system of shear wall & bracings.

F. G+8A & G+5A Buildings Different Floor Level- with Shear Wall

Shear wall is introduced at middle panel in x-direction, Figure 9 shows the original and deformed shape of the building with shear wall and Figure 10 shows the time history plot of 5th floor of both building

![Original & Deformed shape of adjacent buildings with the addition of shear wall](image)

**Fig. 9: Original & Deformed shape of adjacent buildings with the addition of shear wall**

![Displacement time history graph of G+8A & G+5A storey buildings at 5th floor level](image)

**Fig. 10: Displacement time history graph of G+8A & G+5A storey buildings at 5th floor level**

For G+8 storey building maximum positive and negative displacements are 25.3mm at 2.052s and 28.5mm at 2.272s respectively. For G+5 storey building maximum positive and negative displacements are 39.4mm at 2.09s and 47.5 mm at 2.334s respectively. Thus maximum out of phase movement is 72.8mm which is less than expansion joint ie, 80mm. Hence no chance of pounding at any interval of time.

G. G+8A & G+5A Buildings Different Floor Level- with Bracing

Bracing is introduced at end panel in x-direction, Figure 11 shows the original and deformed shape of the building with shear wall and Figure 12 shows the time history plot of 5th floor of both building
For G+8 storey building maximum positive and negative displacements are 25.2mm at 2.458s and 27.8mm at 2.668s respectively. For G+5 storey building maximum positive and negative displacements are 31.6mm at 2.46s and 34.7 mm at 2.664s respectively. Thus maximum out of phase movement is 59.9mm which is less than expansion joint ie, 80mm. Hence no chance of pounding at any interval of time.

II. G+8A & G+5A Buildings Different Floor Level- Combined System of Shear Wall & Bracings

Shear wall is introduced at middle panel in outer frame and bracings are introduced in middle panel in inner frames in x-direction, Figure 13 shows the original and deformed shape of the building with shear wall and Figure 14 shows the time history plot of 5th floor of both building.
For G+8 storey building maximum positive and negative displacements are 28.1mm at 2.066s and 29.3mm at 2.302s respectively. For G+5 storey building maximum positive and negative displacements are 35.7mm at 2.062s and 37.1 mm at 2.304s respectively. Thus maximum out of phase movement is 65.2mm which is less than expansion joint ie, 80mm. Hence no chance of pounding at any interval of time.

### J. Dynamic Response of Soft-Storey Building with Additional Stiffness

Stiffness of the soft-storey buildings are increased by providing shear wall, bracings & combined system of shear wall and bracings.

#### J. G+8A & G+5A Buildings Same Floor Level- with Shear Wall

Shear wall is introduced at end panel in x-direction. Figure 15 shows the original and deformed shape of the building with shear wall and Figure 16 shows the time history plot of 5th floor of both building.

Fig. 15: Original & Deformed shape of adjacent buildings with the addition of shear wall
For G+8A storey building maximum positive and negative displacements are 31.2mm at 2.97s and 37.3mm at 2.736s respectively. For G+5A storey building maximum positive and negative displacements are 36.8mm at 2.99s and 45.5mm at 2.764s respectively. Thus maximum out of phase movement is 76.5mm which is less than expansion joint ie, 80mm. Hence no chance of pounding at any interval of time.

### G+8A & G+5A Buildings Different Floor Level- with Bracings

Bracings are introduced at end panel in x-direction. Figure 17 shows the original and deformed shape of the building with shear wall and Figure 18 shows the time history plot of 5th floor of both building.
For G+8A storey building maximum positive and negative displacements are 33.9mm at 2.214s and 39mm at 2.528s respectively. For G+5A storey building maximum positive and negative displacements are 39.1mm at 2.198s and 39.1 mm at 2.56s respectively. Thus maximum out of phase movement is 73mm which is less than expansion joint ie, 80mm. Hence no chance of pounding at any interval of time.

L. G+8A & G+5A Buildings Different Floor Level- Combined System of Shear Wall and Bracings

Bracings are introduced at end panel of inner frames and shear wall in end panels of outer frames. Figure 19 shows the original and deformed shape of the building with shear wall and Figure 20 shows the time history plot of 5th floor of both building

![Figure 19: Original & Deformed shape of adjacent buildings with the addition of shear wall &bracings](image)

![Figure 20: Displacement time history graph of G+8A & G+5A storeys buildings at 5th floor level](image)

For G+8A storey building maximum positive and negative displacements are 32.2mm at 2.214s and 33.4mm at 2.41s respectively. For G+5A storey building maximum positive and negative displacements are 37.3mm at 2.198s and 38.2 mm at 2.38s respectively. Thus maximum out of phase movement is 70.4mm which is less than expansion joint ie, 80mm. hence no chance of pounding at any interval of time.

V. CONCLUSIONS

The purpose of this study has been to analyze seismic pounding effects between buildings. For this ETABS, a linear and non-linear static and dynamic analysis and design program for three dimensional structures has been used. The non-linear dynamic analysis procedure or time history analysis is carried out to estimate the displacement of the structure. The analysis considered nonlinear pounding analysis of structures with equal and unequal heights. The pounding of the structures are estimated from maximum out of phase movement of the structure. Here I have demonstrated the analysis of G+8A & G+5A framed & soft-storey building with different floor level, I have also done the analysis of 1. Framed buildings, a) Five storey (G+5A) building adjacent to eight storey (G+8A) building with same floor level, b) Five storey (G+5A) building adjacent to another five storey (G+5B) building with same floor level, c) Above models with different floor level, d) Eight storey (G+8A) building adjacent to another eight storey (G+8B) building with same floor level, e) Above models with different floor level. 2. Soft- storey buildings, a) Five storey (G+5A) building adjacent to eight storey (G+8A) building with same floor level, b) Five storey (G+5A) building
adjacent to another five storey (G+5B) building with same floor level, c) Above models with different floor level, d) Eight storey (G+8A) building adjacent to another eight storey (G+8B) building with same floor level, e) Above models with different floor level, which have been created in ETABS. From the comparison studies of the above I have got the results as,

- The adjacent buildings without proper separation gap are affected by pounding damage during strong earthquake.
- Out of phase movement is higher in the case of building with same floor level compared to the building with different floor level in all cases.
- Adjacent soft-storey buildings are more vulnerable to pounding rather than framed buildings, that is, out of phase movement is greater for soft-storey buildings compared to framed buildings.
- It is clear that adjacent building with same height and matching stories will show similar behavior and pounding damage will be limited
- Lateral displacement caused by the impact of two adjacent buildings, decreases in the shorter building, where it increases in the taller one, which may lead to critical condition.
- While designing the buildings pounding must be checked to avoid the damages. vii. If the buildings are in planning stage the easiest way to avoid pounding is to provide the safe separation distance between buildings as given by code.
- Safe separation distance as per FEMA-273 is higher than maximum out of phase movement between buildings. It means that FEMA-273 gives conservative result.
- If the buildings are old and are not in a stage to provide safe gap, then prevention measure should be taken like this study had undertaken, using new shear wall, cross bracing and combined system of both.
- All the prevention methods that are used in this study proved effective to prevent pounding between adjacent famed and adjacent soft-storey buildings.
- It is preferable to construct adjacent buildings with same floor level and with suitable separation gap by considering dynamic analysis to avoid pounding.

REFERENCES