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Seismic Pounding of Adjacent Buildings

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Abstract - *In recent years, the pounding of the adjacent structures has been receiving considerable attention during the earthquake because such structures with inadequate clear spacing between them suffers structural and non-structural damage as a result of collision during earthquake. An expansion joint separates such adjacent buildings which is insufficient to accommodate the lateral movements of buildings under earthquakes. Seismic pounding can be prevented by providing adequate separation distances as specified in the safe code. Sometimes, getting the required safe separations is not possible in metropolitan areas because of the high land value, limited availability of land space and the need for centralized facilities under one roof encourages buildings to be built very close to each other ignoring the effect of seismic pounding during the design. If building separations in metropolitan areas are found to be deficient to prevent pounding, then there should be some secure and cost-effective retrofitting methods to mitigate its effect. The objective is to understand the consequences of seismic pounding on the performance of structural and non-structural components in building.*

Key Words: Structural pounding, Building collision, Adjacent buildings, Seismic separation distance, Pounding analysis

1.INTRODUCTION

The Seismic Pounding can be defined as the collision of adjacent buildings during the earthquakes. This phenomenon is mostly observed in the old buildings which were constructed in the years before earthquake resistant design principles became popular. The principle reason for the pounding effect is the insufficient gap in between the adjacent buildings. Although many current codes specifies a minimum seismic gap, it is still inadequate since the codes necessarily lag behind the current researches and fail to include the effect of other parameters that affect the structural deformation.

Pounding of adjacent buildings may also have worse damage when adjacent buildings with different dynamic characteristics vibrates out of phase and when there is insufficient separation distance. Past seismic codes did not give definite guidelines to preclude pounding, due to economic considerations including maximum and usage requirements, especially in the high density populated areas of cities, there are many buildings worldwide which are already built in contact or extremely close to another, that could suffer pounding damage in future earthquakes. Building structures are often built close to each other as in the case of residential building complexes or in downtown of metropolitan cities where the cost of land is high. Due to the close proximity of these structures, they have often been found to impact each other while responding to earthquake induced strong ground motion. An earthquake can cause sudden movement of the ground that is transferred to the structure through foundation

The highly congested building system in many metropolitan cities constitutes a major concern for seismic pounding damage. For these reasons, it has been widely accepted that pounding is an undesirable phenomenon that should be prevented or mitigated zones in connection with the corresponding design ground acceleration values will lead in many cases to earthquake actions which are remarkably higher than defined by the design codes used up to now. The most simplest and effective way for pounding mitigation and reducing damage due to pounding is to provide enough separation but it is sometimes difficult to be implemented due to detailing problem and high cost of land. An alternative to the seismic separation gap provision in the structure design is to minimize the effect of pounding through decreasing lateral motion which can be achieved by joining adjacent structures at critical locations so that their motion could be in-phase with one another or by increasing the pounding buildings damping capacity by means of passive structural control of energy dissipation system or by seismic retrofitting.

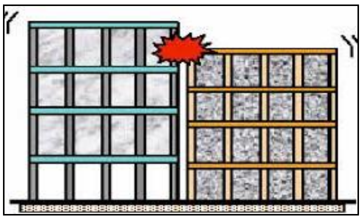

Fig-1: Pounding of Adjacent Buildings

1.1 Causes of Pounding

The various causes of pounding are as follows:-

- Adjacent buildings with the same heights and the same door levels
- Adjacent buildings with same floor levels but different heights
- Adjacent structures with different total height and floor levels
- Structures are situated in a row

- Adjacent units of the same buildings which are connected by one or more bridges or through expansion joints.
- Structures having different dynamic characteristics, which are separated by a distance small enough so that pounding can occur.
- Pounding occurres at the unsupported part (e.g., mid-height) of column or wall.
- Construction according to the earlier code that was vague on separation distance.
- Possible settlement and rocking of the structures located on soft soils.
- Buildings having irregular lateral load resisting systems in plan rotate during an earthquake

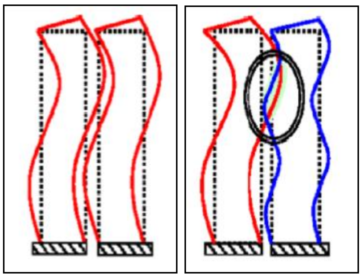

Fig-2 : a) Similar seismic behaviour b) Different seismic behavior

The main objective of this paper is to understand the terms related to structural pounding, causes of pounding, importance of providing enough separation distance and the points to be checked before constructing adjacent buildings. Also discusses on the common failure criteria of the different cases of pounding as well as some mitigation measures. Figure 1 shows the pounding of adjacent buildings and figure 2 shows the similar seismic behavior and different seismic behavior of adjacent buildings.

2. SEISMIC SEPARATION DISTANCE TO AVOID POUNDING

Seismic pounding occurs when the separation distance between adjacent buildings is not large enough to accommodate the relative motion during earthquake events. Seismic codes and regulations worldwide specify minimum separation distances to be provided between adjacent buildings, to preclude pounding, which is obviously equal to the relative displacement demand of the two potentially colliding structural systems. The gap distance between adjacent buildings is usually calculated as the maximum displacement of the two adjacent buildings at the same height (Δmax).

In some codes such as ECP 203 (2007) [21] and the UBC (1997) [22], the minimum required gap distance is calculated as the Square Root of Sum of Squares (SRSS) as follows:

$$\Delta_{max} = \sqrt{(\Delta_1^2 + \Delta_2^2)}$$

Where Δ1: the maximum displacement for one of the adjacent buildings.

Δ2: the maximum displacement for the second building at the same level considered in the first building.

Bureau of Indian Standards clearly gives in its code IS 4326 that a Separation distance is to be provided between buildings to avoid collision during an earthquake. The code is mentions in following Table 1.

Table 1: Gap width/storey (mm) according to IS 1893:1984

Sl.No:	Type of construction	Gap Width/Storey (mm) for Design Seismic Coefficient αh =0.12
1	Box system or frames with shear walls	15.0
2	Moment resistant reinforced concrete frame	20.0
3	Moment resistant steel frame	30.0

Minimum total gap shall be 25 mm. For any other value of αh the gap width shall be determined proportionately.

3. DIFFERENT CASES OF POUNDING

Poundings can be developed between high-rise buildings, between low-rise buildings, as well as between high-rise and low-rise buildings during strong earthquakes. Pounding during earthquake can also take place between a non-structural component and the structure itself as well as between two adjacent components. Earthquakes cause ground shaking; the ground beneath a building is displaced laterally. The loads in the upper part of the building generates inertia effects of this displacement. As a result of this, there will be pounding between adjacent buildings. The resulting shear forces and bending moments in a building are (generally) maximum just above foundation level.

Observation of previous earthquakes shows certain characteristics related to pounding. Buildings of similar height and with similar structural systems tend to suffer less damage than buildings of different height and with different structural systems. This is due to the fact that buildings with the same height will have similar natural frequencies and will tend to move in-phase relative to one another. On the contrary, buildings of different height or with different structural systems will have different natural frequencies and will tend to sway out-of-phase with respect to each other; this may lead to damage that is more serious. This remark illustrates that pounding problems must be treated case by case. A classification of the different type of pounding which can appear is presented below:

3.1 ADJACENT BUILDINGS WITH EQUAL HEIGHT AND WITH ALIGNED FLOOR LEVELS

This type of pounding is known as floor-to-floor pounding. Buildings that are the same height and have matching floors are likely to exhibit similar dynamic behavior. If the buildings pound, floors will impact other floors, so damage usually will be limited to nonstructural components.

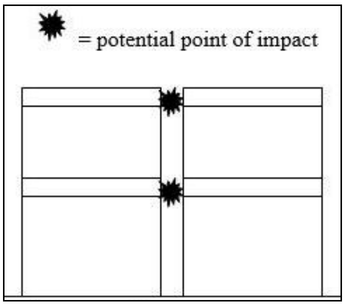

Fig-3: Floor-to-floor pounding

3.2 ADJACENT BUILDINGS WITH NON ALIGNED FLOOR LEVELS

Adjacent buildings with different floor levels can be case of pounding with the floor of one building with the mid column of the other. Such types of pounding is called floor-to-column pounding.

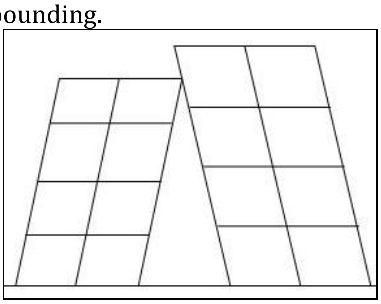

Fig-4: Floor-to-column pounding

This type of pounding occurs in some adjacent buildings in which the floors levels are not in the same heights. Therefore, when shaking with different phases occurs, the floor of one building hits the column of another and causes serious damages which can lead to the fracture of the columns of the storey. Since relatively rigid floor or roof diaphragm may impact an adjacent building at or near mid-column height, causing bending or shear failure in the columns, and consequently storey collapse. This type is the most dangerous pounding that can result in sudden destruction of the structure.

3.3 ADJACENT BUILDINGS WITH UNEQUAL HEIGHT AND WITH ALIGNED FLOOR LEVELS

Pounding of a shorter building on a taller one: When two structures with different heights are adjacent, because of different dynamic properties, the shorter structure hits the adjacent one, which results in floor shearing in higher levels of impact part. It is important to know that the higher in the impact part level, the greater impact is tolerated more intensive response. Moreover, when buildings are of different heights, the shorter building may act as a buttress for the taller neighbour. The shorter building receives an unexpected load while the taller building suffers from a major discontinuity that alters its dynamic response. Since neither is designed to weather such conditions, there is potential for extensive damage and possible collapse.

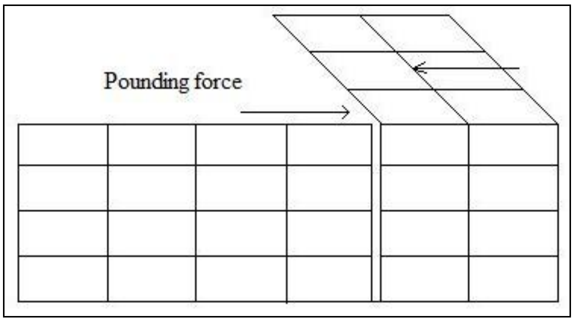

Fig-5: Pounding of shorter on a taller building

3.4 POUNDING OF A HEAVIER ON LIGNTER ONE

Since adjacent buildings may differ in the structural system of floors and/or in their applications, they have different masses, this can cause different phase oscillations, since the lighter building tolerates more intensive response.

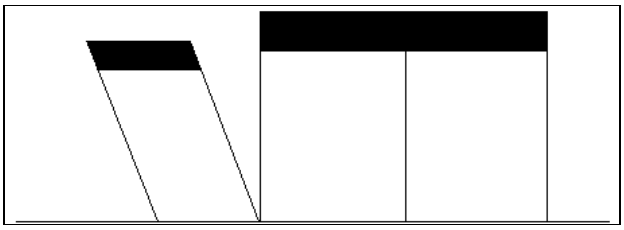

Fig-6: Pounding of heavier on a lighter building

3.5 POUNDING OF TWO ADJACENT BUILDINGS WITH NON-COAXIAL MASS CENTERS

In building with non-coaxial mass centers, the structure may pound on the edge of the adjacent structure and cause strong tensional torques, which can lead to seriously damage to the column on the edges and corners of the pounded building.

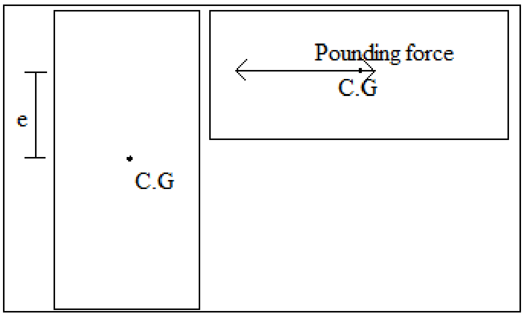

Figure 3.5: Adjacent buildings with non-coaxial mass centers

3.6 POUNDING OF ADJACENT BUILDING WITH SIMILAR VIBRATIONS

They are said to have pendulum–like impact of buildings. This type of impact is usually seen in buildings, which are built completely the same (e.g. small towns). In this type of impact, some similar buildings that oscillate similarly, in strong earthquakes, hit the last building in the series and cause serious displacement in the pounded building. Existence of the same shape of the vibration in some building and the high momentum lead to last building has intensive responses.

4. FACTORS AFFECTING POUNDING

The factors include among others: soil condition, building heights, relative difference between building's heights, separation between adjacent buildings, lateral load resisting structural system, the collision's points location, the peak ground acceleration of the earthquake at the location of building, the fundamental period of the structure, the fill material or expansion joints material (if any), the material of construction (steel, concrete, masonry), story height, type of induced vibrations (in-phase or out-of-phase), damping mechanisms, the adopted methods of pounding mitigation, the location of the structure (standalone or built in a row), the lateral eccentricity and twisting motion (if any), etc. While some of the above mentioned items have trivial impact on the pounding of structures, others are critical and strongly affect the pounding phenomena. The majority of codes are mainly concerned with the separation distance between adjacent building and structural drift (which includes the effect of building height, lateral load resisting system adopted in the studied structures, seismic zone and torsional effects).

5. FAILURES AND DAMAGES

Buildings often are built right up to the property lines in order to make maximum use of space, and historically buildings have been designed as if the adjacent buildings do not exist. As a result, the buildings may impact each other, or pound, during an earthquake. Building pounding can alter the dynamic response of both buildings, and impart additional inertial loads on both structures.

1) Adjacent building with same heights and same floor levels: Those buildings will exhibit similar dynamic behavior. If the buildings pound, floors will impact each other, so damage due to pounding usually will be limited to non-structural components. Generally for cases of same height buildings, pounding location mainly take place at the top except for cases with relatively small gap distance, where pounding takes place at the middle or bottom floors.

2) Adjacent building with distinct total elevation above the ground and various surface levels: When the buildings are of different heights, the shorter building can act as a buttress for the taller building. The shorter building receives an unexpected load while the taller building suffers from a major stiffness discontinuity. Local damages occurs in the cases of adjacent buildings of different floor levels due to the lateral impact of the mid-height of the columns of a building by slabs of the other.

3) Structures established in a row: In such construction, due to variation in dynamic properties of masonry units, pounding in terms of wall damage or bulging out of the wall is commonly observed. The variations in storey height and construction materials and building components usually control the intensity of damage significantly. Buildings on the edge of row housing setup were found to be more damaged than the buildings in between.

4) Adjacent structures with distinct dynamic characteristics: Pounding becomes more critical when the phase difference in the starting time of excitation of the structures is relatively large. In case of adjacent structures with different natural periods, the most affected by pounding are the rigid ones, irrespective of their relative position in a row.

5) Adjacent building with unequal heights, pounding may just arise in columns.

6) Adjacent building with unequal distribution of mass and/or stiffness: When the story mass of both buildings are equal both buildings accompany each other during the pounding and both buildings demonstrate similar displacement histories (phase and amplitude) since the fundamental period of the pounded buildings is somewhat an average of the fundamental periods of the individual buildings. By increment of the story mass, effect of the pounding is reduced for the heavier building while is increased for the lighter building.

7) Buildings having irregular lateral load resisting systems in plan: Rotates during an earthquake, and due to the torsional rotations, pounding occurs near the building periphery against the adjacent buildings.

6. MITIGATION OF POUNDING

Often existing buildings do not have sufficient seismic gap between adjacent buildings to withstand the lateral displacement due to earthquake forces and resulting large damage for moderate earthquake and possibly collapses for heavy earthquake. Provision of supplemental strength in form of additional lateral force-resisting elements such as shear walls, braced or moment frames helps to reduce the lateral displacement by increasing the stiffness of the buildings. Some of the mitigation techniques used to minimize the damages from pounding as follows:

1. In link element technique, forces in links can be same order of base shear magnitude. This link may sometimes totally alter the distribution of forces.
2. Bumper damper elements are link elements that are activated when gap is closed. Such elements reduce energy transfer during pounding and the high frequency pulses. The damper will yield a smaller value for the coefficient of restitution.
3. Supplemental energy devices can be used in the structures for pounding mitigation depending on the additional damping supplied.
4. The use of shear walls that are constructed at right angles to the divided line between two buildings in contact, so that they can be used as bumper elements in the case of pounding.
5. Provide sufficient minimum distance between adjacent structures.
6. Provide sufficient seated length between the decks or provide shock absorbing devices between the decks and bearings under the extremities of the decks in bridges.
7. Buildings having simple regular geometry, uniformly distributed mass and stiffness in plan as well as in elevation, suffer very less damage than buildings with irregular configurations.

From the above reasons, it is widely accepted that pounding is an undesirable phenomenon that should be prevented or mitigated.

4. CONCLUSION

This paper gives effective information about the topic seismic pounding, its causes, cases of pounding, failures and damages as well as important mitigation measures.

• Constructing separated buildings is the best way of preventing structural poundings.
• In this study, it is concluded that constructing adjacent buildings with equal floor heights and separation distances reduces the effects of pounding considerably.
• Existing adjacent buildings which are not properly separated from each other can be protected from effects of pounding by placing elastic materials between them.
• As the PGA value increases, the minimum separation between the structures also increases.
• The separation distance between the two structures decreases, the amount of impact is increases, which is not applicable in all cases. It is only applicable when the impact time is same. It may also decreases when separation distance decreases, which leads to less impact time.
• At resonance condition the response of the structure is more and may lead to collapse of the whole structure.
• The duration of strong motion increases with an increase of magnitude of ground motion.

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BIOGRAPHIES

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