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Pounding Analysis of Adjacent Structures

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ABSTRACT

The aim of this study is to correlate the seismic performance of a RC frame structure at different seismic demand levels with the separation gap that would be inadequate against pounding with an adjacent structure. In this direction nonlinear direct integration seismic analyses have been performed. This study includes the evaluation of the storey (floor to floor) and inter-storey (floor to column) pounding problem at fifteen seismic demand levels, using for each level 2 seismic excitations that have been properly scaled. The seismic performances of the structures without the pounding effect have also been evaluated. The results of the assessment indicate that: (a) Adjacent structure with same stories and equal storey height behaves same as no pounding structures. (b) at all the examined levels of the seismic demand, the local performance of the external column of the tall building that suffers the impact from the upper floor slab of the adjacent shorter structure is the most important issue in the inter-storey pounding phenomenon. (c)The taller structure suffers whiplash effect when pounds on adjacent shorter structure. Thereafter, the minimum required gap distance against pounding between the adjacent structures has been estimated taking into account two different criteria: (a) avoidance of the shear failure in the critical column that suffers the hit and (b) complete avoidance of the contact between the adjacent structures. The separation gap is evaluated at all the seismic demand levels for both pounding cases. In comparison to the IS 1893:2002 provisions the results of this study indicate less conservative separation gap distances between the adjacent structures at different levels of seismic demand.

Keywords: *Structural Pounding, Whiplash Effect, Gap Distance, Gap Element*

1. INTRODUCTION

During earthquake the adjacent buildings having different dynamic characteristics vibrate out of phase and there is insufficient energy dissipation system or separation distance to accommodate the relative motions of adjacent buildings. This may happen not only in buildings but also in bridges and towers, which are constructed close to each other. For reducing the damage due to pounding the very simple and effective way is by providing enough space between the adjacent structures, but sometimes it is difficult to be implemented due to high cost of land in metro cities and everyone wants to construct the building up to their property line. Structural pounding damage in structures can arise from the following:

- Adjacent buildings with the same heights and the same floor levels.
- Adjacent buildings with the same floor levels but with different heights.
- Adjacent structures with different total height and with different 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.
- Pounding occurred at the unsupported part (e.g., mid-height) of column or wall resulting in severe pounding damage.
- The majority of buildings were constructed according to the earlier code that was vague on separation distance.
- Possible settlement and rocking of the structures located on soft soils lead to large lateral defections which results in pounding.

Karayannis *(2004)*[1] investigated influence of the structural pounding on the ductility requirements and the seismic behaviour of reinforced concrete structures designed to EC2 and EC8 with non-equal heights is investigated. Two distinct types of the problem are identified: Type A, where collisions may occur only between storey masses; and Type B, where the slabs of the first structure hit the columns of the other (72 Type A and 36 Type B pounding cases are examined).. In both pounding types the ductility requirements of the columns of the taller building are substantially increased for the floors above the highest contact storey level probably due to whiplash behavior. The most important issue in the pounding type B is the local response of the column of the tall structure that suffers the hit of the upper floor slab of the adjacent shorter structure. In all the examined cases this column was in a critical condition due to shear action and in the cases where the structures were in contact from the beginning of the excitation, this column was also critical due to high ductility demands.

Pant *et al.(2012)* [2] studied the effects of seismic pounding on the structural performance of a base-isolated reinforced concrete (RC) building are investigated, with a view to evaluate the influence of adjacent structures and separation between structures on the pounding response. building shows good resistance against shear failure and the predominant mode of failure due to pounding is flexural.

Chitte *et al. (2014)* [3] studied about the seismic pounding between the adjacent building structures subjected to near field and far field earthquakes. Two models of G+5 storied building, one with live load 1.5KN/m2, other with 2 KN/m2 and a model of G+8 storied building with live load 1.5 KN/m2 were modeled. All other properties were almost kept the same. Time historey analysis of building structures were done to examine the exact nonlinear behaviour of the building structures using SAP2000.They concluded that the displacement for near source is much greater than the far source ground motion.

Ravindranatha *et al. (2015)* [4] studied on the seismic pounding between adjacent buildings. Prevention techniques of pounding between adjacent buildings due to earthquakes are studied. An adjacent building combination of G+8 and G+5 storeys with 80 mm expansion joint was analysed using time historey of Elcentro earthquake data. The building is special moment resisting frame considered to be situated in seismic zone IV having medium soil and intended for residential use. It is concluded that all the prevention methods that are used in this study proved to be effective to prevent pounding between adjacent buildings and a safe separation distance should be provided according to FEMA-273. As pounding is observed at fifth floor due to positive displacement of eight storey and negative displacement of five storey buildings. To prevent this, FEMA 273-1997(Federal Emergency Management Agency) provides safe separation distances between adjacent buildings.

$$S = \sqrt{D_1^2 + D_2^2} \qquad (1)$$

It is SRSS (Square Root of the Sum of the Squares) Method

$$S = D_1 + D_2 \qquad (2)$$

It is Absolute Method.

Where,
D_1 = Peak displacement of building No. 1
D_2 = Peak displacement of building No. 2
S should not be greater than the distance between adjacent buildings.

2. OBJECTIVE OF STUDIES

- To evaluate the effects of structural pounding on the building structures.
- Effect of different separation gap on storey displacement, base shear, pounding force and frequency of adjacent structures is going to be study.

3. METHOD OF ANALYSIS

3.1 Contact element method

The contact element approach is a very widely used formulation because of its easy adaptability and logical nature to model impact. The impact phenomenon is modeled by using a contact element that is activated when the gap between the structures closes. The simplest contact element consists of a linear elastic element. The spring is assumed to have restoring force characteristics such that only when the relative distance between the masses becomes smaller than the initial distance (gap), the spring contracts and generates forces, which enable us to consider the phenomenon of pounding within the framework of an ordinary response analysis. This collision spring is assumed to be the axial stiffness of the floors and the beams in each storey. The force in the contact element may be expressed according to:

$F_p = K_p\,[u_1 - u_2 - g_p]$ if $u_1 - u_2 - g_p \geq 0$ (Buildings getting closer)

$F_{p=0}$ if $u_1 - u_2 - g_p < 0$ (Buildings getting closer)

Where u_1 and u_2 are the displacements of the impacting bodies, k_p is the spring constant of the element and g_p is the static separation between the structures.

3.2 Gap Element

Gap has been defined as link elements in ETABS (Fig.1). It is a compression-only element required to assess the force of pounding and simulate the effect of pounding. The purpose of the gap element is to transmit the force through link only when contact occurs and the gap is closed. The nonlinear force-deformation relationship is given by Eqn.

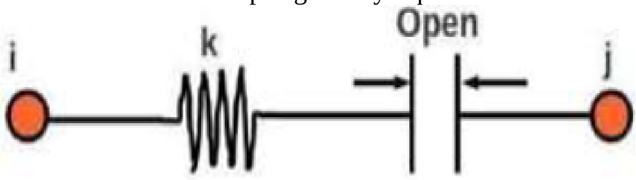


Fig. 1: Gap Element

$$f = \begin{cases} K(d - open) & if\ d - open < 0 \\ 0 & otherwise \end{cases}$$

Where K is the spring constant, d denotes the displacement, and open is the initial gap opening, which must be zero or positive.
The way of selecting stiffness for the gap elements is chosen as 100 times greater value than the relation AE/L. It this worth mentioning that A is the cross-sectional area of the element, E is the modulus of elasticity, and L is the length of the element in the direction perpendicular to the contact surfaces. Therefore, in this model K is calculated as follows:

$$K = \frac{EA}{L} \times 100$$

$$K = \frac{Modulus\ od\ elasticity\ of\ concrete\ X\ area\ of\ contact\ surface}{length\ of\ element\ of\ contact\ surface} X\ 100$$

3.2 Formulation of Pounding Analysis

Nonlinear dynamic analysis has been carried out considering familiar earthquake seismic record. The governing equations of motion are obtained considering equilibrium of all forces at each degree of freedom. The equations of motion for the structure are written in Eq.

$$[M]\{\ddot{y}_b\} + [C]\{\dot{y}\} + [K]\{y\} = -[M][T_g]\{\ddot{y}_g\}$$

Where, [M], [K] and [C] are the mass, damping and stiffness matrices of the superstructure respectively;{y} and $\{y_b\}$, are displacement of super structure and base; $\{\ddot{y}_b\}$ and $\{\ddot{y}_g\}$ are base acceleration and acceleration relative to the ground; $[T_g]$ is the earthquake influence coefficient matrix.
All nonlinearities are restricted to the nonlinear link elements only. The above dynamic equilibrium equations considering the super structure as elastic and link as nonlinear can be written

$$[M]\{\ddot{y}(t)\} + [C]\{\dot{y}(t)\} + [K_L]\{y(t)\} + r_N(t) = [-r_N(t) - K_N(t)]$$

Where,

$$K = K_L + K_N$$

K_L= stiffness matrix of all linear elements; K_N = stiffness matrix for all of the nonlinear degrees of freedom. C is the proportional damping matrix; M is the diagonal mass matrix; r_N is the vector of forces from nonlinear degrees of freedom in the gap elements; y, $\dot{y}$ and $\ddot{y}$ are the relative displacement, velocity and acceleration with respect to ground; r is the vector of applied loads. The effective stiffness at nonlinear degrees of freedom is arbitrary, but varies between zero and the maximum stiffness of that degree of freedom.

4. STRUCTURAL MODELING AND ANALYSIS

In order to study pounding, a three dimensional reinforced concrete moment resisting frame buildings is taken and analyzed in SAP2000. The two buildings consist of twenty stories (G+19) and fifteen stories (G+14). All columns in all models are to be fixed at the base. The height of all floors is 3m and also for studying floor to column pounding a floor height of 3m is also used but ground floor height of 15 storey building is taken as 1.5 m. Slab of 20 stories and 15 stories is modeled as rigid diaphragm element of 120 mm thickness respectively, for all stories considered. Live load on floor is taken as 3kN/m^2. The seismic weight is calculated conforming to IS 1893- 2002(part-I). The unit weights of concrete is taken as 24 KN/m^3. The grade of concrete for column, beam and slab is M-25. Both buildings are analyzed in SAP2000. To observe pounding, Time Historey Analysis is carried out taking data of Tabasa (PGA: 0.9g) and Cape Mendocino (PGA: 1.4g) ground motion database. The separation gap used are 20 mm, 50 mm, 100 mm, 200 mm and 4 m (Non Pounding).

The effective stiffness of gap element is 5500 KN/m. Gap elements are provided in three node points of the buildings where the shorter building collide with the taller one The following studies are carried out in order to observe pounding between adjacent buildings

Case I: Buildings with equal number of stories and equal storey height.

Case II: Buildings with equal number of stories and different storey height.

Case III: Buildings with different number of stories and equal storey height.

Case IV: Buildings with different number of stories and different storey height.

Table 1: Details of Model

Details		A	B	C
Storey		G+19	G+14	G+14
Dimensions	Plan	Two- 3m bay (X and Y direction)	Two- 3m bay (X and Y direction)	Two- 3m bay (X and Y direction)
	Storey Height	3 m	3 m	3 m (Except Ground Storey height: 1.5 m)
Load	Live load	3 KN/m^2	3 KN/m^2	3 KN/m^2
	Wall Load	14.4 KN/m	14.4 KN/m	14.4 KN/m
Sections	Wall	0.3 m thick	0.3 m thick	0.3 m thick
	Slab	125 mm thick	125 mm thick	125 mm thick
	Beam	300 x 600 mm^2	300 x 600 mm^2	300 x 600 mm^2
	Column	300 x 900 mm^2	300 x 900 mm^2	300 x 900 mm^2
Material Property	Concrete	M 25	M 25	M 25
		Unit Weight: 25 KN/m^3	Unit Weight: 25 KN/m^3	Unit Weight: 25 KN/m^3
		E=25000 N/mm2	E=25000 N/mm2	E=25000 N/mm2
	Brick	Unit Weight: 20 KN/m^3	Unit Weight: 20 KN/m^3	Unit Weight: 20 KN/m^3

5. RESULT AND DISCUSSION

5.1 Storey Displacement:

Case I: Buildings with equal number of stories and equal storey height.

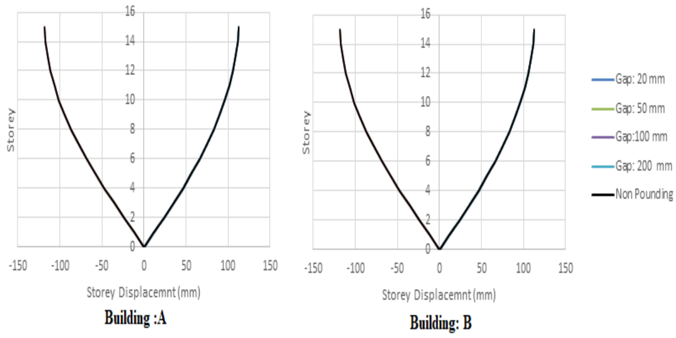


Fig. 2: Storey Displacement- Equal Number of Stories and Different Storey Height: Tabas Earthquake

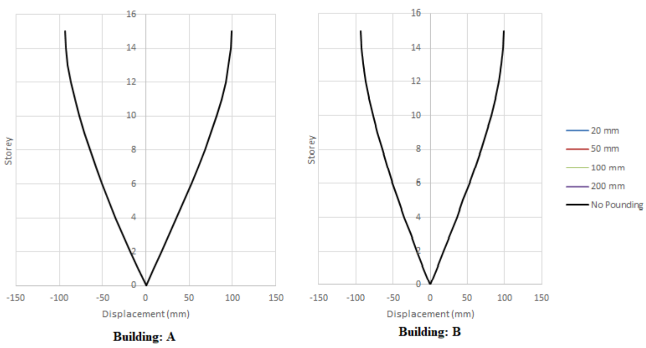


Fig. 3: Storey Displacement- Equal Number of Stories and Different Storey Height: Cape Mendocino Earthquake

Case II: Buildings with equal number of stories and different storey height

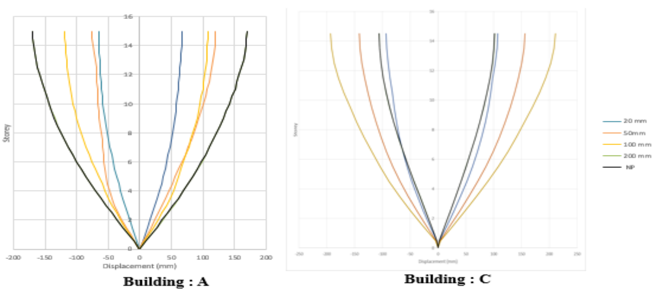
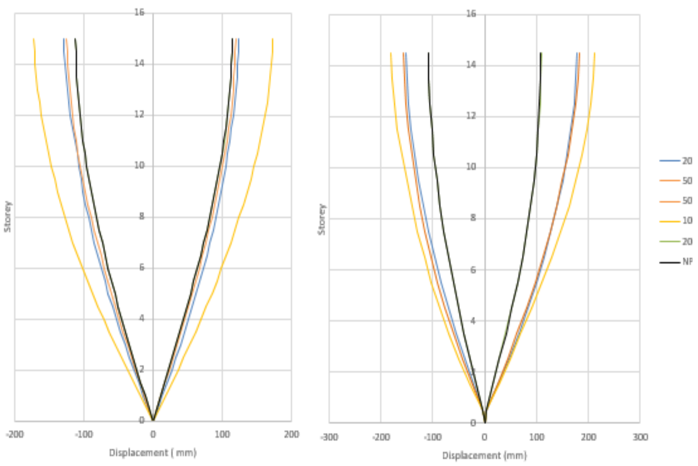


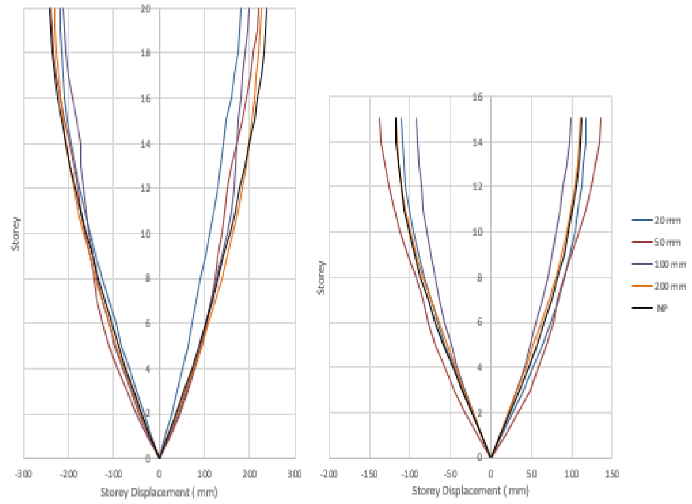
Fig. 4: Storey Displacement- Equal Number of Stories and Different Storey Height: Tabas Earthquake



Building : A **Building : C**

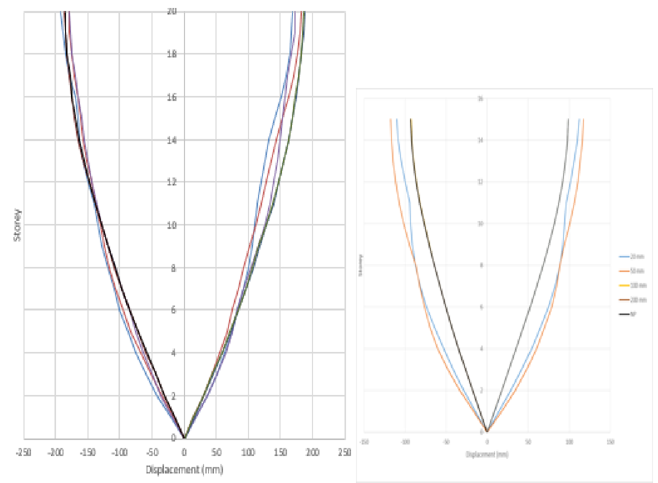
Fig. 5: Storey Displacement- Equal Number of Stories and Different Storey Height: Cape Mendocino Earthquake

Case III: Buildings with Different number of stories and equal storey height.



Building : A **Building : B**

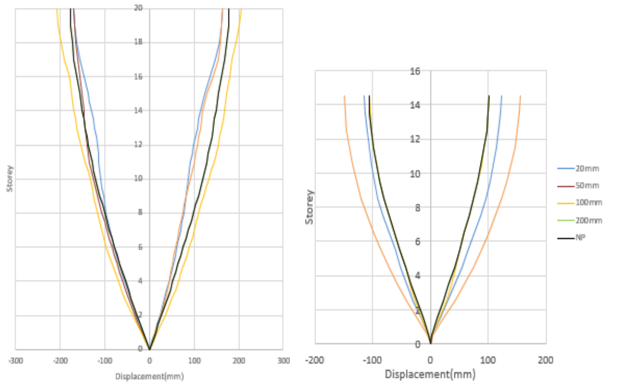
Fig. 6: Storey Displacement- Different Number of Stories and Equal Storey Height: Tabas Earthquake



Building : A **Building : B**

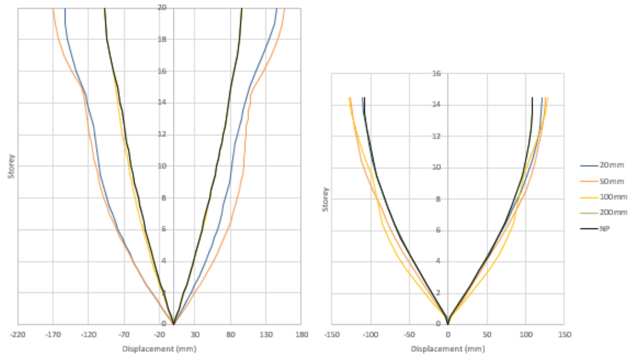
Fig. 7: Storey Displacement- Different Number of Stories and Equal Storey Height: Cape Mendocino Earthquake

Case IV: Buildings with different number of stories and different storey height



Building : A **Building : C**

Fig. 8: Storey Displacement- Different Number of Stories and Different Storey Height: Tabas Earthquake

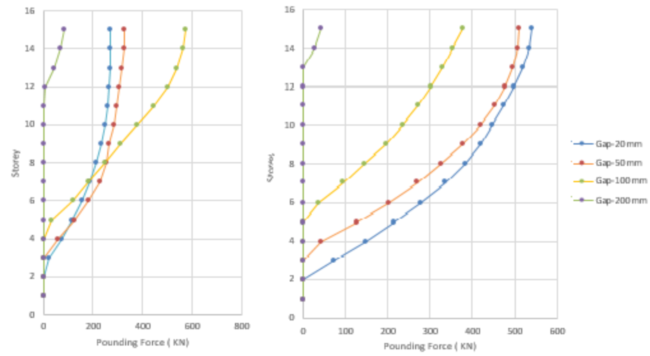


Building : A **Building : C**

Fig. 7: Storey Displacement- Different Number of Stories and Different Storey Height: Cape Mendocino Earthquake.

5.2 Pounding Force

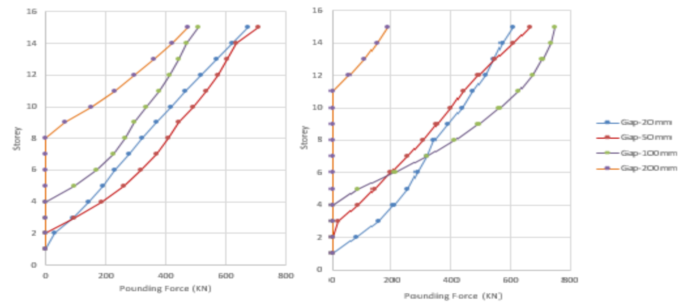
Case II: Buildings with equal number of stories and different storey height



Tabas **Cape Mendocino**

Fig. 8: Pounding Force- Buildings with equal number of stories and different storey height

Case III: Buildings with Different number of stories and equal storey height.



Tabas **Cape Mendocino**

Fig. 9: Pounding Force- Buildings with different number of stories and equal storey height

Case IV: Buildings with different number of stories and different storey height

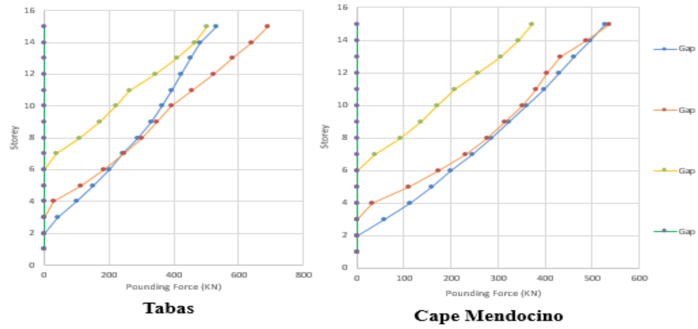


Fig. 9: Pounding Force- Buildings with different number of stories and different storey height

5.3 Base Shear

Structure	Earthquakes	Base Shear (KN)				
		20 mm	50 mm	100 mm	200 mm	4 m (No Pounding)
G+14: Equal	Tabas	35067.793	35067.793	35067.793	35067.793	35067.793
	Cape Mendocino	26183.245	26183.245	26183.245	26183.245	26183.245
G+14: Unequal	Tabas	31046.392	48893.646	59363.07	37384.67	37283.93
	Cape Mendocino	47276.967	45913.563	56423.583	37865.85	37865.85
G+19 & G+14: Equal	Tabas	36723.664	46575.133	43799.983	39876.08	39876.08
	Cape Mendocino	42765.442	45103.458	36027.667	31638.779	31274.391
G+19 & G+14: Unequal	Tabas	39222.485	43046.86	51596.661	30746.786	30746.786
	Cape Mendocino	3741.699	41298.70	34391.03	30441.312	30441.312

5.4 Frequency of Structure

Mode	G+14: Equal		G+19 & G+14: Equal		G+14: Unequal		G+19 & G+14: Unequal	
	Pounding (Gap)	No Pounding	Pounding (Gap)	No Pounding	Pounding (Gap)	No Pounding	Pounding (Gap)	No Pounding
1	2.879	2.879	2.402	2.171	3.243	3.041	2.727	2.586
2	5.164	5.367	4.460	2.879	5.367	3.457	4.574	3.041
3	8.607	8.607	6.985	6.498	9.422	9.087	7.794	7.372
4	9.615	9.734	9.102	8.607	10.884	10.332	9.554	9.087
5	14.239	14.239	11.167	10.786	15.291	15.025	12.315	11.989
6	14.869	14.946	14.467	14.239	17.367	17.092	15.297	15.025
7	19.716	19.716	15.334	15.006	20.991	20.785	17.205	16.998
8	20.174	20.229	19.252	19.134	23.836	23.661	20.983	20.785
9	24.976	24.976	19.997	19.716	26.466	26.298	21.807	21.671
10	25.339	25.381	23.278	23.143	30.091	29.968	25.973	25.865

6. CONCLUSION

6.1 Storey Displacements

- The structural behaviour of the building is altogether different with and without consideration of pounding.
- Adjacent buildings of the same loading, same structural system and same floor levels encountered same oscillation and same mode of vibration. As a result, no pounding occurred. It is preferable to construct adjacent buildings with same floor level and with suitable separation gap by considering dynamic analysis to avoid pounding. On the other hand buildings of different mode of vibration experienced pounding during earthquake excitation.
- During pounding smaller building experience more displacement and liable to greater damage than larger building.
- Location of pounding is one of the important factor to be considered. It is more severe in the case of node to column pounding.
- The mass of the colliding buildings increases the effect of seismic pounding.
- The slabs were found to have a high contribution in the impact force distribution due to its infinite in-plane stiffness. However, the case of non-corresponding floor levels in which the slab of one building hits the mid height of column of the adjacent building, increases the shear stresses in columns . This unexpected stress causes local damage in the collided columns increasing the possibility of the buildings collapse.
- The location of maxima for different functions such as BM, SF are different for pounding and buildings without consideration of pounding. As a result the building element shall be subjected to forces of higher magnitude for which it was not designed. This might be one of the major reasons behind the collapse or damage of the structure.
- From this study, it is clear that the designer should include the effect of pounding for closely spaced buildings.
- In case of pounding, constructing the buildings by providing safe separation distance between them is the best way of preventing structural pounding. However if adjacent buildings must be constructed for any reason, these structures must be separated with seismic gaps as given in IS 1893 (Part I): 2002

6.2 Pounding Force

- Pounding forces depends very much on the characteristics of the earthquake records and the dynamic characteristics of the adjacent buildings.
- .The largest pounding forces occur when there is a difference in height of the adjacent buildings due to the whiplash effect. Highest values of pounding forces occur near the top of the building.
- In generally pounding forces decreases as the separation distance increases. However, very small separation distance may prevent the build-up of momentum of the moving masses thus reducing the impact forces. However, this depends very much on the characteristics of earthquake record.

6.3 Base Shear

- Base shear of building decreases as the separation distance increases, but in case of different storey structure is increases though the separation distance increases. It is due to high impact forces generated in the structure.
- In no pounding case base shear value is lowest.

6.4 Frequency

- This study clearly shows that the pounding results depend on the ground motion characteristics and the relationship between the buildings fundamental period.
- The Effect of earthquake record is not limited to just the value of force; it affects the frequency of hits also.

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