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Parametric Characterization and Analysis of Pounding Behavior Adjacent Multi-Storied Buildings of Varying Heights

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Abstract: Many past earthquake studies show that during strong vibrations, the adjacent building structures which are closely spaced to each other are vulnerable to severe damage when the adjacent buildings are not at an adequate distance to accommodate their relative displacements. The primary goal of this research is to find out the minimum separation gap between buildings of varying height at the same floor-to-floor height level. SAP 2000 software is used to analyze the structural behavior of building during the earthquake.Three building models are taken for the study, one is six floors (G+6) and another two are nine floors (G+9), and twelve floors (G+12) respectively. Six floors (G+6)& twelve floors (G+12) structures have the same floor to floor height and plan and same beam and column size (equal stiffness) and G+9 buildings have floor to floor height are same but different beam and column sizes (different stiffness). The linear dynamic (RSA) analysis method is used to calculate the response (Displacement, frequency at fundamental time, Base Shear) of the structure at different floors levels. Response (top story displacements) calculated from the response spectrum is compared with the provisions of seismic gap per story height given in IS 4326: 2005.

I. INTRODUCTION

Many severe earthquakes have occurred in India in the last fewdecades. More than 50% area in the country is considered prone to heavy damage due to earthquakes. Nowadays with the fast-growing population and growth of metropolitan cities, land limitation became a very serious issue. To counter the land shortage issues in metro cities, the construction of high-rise buildings near to each other are rapidly taking place which may cause a pounding effect during an earthquake.

During an earthquake, the pounding effect in the building refers to collisions between buildings or collision between different parts of the same building. The unequal response of adjacent structures of varying heights and dynamic characteristics results in pounding. Researchers recognized that due to pounding action, buildings with varied structural systems, masses, and heights could have a serious problem that can be a significant threat to safety of structures. Adjacent buildings which have the same structural systems and same floor levels will exhibit alike behavior. Pounding forces decrease due to an increase in the lateral stiffness and displace reduces due to the application of coupled shear wall (Jagadeesh and Bhargavi 2020). Due to ground motion, lower-rise buildings are more vulnerable to damage than higher-rise buildings. In pounding situations, the joint acceleration and joint displacement of lower-rise buildings adjacent to the higher-rise building is greater than in non-pounding cases. In pounding situations, the joint acceleration and joint displacement of lower-rise buildings adjacent to the higher-rise building is greater than that in non-pounding cases. That's why lower-rise buildings are more vulnerable to damage than higher-rise buildings (Bhatt and Lamichhanne 2019). Seismic pounding affects adjacent buildings that lack adequate separation gaps. With a greater separation gap, the pounding effect can be reduced. Bracings, shear walls, and dampers can be used effectively to reduce pounding. (Nishath and Abhilash). The separation width between the structures cannot be widened all the time to accommodate the relative displacement of both structures; but, the relative displacement can be reduced by adding extra stiffeners, such as cross bracings. (Ravindranatha,Karanth, Shivananda, and H.L Suresh). Response Spectrum results for pounding case are studied to obtain the maximum storey displacements building with brick infill wall. By introducing shear walls above brick infill walls at appropriate places, the displacement of structures reduces gradually. When the separation distance available is insufficient, shear walls can be used to reduce the minimum seismic gap between structures. Pounding effect can be reduce by providing energy dissipaters such as springs and viscoelastic dampers in the building (Keerthi, Prabhakara, and Ravi Kumar 2015). The longitudinal response of the building is strongly affected by impacting forces, whereas the transverse response is almost non-existent due to the only friction force acting in the transverse direction. As the pounding force decreases at greater separation, the damage to adjacent structures decreases. Building displacements can be considerably decreased by constructing a shear wall that controls pounding and reduces the effect of pounding on buildings. (Jamal and Vidyadhara 2013).

A. Objectives of the study

Analyzing the displacement of buildings for six Storey (G+6) and twelve Storey(G+12) rigid floor diaphragm building cases (Buildings with same stiffness and floor to floor height) to enable movement, to minimize the effect of pounding due to earthquake by Linear Dynamic Analysis (Response Spectrum method) and comparing them with a seismic gap provided by IS Codes. Analyzing the displacements between adjacent building combinations for the same floor to floor height and different stiffness i.e., six-story (G+6) and nine-story (G+9) & nine-story (G+9) and twelve-story (G+12) rigid floor diaphragm building cases to enable movement, to minimize the effect pounding due to earthquake by Dynamic linear Analysis (Response Spectrum method) and comparing them with a seismic gap provided by IS Codes. To compare the frequency (cycle/sec) of earthquakes for all structures by calculating the fundamental natural period of vibration of the structures.

IS Code Provisions of the minimum gap for pounding effect between adjacent structures -

According to IS 4326:2005 –the following clauses gives provisions for the seismic gap between adjacent Structures -

B. Separation of Adjoining Structures

1) For buildings with varying overall heights or storey heights and varying dynamic properties, separation of adjacent structures or parts of the same structures is required. This is to avoid clashing with each other in the case of an earthquake.
2) As noted in clause 5.1.1, the minimum width of separation gaps shall be as specified in Table1 for different types of structures.

Table 1 Adjoining Structures gap width per storey

Type of building Construction	for Design Seismic Coefficient of a_h =0.12 Gap Width required per Storey, in mm
Frame structure with shear wall(Box type construction)	15.0 mm
Moment resistant RCC frame structure	20.0 mm
Moment resistant steel frame structure	30.0 mm

NOTE - Minimum seismic gap between buildings are 25 mm. For different a_h value the separation gap shall be calculated accordingly.

C. According to IS 1893-2016, the following are the Provisions of separation between adjacent units-

Clause 11.2 Separation gap between Adjacent Units

To avoid pounding when two adjacent structures or adjacent parts of the same structure deflect towards each other, they must be spaced by R times the total of the measured storey displacements distance. If the storey heights at different levels of two nearby structures have the same height then R/2+25 mm might be used instead of factor R.

The response of adjoining structures about external force is mostly because of the following situations:

1) When the seismic gap between adjoining structures is insufficient.
2) When structures have adequate gap but they are linked by one or more than one additional members.
3) When adjoining structures have distinct dynamic properties like mass, height, geometry. It is practically impractical to make two structures with same dynamic properties.
4) If the dynamic properties of two structures are exactly equivalent, there will be no pounding although, the seismic gap is zero.

II. METHODOLOGY

SAP 2000 V16 is used for Response spectrum method of analysis of the structures -

A. Linear Dynamic Analysis (RSA)

R.S.A is a dynamic linear analysis method that measures the contribution from each natural mode of vibration to calculate the maximum seismic response of a basically elastic structure.We are primarily interested in calculating floor response (displacements, fundamental natural period of vibration, and frequency) at various storey levels for various load combinations as per IS 1893:2016. The number of modes should also be evaluated using the fundamental natural period and modal mass participation ratios.

Structure Modeling and Analysis

Three structure models are modeled in SAP 2000. The followings are the Size of different components of buildings.

Location of the structures = Delhi NCR Region (Seismic Zone IV)

Type of soil = II (Medium or Stiff soils)

R = 5.0 Special moment resisting frame system kind of lateral load resisting system

I = 1.5 importance factor

Table 2 Material and member Properties

Structural components	G+6 Structure	G+12 structure	G+9 structure
Height	21.2 m	39.2 m	30.2 m
Plan dimension	17.5 m × 14 m	17.5 m × 14 m	17.5 m × 14 m
Beam size	0.35 m × 0. 45 m	0.35 m× 0.45 m	0.3 m × 0.4 m
Column size	0.4 m × 0.4 m	0.4 m × 0.4 m	0.4 m × 0. 4 m
Slab size	0.125 m	0.125 m	0.125 m
Concrete	M30 For beam and column and M20 for slab	M30 For beam and column and M20 for slab	M30 For beam and column and M20 for slab
Rebar	HYSD 500 MPA	HYSD 500 MPA	HYSD 500 MPA

B. Loading

1) Self-weight of the Structure = Dead Load
2) Live load =3.0 KN/m^2 for(G+6) &(G+9) building
3) Live load = 4.0 KN/m^2 (G+12) building
4) Roof Live Load = 1.0 KN/m^2
5) Earthquake load =As per provisions of IS 1893:2016
6) Wind loading = As recommended by IS 875 Part III

C. Modeled Elevated View of Structures

Following are the characteristics of the modeled structures-

1) All the models are of equal floor to floor heights with the height of ground floor 3.2 m and the rest of floors with 3 m center to center.
2) Member properties of G+6 and G+12 is the same but member properties of G+9 are different from the rest of the two.

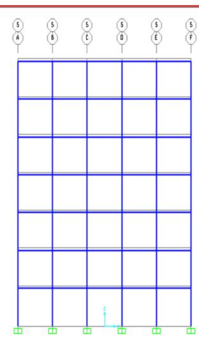

Figure 1. (G+6) structure

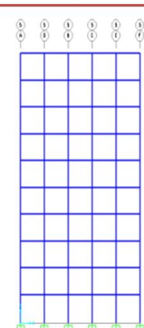

Figure 2. (G+9) structure

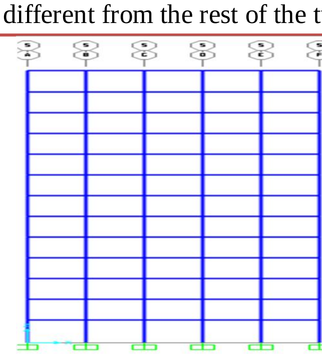

Figure 3. (G+12)structure

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III. RESULT AND DISCUSSION

A. Response Spectrum Analysis

SAP2000 is used to compute the response of a six-story (G+6), nine-storey (G+9), and twelve (G+12) buildings for rigid floor diaphragm by Linear Dynamic (response spectrum) analysis.

For seismic pounding gap between adjacent structures following results are observed –

1) Natural frequencies
2) Modal mass participation ratio
3) Displacements of the joints at different floor level

In SAP 2000, response spectrum analysis was performed using the response spectra specified in IS 1893(part1) 2002.

B. Results For six Floors (G+6) Structure

Number of modes taken in analysis = 20
Modal Load Participation Ratios

Table 3. Modal mass Participation Ratios

Case	Output Response	Direction	Percentage mass Participation in Static Analysis	Percentage mass Participation in Dynamic Analysis
Modal Analysis	Acceleration	U.X	100	98.6809
Modal Analysis	Acceleration	U.Y	100	98.6802
Modal Analysis	Acceleration	U.Z	93.7676	77.7000

According to IS 1893 2002 Part 1 clause 7.7.5.2 Modes to be taken in RSA –
Modal mass participation ratio are more than 90%,It means number of modes taken in the analysis are sufficient.

1) Displacement at the top Story in G+6 Building

Following are the results from different load combinations-

a) The greatest displacements in the X and Y directions for the load combinations 1.2(Dead.Load+Live Load +EQX) and 1.2(Dead.Load+Live Load +EQY) are 0.039778 and 0.040640, respectively.
b) The maximum displacements in the X and Y directions for the load combinations 0.9Dead Load+1.5 EQX and 0.9Dead Load +1.5EQY are 0.048031 and 0.049150, respectively.
c) The maximum displacements in the X and Y directions for the load combinations of 1.5(Dead .Load+EQX) and 1.5(Dead Load+EQY) are 0.049725 and 0.050796, respectively.

2) Story Drift

Following are the results of story drift for six-story structures-

Table 5 Story drift ratio per story number

Story number	Displacement in direction-X	Story drift ratio in the direction -X	Displacement in direction-Y	Story drift ratio in the direction-Y
6	0.048301	0.000987	0.049150	0.0009376
5	0.045340	0.001545	0.046337	0.0015803
4	0.040703	0.002070	0.041596	0.002141
3	0.034493	0.002539	0.035173	0.007812
2	0.026876	0.0029116	0.027361	0.002980
1	0.018141	0.003184	0.018421	0.009751
Ground story	0.008587	0.002862	0.008670	0.002890

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3) Story number Vs Storey displacement & story number Vs story drift ratio plot

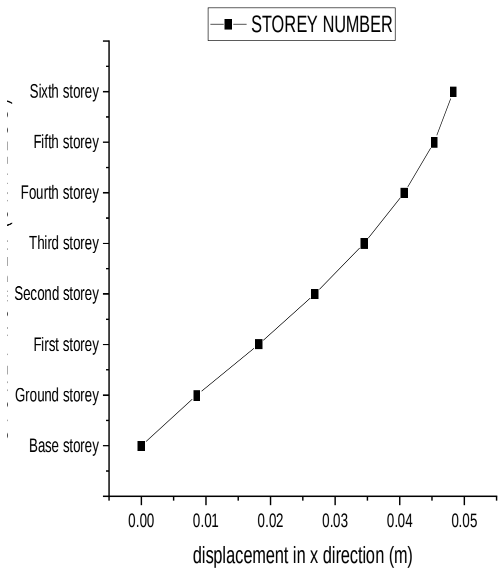


Figure 4.Storey level Vs displacement curve in the X direction

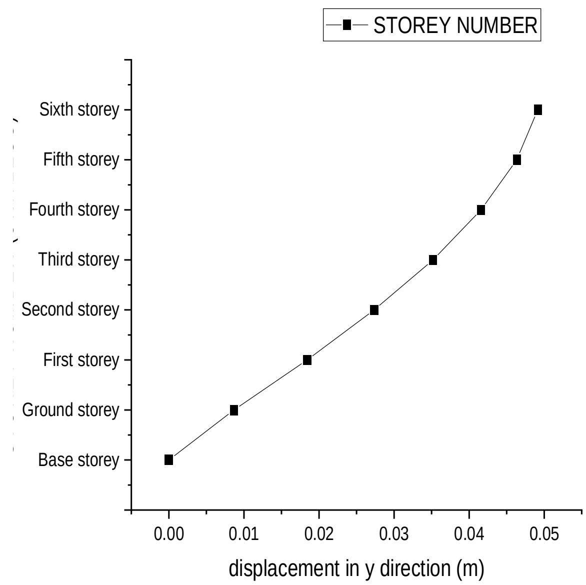


Figure 5.Storey level Vs displacement curve in Y-direction

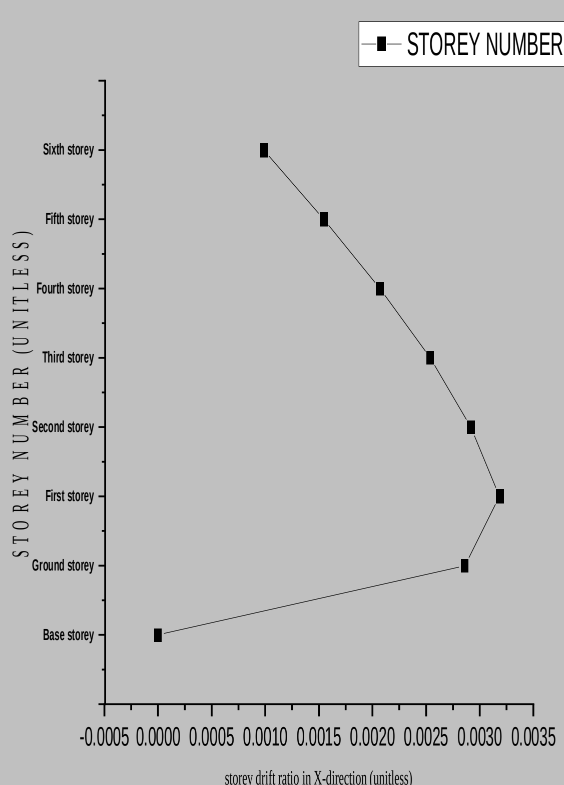


Figure 6. Story level Vs story drift in X-direction

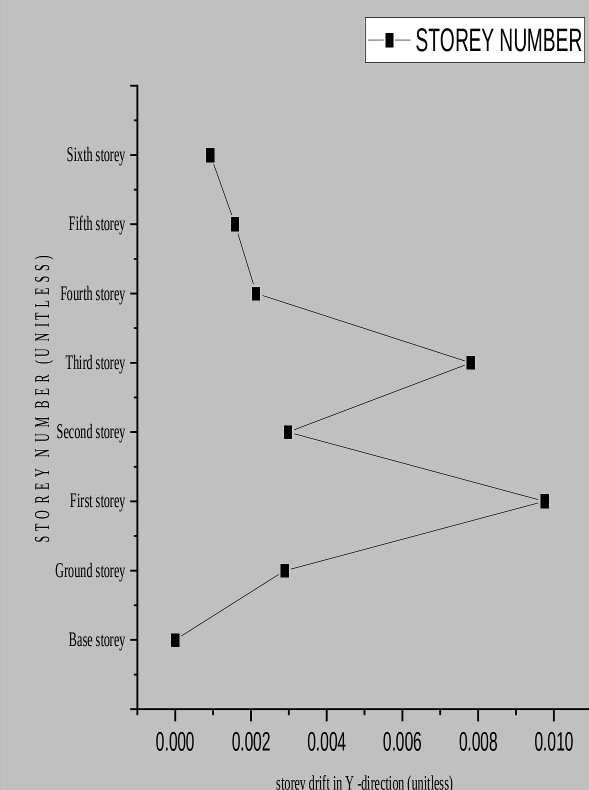


Figure 7. Storey level Vs story drift in Y-direction

C. *Results for Nine-story (G+9) Structure*

Modal mass participation ratios

Number of modes considered =40

Table 6.Modal mass Participation Ratios

CASE	Output Response	Direction	Percentage Participation in Static Analysis	Percentage Participation in Dynamic Analysis
Modal Analysis	Acceleration	U.X	100	99.0226
Modal Analysis	Acceleration	U.Y	100	99.0215
Modal Analysis	Acceleration	U.Z	98.3572	83.7064

According to IS 1893 2002 Part 1 clause 7.7.5.2 Modes to be taken in RSA-
Modal mass participation ratio are more than 90%, It means number of modes taken in the analysis are sufficient.

1) *Top story Displacement of nine-story G+ 9 Building*

a) The maximum displacements in the X & Y directions for the load combinations 1.2(Dead.Load+Live Load+EQX) and 1.2(Dead.Load+Live Load +EQY) are 0.108684 m and 0.111641 m, respectively.

b) The maximum displacements in the X and Y directions for the load combinations 0.9Dead.Load+1.5 EQX and 0.9Dead Load+1.5EQY are 0.135894 m and 0.133390 m respectively.

2) *Story Drift*

Following are the results of story drift of G+ 9 building –

Table 8. Story drifts Vs story number

Story number	Displacement in direction-X	Story drift in direction-X	Displacement in direction-Y	Story drift in direction-Y
9	0.100971	0.0010513	0.104201	0.0011103
8	0.097817	0.0017353	0.100870	0.0018063
7	0.092611	0.0023473	0.095451	0.0024656
6	0.085569	0.0029510	0.088054	0.0030653
5	0.076716	0.0034820	0.078858	0.0034336
4	0.066270	0.0039630	0.068557	0.0042690
3	0.054381	0.0044207	0.055750	0.0045363
2	0.041187	0.0047760	0.042141	0.0049146
1	0.026859	0.0049816	0.027397	0.0050723
Ground story	0.011914	0.0037231	0.012180	0.0038062

3) Story number Vs Storey displacement & story number Vs story drift ratio plot for nine-story structure

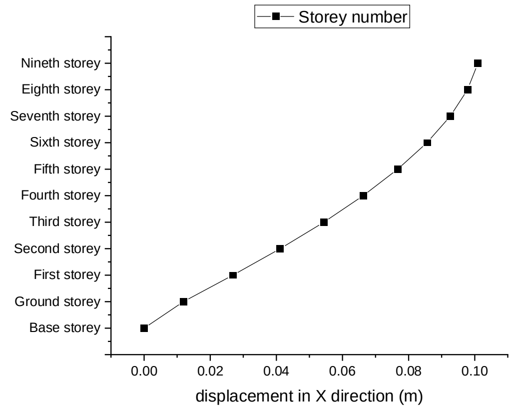


Figure8. Story level Vs displacement in X-direction

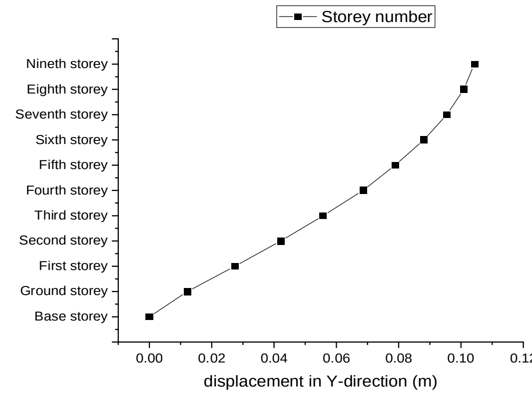


Figure 9. Story level Vs displacement in Y-direction

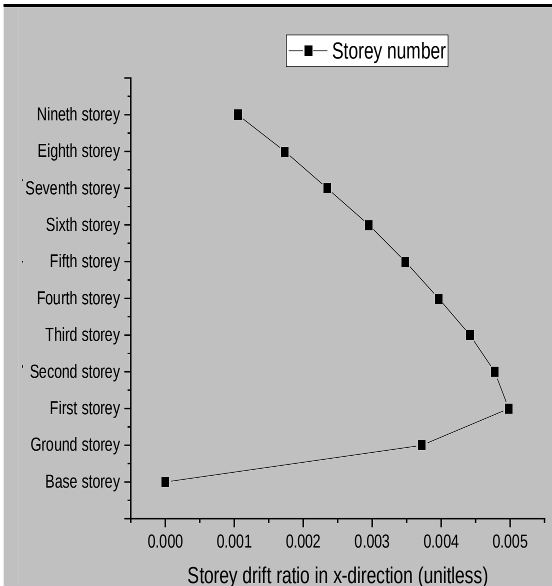


Figure 10. Story drift ratio Vs story level in the X direction

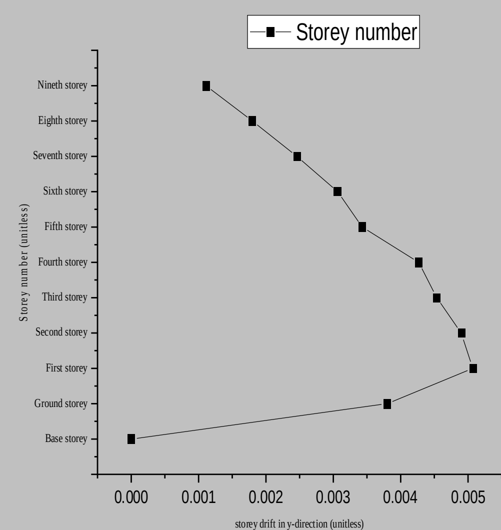


Figure 11. Story drift ratio Vs story level in the X direction

D. Results for Twelve-story (G+12) Structure

Modal mass participation ratios

Number of modes considered =50

Table 9. Modal mass Participation Ratios

CASE	Output Response	Direction	Percentage Participation in Static Analysis	Percentage Participation In Dynamic Analysis
Modal analysis	Acceleration	U.X	100	99.9993
Modal analysis	Acceleration	U.Y	100	99.9993
Modal analysis	Acceleration	U.Z	98.6309	84.1138

According to IS 1893 2002, Part 1 clause 7.7.5.2 Modes to be taken in RSA –
Modal mass participation ratio are more than 90%, It means number of modes taken in the analysis are sufficient.
Displacement of top story of twelve story building

Following are the results from different load combinations-

- The maximum displacements in the X and Y directions for the load combinations 0.9 Dead Load+1.5 EQX and 0.9 Dead.Load+1.5EQY are 0.226705 m and 0.232030 m, respectively.
- The maximum displacements in the X and Y directions are 0.214083m and 0.219954m, respectively, for the load combinations of 1.5(Dead Load +EQX) and 1.5(Dead Load+EQY).

1) Storey Drift

Following are the results of storey drift of twelve (G+ 12) storey –

Table 11 storey drift Vs storey number

Storey number	Displacement in direction-X	Storey drift in direction-X	Displacement in direction-Y	Storey drift in direction-Y
12	0.219806	0.001409	0.203207	0.001463
11	0.215577	0.002087	0.198816	0.002078
10	0.209316	0.002756	0.192581	0.002680
9	0.201048	0.003365	0.184540	0.003223
8	0.190953	0.003917	0.174869	0.003711
7	0.179200	0.004421	0.163735	0.004150
6	0.165937	0.004883	0.151283	0.004551
5	0.151288	0.005310	0.137629	0.004921
4	0.135358	0.005682	0.122866	0.005239
3	0.118310	0.005871	0.107148	0.005391
2	0.100697	0.006229	0.090974	0.005701
1	0.082008	0.007460	0.073869	0.006746
Ground story	0.059627	0.018637	0.053631	0.016759

Story number Vs Storey displacement & story number Vs story drift ratio plot for nine-story structure

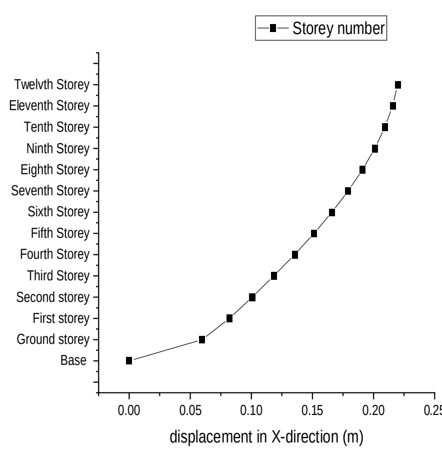


Figure12. Story level Vs displacement in X-direction

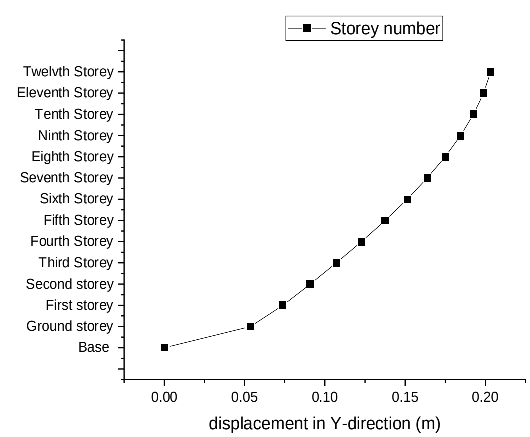
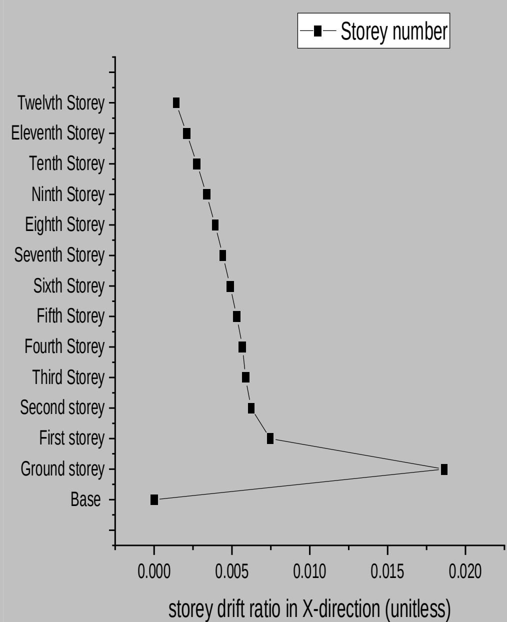


Figure 13.story level Vs displacement in Y-direction



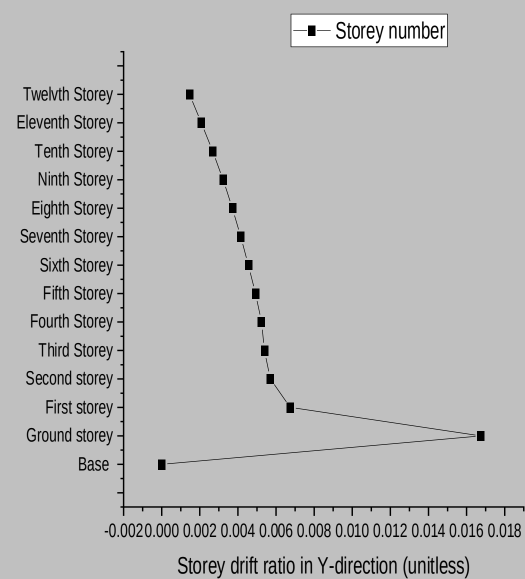


Figure15. story drift ratio Vs story level in X-direction

Figure14. story drift ratio Vs story level in X-direction

After summarizing responses of all the structures by response spectrum analysis, we can conclude with the following results for seismic gap calculation.

Table 12 Comparison of the response of all the structures

Type of response	G+6	G+9	G+12
Maximum Base Shear	3704.842 KN	4193.654 KN	8506.03 KN
Fundamental time	0.720306 sec	1.065538 sec	1.593120 sec
Frequency at fundamental time period	1.3882 cyc/sec	0.93849 cyc/sec	0.6277 cyc/sec
Maximum X-direction displacement	0.049725m	0.135894m	0.226705 m
Maximum Y-direction displacement	0.050796m	0.139521m	0.232030 m
Maximum separation distance between two buildings (for Design Seismic Coefficient of a_h =0.12 the value of GapWidth/Storey)	0.120 m	0.180 m	0.240 m

IV. CONCLUSIONS

A. Natural frequency is inversely related to building height, i.e., as the building's height increase, the natural frequency falls down. Natural frequency is inversely related to building height, i.e., as the building's height rises, the natural frequency reduces.

B. The shorter building will be affected more due to the high frequency of vibration than the taller building.

C. For all structures, the modal mass participation ratios are greater than 90%, indicating that the number of modes included in RSA is acceptable.

D. Story drift of all story levels in X and Y direction for all the structures is less than the story drift limit provided by IS 1893 2016 that is 0.004 times the height of the story.

E. In the adjacent building combinations of six-story and twelve-story buildings, the maximum X-direction displacements are 0.04972 m & 0.226705 m respectively and Y-direction displacements are 0.050796 m & 0.232030 m respectively which is less than the separation distance of 0.240 m provided by IS 4326 2005.

F. In the adjacent building combinations of six-story and nine-story buildings, the maximum X-direction displacements are 0.04972 m & 0.135894 m respectively and Y-direction displacements are 0.050796 m & 0.139521 m respectively which is less than the separation distance of 0.180 m provided by IS 4326 2005.

G. In the adjacent building combinations of nine-story and twelve-story buildings, the maximum X-direction displacements are 0.135894 m & 0.226705 m respectively and in Y-direction displacements are 0.139521 m & 0.232030 m respectively which is less than the separation distance of 0.240 m as recommended by IS 4326 2005.

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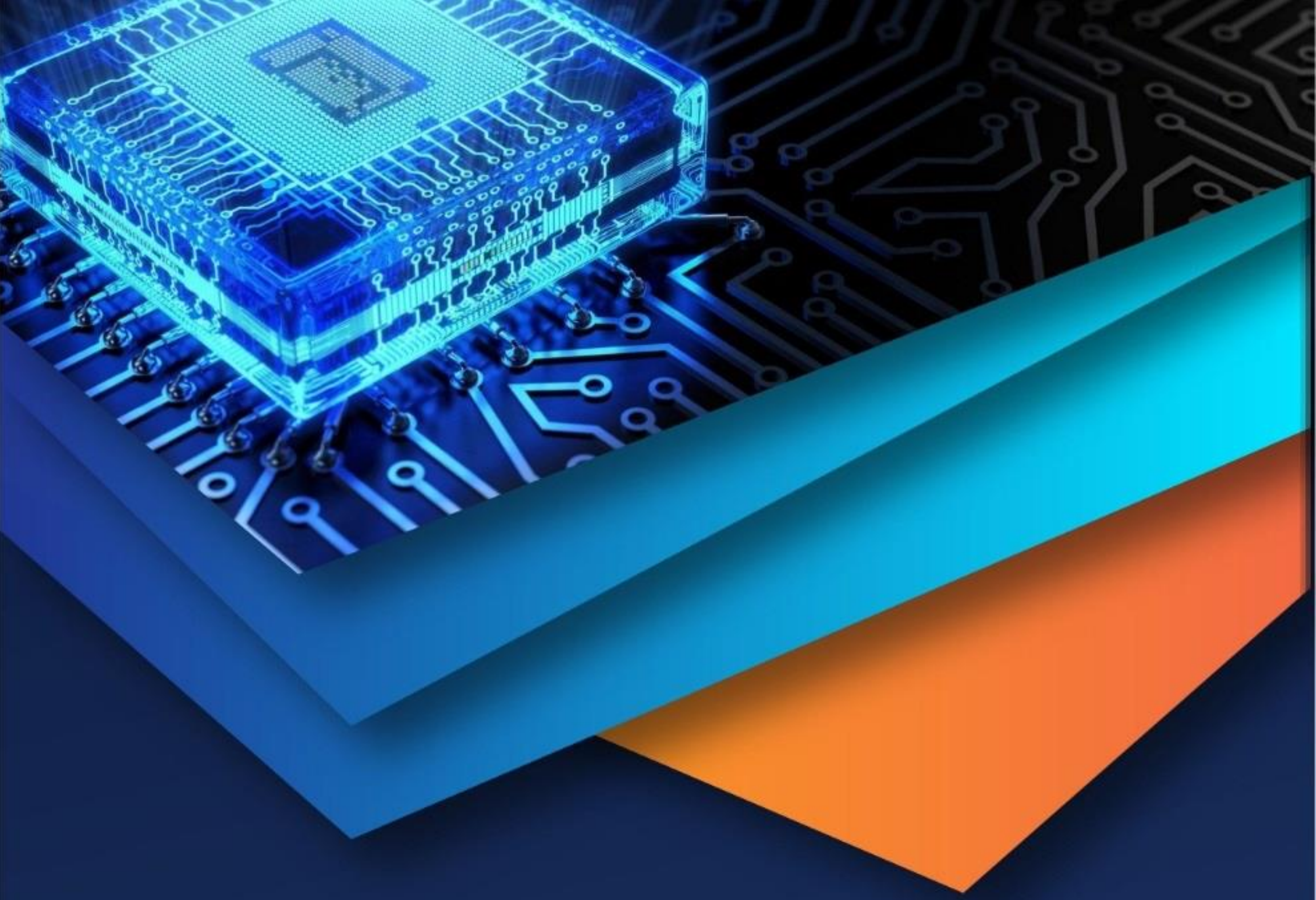

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