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Seismic Analysis of Structures on Sloped Ground Incorporating Angle Diagrid and Bracing Systems using ETABS

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Abstract: In recent years, construction of buildings on sloping ground has increased due to rapid urbanization and shortage of flat land, especially in hilly regions. However, such buildings exhibit complex structural behavior under seismic loading due to irregular geometry, unequal column heights, and variation in stiffness. Therefore, it becomes necessary to study and improve their seismic performance using suitable structural systems. In the present study, a comparative seismic analysis of normal building and sloped building is carried out using ETABS software. Different lateral load-resisting systems such as diagonal bracing, X-bracing, V-bracing, and diagrid system are considered to evaluate their effectiveness. The buildings are analyzed under seismic Zones II and III as per IS 1893:2016. Important parameters such as storey displacement, storey drift, and storey shear are studied to understand the structural response under earthquake loading. The results of the analysis indicate that sloped buildings are more vulnerable to seismic forces compared to normal buildings due to irregularity and short column effect. It is observed that the inclusion of bracing systems significantly improves the seismic performance by reducing displacement and drift. Among all systems, X-bracing and diagrid systems show better performance due to higher stiffness and efficient load distribution. The study highlights the importance of proper structural configuration and selection of suitable bracing system for ensuring safety and stability of buildings in seismic regions.

Keywords: Seismic Analysis, Sloped Building, ETABS, X-Bracing, V-Bracing, Diagonal Bracing, Diagrid System, Storey Displacement, Storey Drift, Storey Shear.

I. INTRODUCTION

Rapid urbanization and population growth have increased the demand for construction in hilly and sloped regions. Due to shortage of flat land in urban areas, engineers and planners are now forced to construct buildings on sloping ground. However, buildings constructed on slopes behave very differently compared to buildings constructed on level ground. In flat ground structures, the foundation level remains uniform, and the load distribution is symmetrical. But in sloping ground, the variation in ground elevation leads to unequal column heights, which causes irregular distribution of mass and stiffness along the height of the structure. This results in complex structural behaviour, especially under seismic loading conditions. Earthquakes are one of the most destructive natural disasters that can cause severe damage to structures and loss of life. Therefore, it is very important to study the behaviour of structures under seismic forces, especially when they are constructed on sloped terrain.

II. RESEARCH METHODOLOGY

Building Parameters:
The structural parameters considered for modelling the building are given below:

Table 3.1: Data / Parameters for Analysis

Parameter	Value
Storey Height	3.1 m
Wall Thickness	300 mm
Slab Thickness	150 mm
Beam Size	300 × 600 mm
Column Size	400 × 700 mm
Building Frame System	Special Moment Resisting Frame (SMRF)
Parapet Height	750 mm
Support Condition	Fixed
Plan Dimension	24 m × 24 m
Spacing (X & Y Direction)	3.5 m
Number of Storeys	G+10
Bracing Section	ISMC 350
Damping Ratio	5%

Modelling Procedure in ETABS:

The modelling of the structure is an important step in the analysis process, as it directly affects the accuracy of results. In the present study, the structural models of both normal and sloped buildings are developed using ETABS software. ETABS is widely used for the analysis and design of multi-storey buildings due to its advanced features and user-friendly interface. The modelling procedure includes defining material properties, section properties, geometry of the structure, and boundary conditions. All structural elements such as beams, columns, slabs, and bracing members are carefully modeled to represent actual field conditions. Proper attention is given to the alignment of members, especially in sloped buildings where variation in column height exists. The loads and load combinations are also defined as per relevant IS codes to ensure realistic simulation of seismic conditions.

The modelling of the structure is carried out step-by-step in ETABS software as follows:

1. Define grid system and storey data
2. Create structural elements (beams, columns, slabs)
3. Assign material properties
4. Define section properties
5. Model sloped ground using varying column heights
6. Assign bracing and diagrid members
7. Apply boundary conditions (fixed supports)
8. Define load cases (dead load, live load, seismic load)
9. Apply Response Spectrum function
10. Run analysis and extract results

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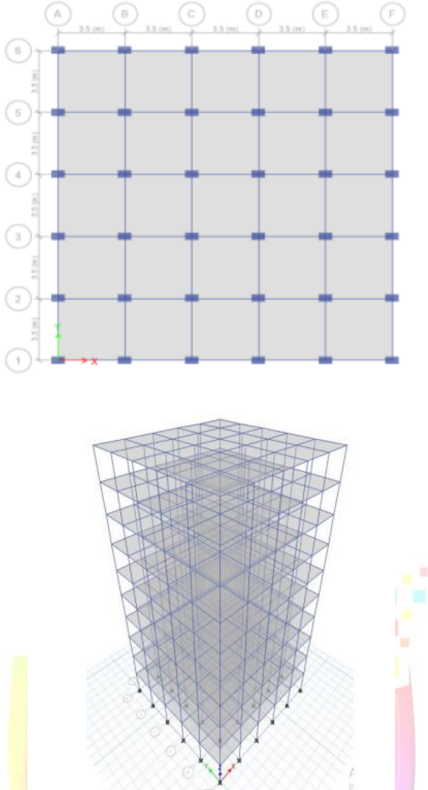


Figure 3.1: Plan and 3D Model of Normal Building

This figure shows the plan and 3D model of the normal building constructed on flat ground. All columns have equal height, resulting in a regular and symmetrical structure. The model represents a typical building without any irregularities. It helps in understanding the basic structural behavior under seismic loading. This model is used for comparison with sloped building models to study the effect of slope and bracing systems.

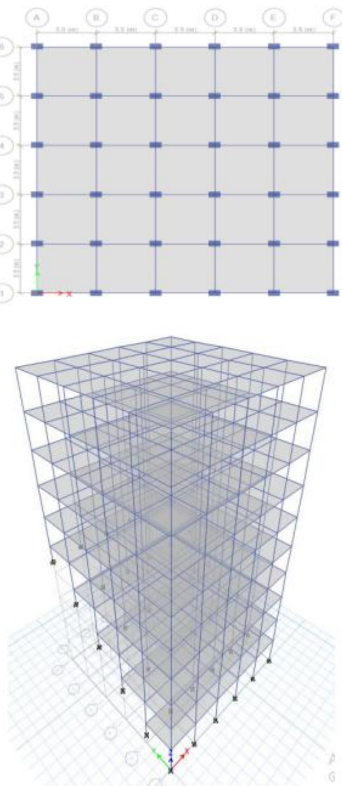


Figure 3.2: Plan and 3D Model of Sloped Building

This figure shows the plan and 3D model of the sloped building without any bracing system. The variation in column heights is clearly visible due to the sloping ground condition. The model represents the basic structural configuration used for analysis. It helps in understanding the irregular behavior of the structure under seismic loading. This model is used as a reference to compare the performance of different bracing systems.

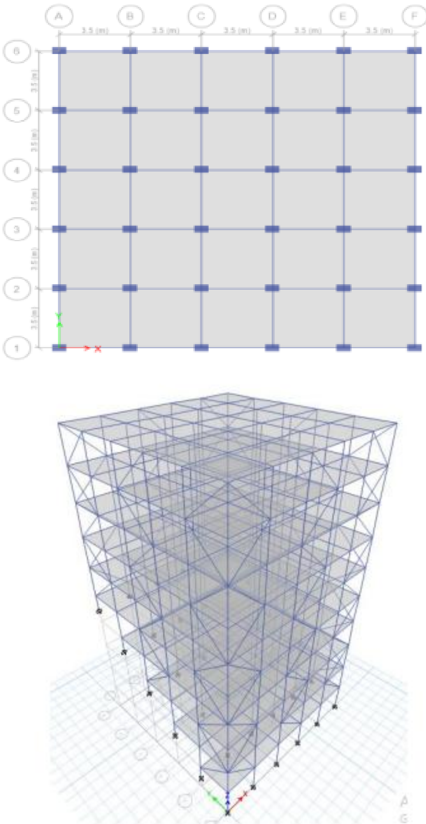


Figure 3.3: Plan and 3D Model of Sloped Building with Diagonal Bracing

This figure shows the plan and 3D model of the sloped building with diagonal bracing system. The inclined bracing members are provided between beams and columns to resist lateral loads. The sloping ground condition is clearly visible due to variation in column heights. The diagonal bracing increases the stiffness of the structure and reduces displacement during seismic loading. It also improves load transfer and enhances overall stability of the building.

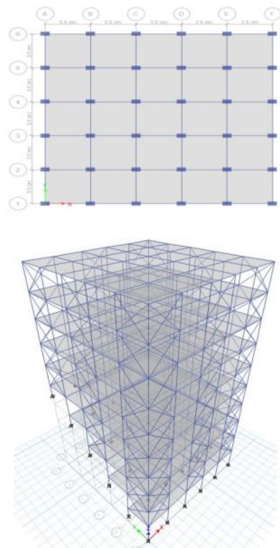


Figure 3.4: Plan and 3D Model of Sloped Building with X Bracing

This figure shows the plan and 3D model of the sloped building with X-bracing system. The diagonal members cross each other between columns, forming an “X” shape which provides high lateral stiffness. The variation in column heights due to sloping ground is clearly visible in the model. The X-bracing system effectively resists earthquake forces by reducing displacement and storey drift. It ensures better load distribution and improves the overall stability of the structure.

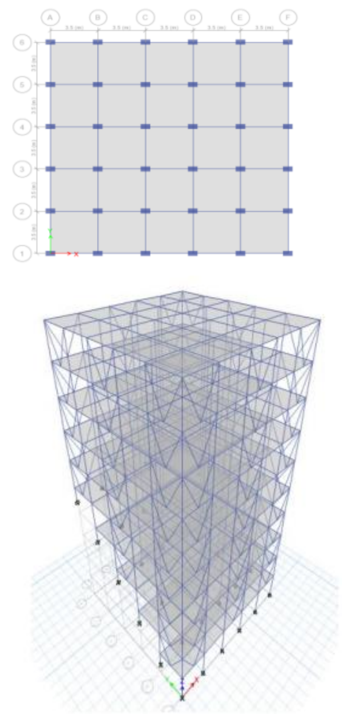


Figure 3.5: Plan and 3D Model of Sloped Building with V Bracing

This figure shows the plan and 3D model of the sloped building with V-bracing system. The diagonal members are connected from columns to the beam, forming a “V” shape which helps in resisting lateral loads. The sloping ground condition is clearly seen due to variation in column heights. The V-bracing increases the stiffness of the structure and reduces displacement during earthquake loading. It also provides better load distribution while allowing some flexibility in architectural planning.

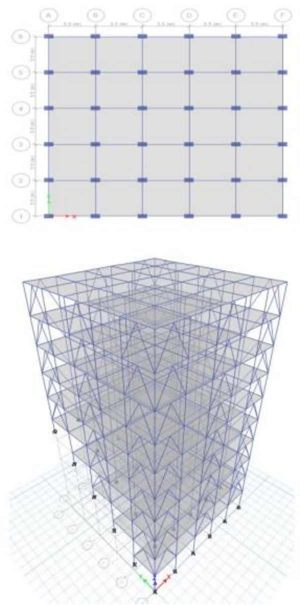


Figure 3.6: Plan and 3D Model of Sloped Building with Inverted V Bracing

This figure shows the plan and 3D model of the sloped building provided with inverted V (Chevron) bracing system. The bracing members are connected to the beam at a common point, forming a V-shape which helps in transferring lateral loads effectively. The sloping ground condition is visible due to variation in column heights. This bracing system improves the stiffness of the structure and reduces displacement under seismic loading. It also allows space for architectural openings while maintaining structural stability.

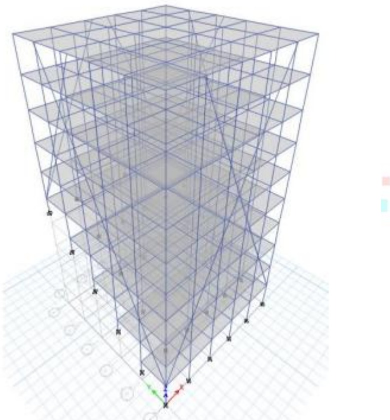


Figure 3.7: Plan and 3D Model of Sloped Building with 63⁰ Diagrid Bracing

III. RESULTS AND DISCUSSION

4.2 Comparison of Normal Building in Seismic Zones II & III

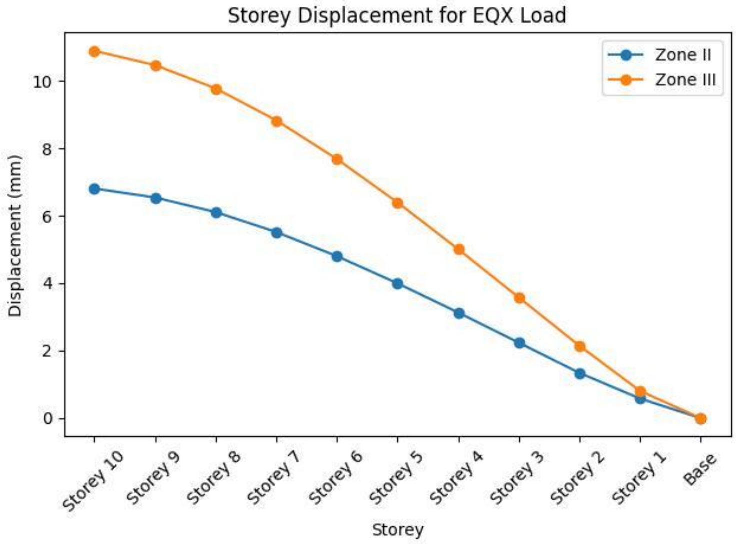
The seismic analysis of a normal building has been carried out for two different seismic zones, namely Zone II and Zone III, to understand how the structure behaves under varying earthquake intensities. As per Indian Standard IS 1893 (Part 1): 2016, Zone II represents a low seismic risk area, while Zone III represents a moderate seismic risk area. The main objective of this comparison is to evaluate how structural parameters such as displacement, drift, and shear vary with increase in seismic intensity.

4.2.1 Storey Displacement

Table 4.1: Storey Displacement for EQX Load (Zone II & Zone III)

Storey	Zone II Displacement (mm)	Zone III Displacement (mm)
Storey 10	6.804	10.886
Storey 9	6.540	10.463
Storey 8	6.107	9.772
Storey 7	5.516	8.826
Storey 6	4.800	7.680
Storey 5	3.995	6.391
Storey 4	3.130	5.009
Storey 3	2.236	3.577

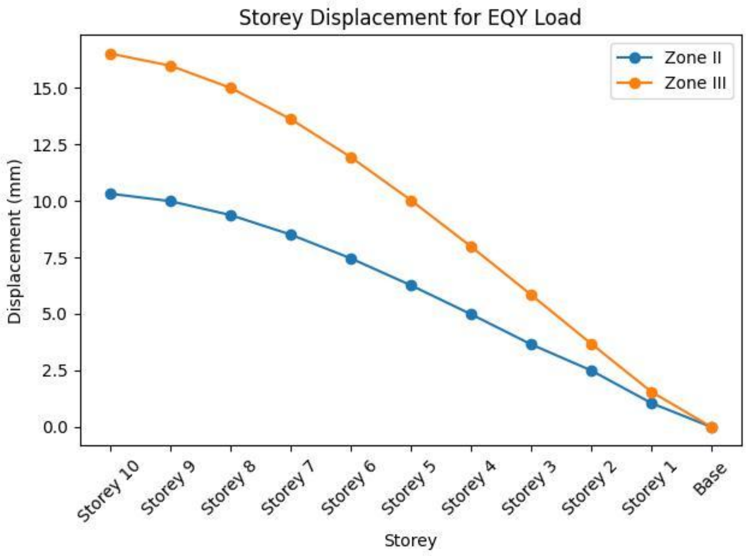
Storey 2	1.340	2.145
Storey 1	0.580	0.806
Base	0.000	0.000



Graph 4.1: Storey Displacement for EQX Load (Zone II & Zone III)

Table 4.2: Storey Displacement for EQY Load (Zone II & Zone III)

Storey	Zone II Displacement (mm)	Zone III Displacement (mm)
Storey 10	10.313	16.502
Storey 9	9.982	15.971
Storey 8	9.368	14.989
Storey 7	8.507	13.611
Storey 6	7.456	11.929
Storey 5	6.267	10.027
Storey 4	4.987	7.980
Storey 3	3.655	5.847
Storey 2	2.502	3.684
Storey 1	1.061	1.561
Base	0.000	0.000



Graph 4.2: Storey Displacement for EQY Load (Zone II & Zone III)

The results show that displacement increases as the seismic zone increases from Zone II to Zone III. From your data, the displacement at the top storey increases by approximately 37.50% for both EQX and EQY directions.

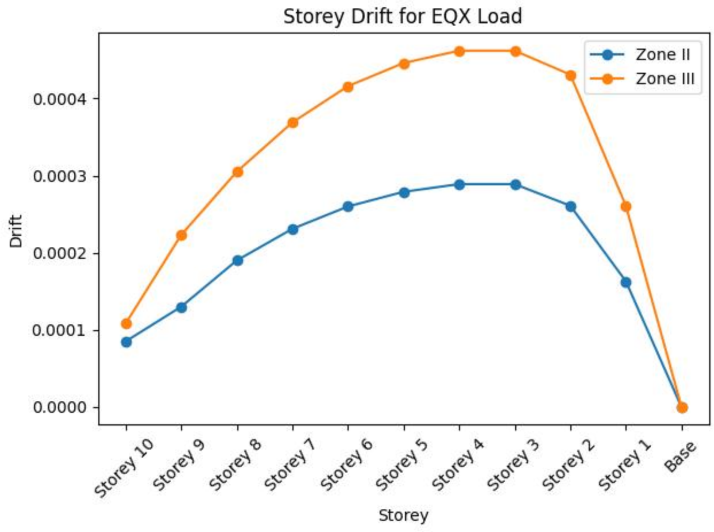
Observation:

1. EQY load shows slightly higher displacement compared to EQX
2. Maximum displacement occurs at top storey

4.2.2 Storey Drift

Table 4.3: Storey Drift for EQX Load (Zone II & Zone III)

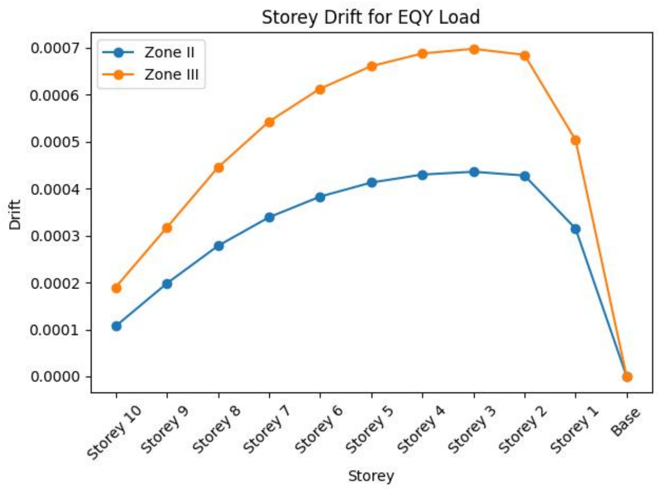
Storey	Zone II Drift	Zone III Drift
Storey 10	0.000085	0.000108
Storey 9	0.000130	0.000223
Storey 8	0.000190	0.000305
Storey 7	0.000231	0.000369
Storey 6	0.000260	0.000416
Storey 5	0.000279	0.000446
Storey 4	0.000289	0.000462
Storey 3	0.000289	0.000462
Storey 2	0.000261	0.000431
Storey 1	0.000163	0.000261
Base	0.000000	0.000000



Graph 4.3: Storey Drift for EQX Load (Zone II & Zone III)

Table 4.4: Storey Drift for EQY Load (Zone II & Zone III)

Storey	Zone II Drift	Zone III Drift
Storey 10	0.000107	0.000190
Storey 9	0.000198	0.000317
Storey 8	0.000278	0.000445
Storey 7	0.000339	0.000543
Storey 6	0.000383	0.000613
Storey 5	0.000413	0.000661
Storey 4	0.000430	0.000688
Storey 3	0.000436	0.000698
Storey 2	0.000428	0.000685
Storey 1	0.000315	0.000504
Base	0.000000	0.000000



Graph 4.4: Storey Drift for EQY Load (Zone II & Zone III)

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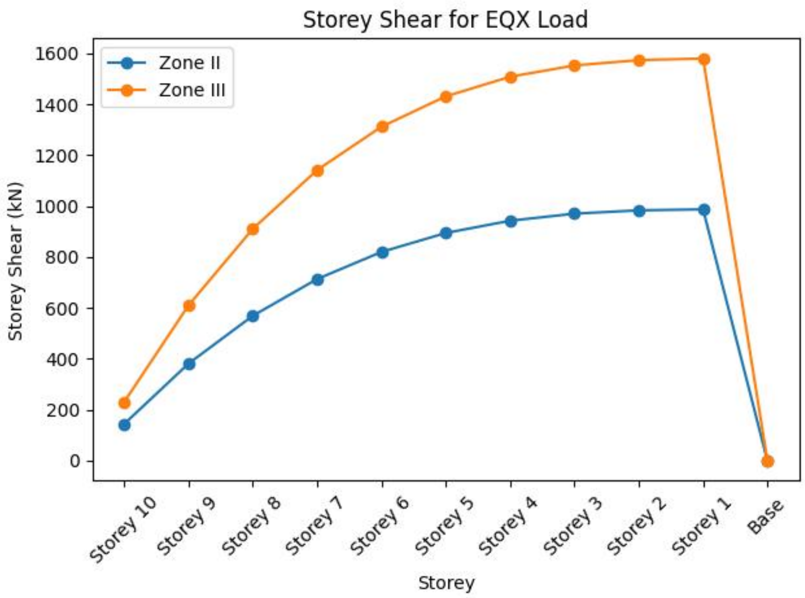
The storey drift is maximum at middle storeys (Storey 3 and 4). The drift increases by approximately:
1. 37.44% (EQX load)
2. 37.53% (EQY load)

Observation:
1. Zone III shows higher drift compared to Zone II
2. EQY load produces slightly higher drift

4.2.3 Storey Shear

Table 4.5: Storey Shear for EQX Load (Zone II & Zone III)

Storey	Zone II Shear (kN)	Zone III Shear (kN)
Storey 10	144.4517	231.1228
Storey 9	381.6076	610.5772
Storey 8	569.3831	911.0130
Storey 7	713.5715	1141.7143
Storey 6	819.9649	1311.9439
Storey 5	894.3547	1430.9675
Storey 4	942.5276	1508.0441
Storey 3	970.2584	1552.4134
Storey 2	983.2871	1573.2594
Storey 1	987.2473	1579.5957
Base	0.0000	0.0000

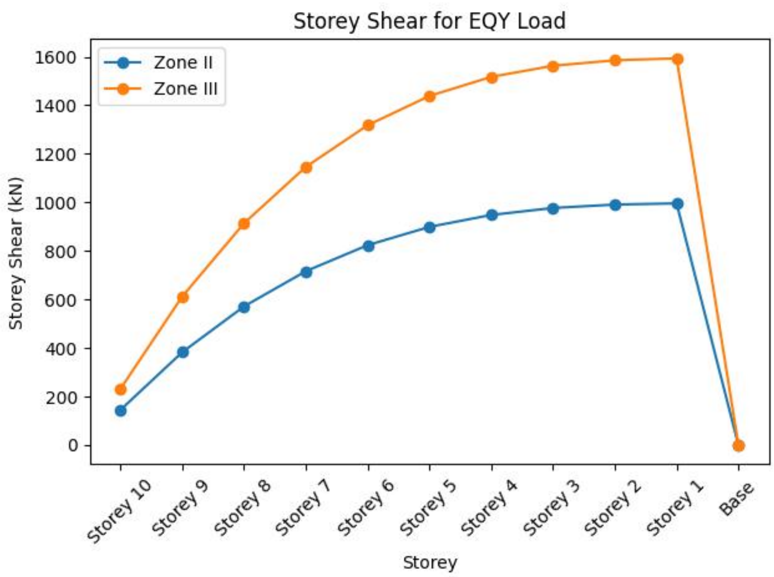


Graph 4.5: Storey Shear for EQX Load (Zone II & Zone III)

Table 4.6: Storey Shear for EQY Load (Zone II & Zone III)

Storey	Zone II Shear (kN)	Zone III Shear (kN)

Storey 10	144.8119	231.6991
Storey 9	382.7622	612.4193
Storey 8	571.3843	914.2149
Storey 7	716.4600	1146.3360
Storey 6	823.7726	1318.0362
Storey 5	899.1064	1438.5702
Storey 4	948.2434	1517.1894
Storey 3	976.9565	1563.1303
Storey 2	990.9841	1585.5746
Storey 1	995.9196	1593.4713
Base	0.0000	0.0000



Graph 4.6: Storey Shear for EQY Load (Zone II & Zone III)

The maximum storey shear occurs at the bottom storey (Storey 1). The shear increases by approximately 37.50% when moving from Zone II to Zone III.

Observation:

1. Shear decreases from bottom to top
2. EQY load produces slightly higher shear

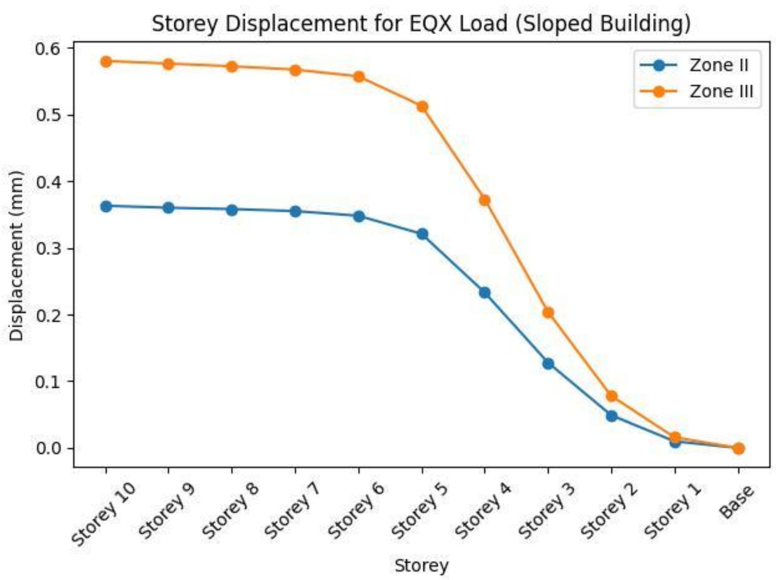
4.3 Comparison of Sloped Building in Seismic Zones II & III

The behavior of buildings constructed on sloped ground is quite different from buildings on level ground due to irregular geometry, unequal column heights, and variation in stiffness. In this study, the sloped building is analyzed under Seismic Zone II (low seismic risk) and Seismic Zone III (moderate seismic risk) to understand its structural response under earthquake loading. As per IS 1893, Zone III has higher seismic intensity compared to Zone II. Therefore, it is expected that all response parameters such as displacement, drift, and shear will be higher in Zone III.

4.3.1 Storey Displacement

Table 4.7: Storey Displacement for EQX Load (Sloped Building – Zone II & Zone III)

Storey	Zone II Displacement (mm)	Zone III Displacement (mm)
Storey 10	0.363	0.580
Storey 9	0.360	0.576
Storey 8	0.358	0.572
Storey 7	0.355	0.567
Storey 6	0.348	0.557
Storey 5	0.321	0.513
Storey 4	0.233	0.373
Storey 3	0.128	0.204
Storey 2	0.049	0.078
Storey 1	0.010	0.016
Base	0.000	0.000

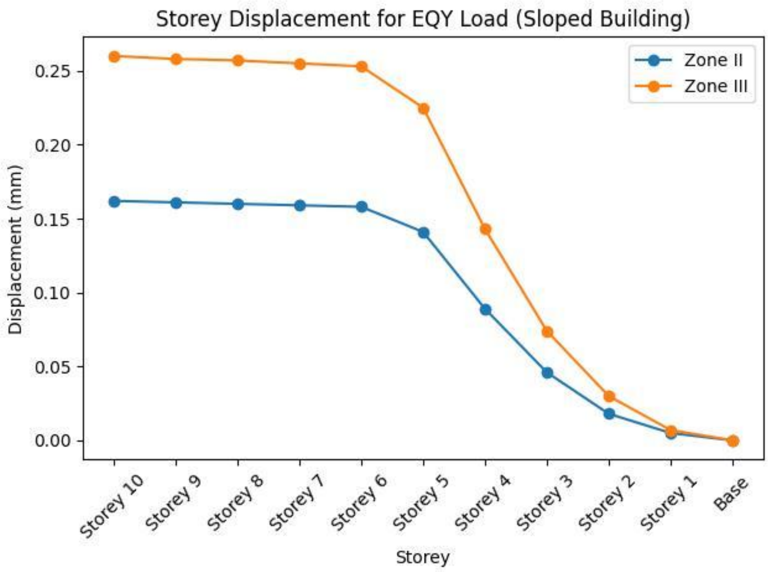


Graph 4.7: Storey Displacement for EQX Load (Sloped Building – Zone II & Zone III)

Table 4.8: Storey Displacement for EQY Load (Sloped Building – Zone II & Zone III)

Storey	Zone II Displacement (mm)	Zone III Displacement (mm)
Storey 10	0.162	0.260
Storey 9	0.161	0.258

Storey 8	0.160	0.257
Storey 7	0.159	0.255
Storey 6	0.158	0.253
Storey 5	0.141	0.225
Storey 4	0.089	0.143
Storey 3	0.046	0.074
Storey 2	0.018	0.030
Storey 1	0.005	0.007
Base	0.000	0.000



Graph 4.8: Storey Displacement for EQY Load (Sloped Building – Zone II & Zone III)

1. EQX displacement increases by 37.41%
2. EQY displacement increases by 37.70%

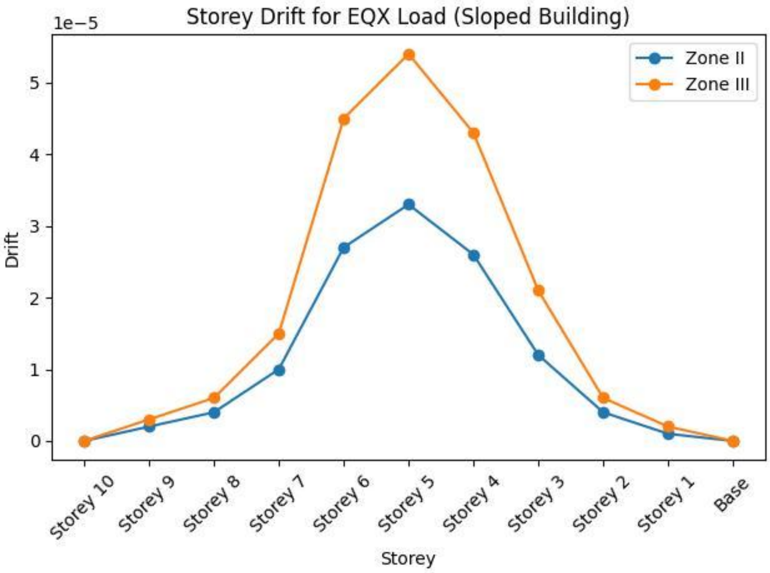
Observation:
1. Displacement is higher in sloped buildings due to irregularity
2. Maximum displacement observed at lower storeys

4.3.2 Storey Drift

Table 4.9: Storey Drift for EQX Load (Sloped Building – Zone II & Zone III)

Storey	Zone II Drift	Zone III Drift
Storey 10	0.000000	0.000000
Storey 9	0.000002	0.000003
Storey 8	0.000004	0.000006
Storey 7	0.000010	0.000015

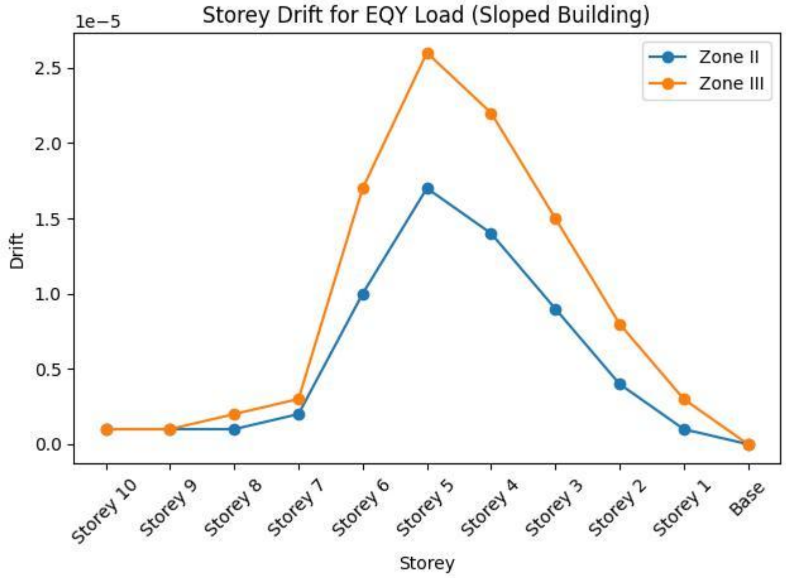
Storey 6	0.000027	0.000045
Storey 5	0.000033	0.000054
Storey 4	0.000026	0.000043
Storey 3	0.000012	0.000021
Storey 2	0.000004	0.000006
Storey 1	0.000001	0.000002
Base	0.000000	0.000000



Graph 4.9: Storey Drift for EQX Load (Sloped Building – Zone II & Zone III)

Table 4.10: Storey Drift for EQY Load (Sloped Building – Zone II & Zone III)

Storey	Zone II Drift	Zone III Drift
Storey 10	0.000001	0.000001
Storey 9	0.000001	0.000001
Storey 8	0.000001	0.000002
Storey 7	0.000002	0.000003
Storey 6	0.000010	0.000017
Storey 5	0.000017	0.000026
Storey 4	0.000014	0.000022
Storey 3	0.000009	0.000015
Storey 2	0.000004	0.000008
Storey 1	0.000001	0.000003
Base	0.000000	0.000000



Graph 4.10: Storey Drift for EQY Load (Sloped Building – Zone II & Zone III)

CONCLUSION

Based on the detailed seismic analysis carried out using ETABS for normal and sloped buildings with different bracing systems, the following conclusions are drawn:

1. Seismic response of structures depends on stiffness, geometry, and load-resisting system.
2. Buildings on sloped ground show irregular and complex behavior compared to normal buildings.
3. Seismic Zone III produces higher displacement, drift, and shear than Zone II.
4. Maximum displacement occurs at the top storey, while maximum shear occurs at the base.
5. Storey drift values are within permissible limits as per IS 1893.
6. Sloped buildings experience higher deformation due to uneven column heights.
7. Short column effect in sloped buildings leads to stress concentration.
8. Bracing systems significantly improve seismic performance and structural stability.
9. Diagonal bracing reduces displacement and provides better load transfer.
10. X-bracing gives maximum stiffness and best seismic performance among all systems.
11. V-bracing provides moderate stiffness with better architectural flexibility.
12. Braced structures show less displacement and drift compared to unbraced structures.
13. Proper selection of bracing system enhances safety, serviceability, and durability.
14. Sloped buildings require special design considerations in seismic zones.

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