Seismic Behavior of Outrigger Structural System on Hill Slope Buildings with Variations in Slope

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***Abstract*—High-rise buildings constructed on hill slopes are highly vulnerable to seismic forces due to structural irregularities such as short-column effects, stiffness variation, and torsional response. This study evaluates the seismic performance of a G+20 reinforced concrete building located on a 10° hill slope in Guwahati (Seismic Zone V) by comparing a conventional shear wall system with a dual outrigger–shear wall system. Three-dimensional models were developed in ETABS and analyzed using Equivalent Static Analysis, Response Spectrum Analysis, and Nonlinear Time History Analysis in accordance with IS 1893:2016 and other relevant Indian Standards. Structural performance was assessed using storey displacement, inter-storey drift, storey shear, and dynamic response parameters. A supplementary parametric study for 15°, 20°, and 25° hill slopes was also carried out to evaluate the influence of terrain inclination. The results indicate that the dual outrigger–shear wall system significantly improves lateral stiffness, reduces displacement and drift, and enhances the overall seismic performance of high-rise buildings on sloping terrain. The study provides practical guidance for the seismic design of tall reinforced concrete buildings in hilly regions.**

I. INTRODUCTION

1.1 General

Rapid urbanization, population growth, and limited availability of land have accelerated the construction of high-rise buildings across India. In hilly regions, the scarcity of level terrain has further encouraged vertical development on sloping ground. Although such construction optimizes land utilization, it introduces significant structural challenges due to irregular geometry, varying foundation levels, unequal column heights, and non-uniform stiffness distribution. These irregularities make buildings on sloping terrain more susceptible to seismic damage than similar structures constructed on level ground. Therefore, the selection of an efficient lateral load-resisting system is essential to ensure structural safety, stability, and serviceability under earthquake loading.

1.2 Structural behaviour of high-rise buildings on sloping terrain

The seismic response of high-rise buildings on sloping terrain is governed by irregular mass and stiffness distribution, short-column effects, torsional behaviour, and increased overturning moments. Conventional reinforced concrete moment-resisting frames and shear wall systems effectively resist lateral loads in medium-rise buildings but may become less efficient as building height increases. Outriggers and belt truss systems improve structural performance by connecting the central core to the perimeter columns, thereby increasing lateral stiffness and reducing storey displacement, inter-storey drift, and overturning effects. The combined action of shear walls and outriggers enhances the overall seismic resistance of tall buildings and provides a more efficient structural system for earthquake-prone regions.

1.3 Present investigation

The present study investigates the seismic performance of a G+20 reinforced concrete building constructed on a 10° hill slope in Guwahati, Assam (Seismic Zone V). Two structural configurations a conventional shear wall system and a dual outrigger–shear wall system were modelled using ETABS. The structural behaviour was evaluated using Equivalent Static Analysis, Response Spectrum Analysis, and Nonlinear Time History Analysis in accordance with

IS 1893 (Part 1):2016, IS 456:2000, IS 875 (Part 3):2015, IS 800:2007, and IS 16700:2023. The performance of both systems was compared based on storey displacement, inter-storey drift, storey shear, base reactions, and dynamic characteristics. In addition, a supplementary parametric study considering hill slopes of 15°, 20°, and 25° was conducted to examine the influence of terrain inclination on the seismic response of high-rise buildings.

II. LITERATURE REVIEW

Herath et al. (2017) investigated the performance of outrigger and belt truss systems in tall buildings subjected to lateral loads. Their study showed that the outrigger system significantly reduced lateral displacement and improved the overall structural stiffness and stability.

Wu and Li et al. (2017) examined the behaviour of outrigger-to-core connections in reinforced concrete buildings. The study recommended proper reinforcement detailing to ensure efficient force transfer and improve the seismic performance of tall structures.

Zhang et al. (2019) evaluated the reliability of outrigger systems under multi-hazard loading conditions. Their findings indicated that outriggers effectively reduced drift demand and enhanced the serviceability and safety performance of high-rise buildings.

Khan et al. (2020) compared single, dual, and multiple outrigger configurations for seismic loading. The study concluded that the dual outrigger system provided the optimum balance between structural efficiency and material utilization.

Matin et al. (2020) investigated the influence of belt truss depth on the behaviour of outrigger structures. The results demonstrated that deeper belt trusses improved lateral stiffness and enhanced force distribution to the exterior columns.

Al-Nimry and Resheidat et al. (2020) studied the seismic behaviour of dual outrigger systems under bidirectional earthquake loading. They reported considerable reductions in storey displacement, inter-storey drift, and overturning moments compared with conventional systems.

III. NEED OF THE STUDY

1. High-rise buildings on sloping terrain are more vulnerable to seismic effects due to stiffness irregularities and short-column effects.
2. Limited research is available on dual outrigger–shear wall systems for buildings on hill slopes.
3. This study evaluates an efficient lateral load-resisting system for earthquake-prone regions.

IV. OBJECTIVE OF THE STUDY

1. To model and analyse a G+20 RC building using ETABS.
2. To compare the seismic performance of conventional shear wall and dual outrigger–shear wall systems.
3. To evaluate structural responses such as storey displacement, drift, and storey shear.
4. To study the effect of different hill slope angles on seismic behaviour.

V. SCOPE OF THE STUDY

1. The study considers a G+20 RC building located on sloping terrain in Seismic Zone V.
2. Seismic analyses are performed using Equivalent Static, Response Spectrum, and Nonlinear Time History methods.
3. Structural performance is evaluated based on displacement, drift, and storey shear.
4. The study also investigates the influence of different hill slope angles on building response.

VI. METHODOLOGY

The present study investigates the seismic performance of a G+20 reinforced concrete building constructed on a 10° hill slope in Guwahati, Assam (Seismic Zone V). Two three-dimensional structural models were developed in ETABS: Model A, consisting of a conventional reinforced concrete moment-resisting frame with shear walls, and Model B, incorporating a dual outrigger–shear wall system. The building has plan dimensions of 18 m × 18 m, a total height of 64.3 m, and was modelled with M40 concrete for columns and shear walls, M30 concrete for beams and slabs, and Fe500 reinforcement.

The structural models were developed in accordance with IS 456:2000, IS 1893 (Part 1):2016, IS 875 (Part 3):2015, IS 800:2007, and IS 16700:2023. Gravity loads, superimposed dead loads, live loads, and seismic loads were assigned as per the relevant Indian Standards. Fixed-base support conditions and medium soil (Type II) were considered throughout the analysis. In Model B, dual outriggers were provided at approximately 0.5H and 0.7H of the building height to improve lateral stiffness and reduce seismic response.

Two structural models were considered for the seismic performance evaluation of a G+20 (21-storey) reinforced concrete building constructed on hill slopes. Model A consisted of a reinforced concrete moment-resisting frame with a conventional shear wall, while Model B incorporated a reinforced concrete dual outrigger–shear wall system. Both models had identical geometric properties, including a total height of 64.3 m, plan dimensions of 18 m × 18 m, a 3.5 m ground storey height, and 3.2 m typical storey height. The structural members were designed using M40 concrete for columns (and shear walls in Model B), M30 concrete for beams and slabs, and Fe500 HYSD reinforcement. A 150 mm thick slab was adopted in both models. The applied loading consisted of a live load of 3.75 kN/m² and a superimposed dead load of 13.75 kN/m², with a fixed-base support condition. Seismic analysis was performed for Seismic Zone V using a zone factor (Z) of 0.36, an importance factor (I) of 1.2, a response reduction factor (R) of 5.0, medium soil (Type II), and a 5% damping ratio. A basic wind speed of 47 m/s was considered, and the building was analysed for hill slope angles of 10°, 15°, 20°, and 25°. Model A employed a conventional shear wall system, whereas Model B utilized a 300 mm thick shear wall integrated with RC outriggers located at 0.5H and 0.7H of the building height. The fundamental time period was 1.395 s for Model A and 1.279 s for Model B, indicating greater lateral stiffness in the dual outrigger system. Both models were evaluated using the Equivalent Static Analysis (ESA), Response Spectrum Analysis (RSA) with Complete Quadratic Combination (CQC), and Nonlinear Time History Analysis (NLTHA) methods.

The seismic behaviour of both models was evaluated using Equivalent Static Analysis (ESA), Response Spectrum Analysis (RSA) employing the Complete Quadratic Combination (CQC) method, and Nonlinear Time History Analysis (NLTHA) using five spectrum-compatible ground motion records. The structural responses were assessed in terms of storey displacement, inter-storey drift, storey shear, base reactions, and dynamic characteristics.To examine the influence of terrain inclination, a supplementary parametric study was conducted for 15°, 20°, and 25° hill slopes using a reduced-order multi-degree-of-freedom (MDOF) model. The analytical results obtained from both structural systems were compared to evaluate the effectiveness of the dual outrigger–shear wall system in enhancing the seismic performance of high-rise buildings constructed on sloping terrain.

Table 1. Structural Member Dimensions for Model A

Structural Member	Storey Range	Size (mm × mm)	Concrete Grade
Column	(Storeys 1–2)	900 × 900	M40
	Storeys 3–8	750 × 750	M40
	Storeys 9–16	600 × 600	M40
	Storeys 17–20	530 × 530	M40
Beam	Storeys 1–15	380 × 530	M30
	Storeys 16–20	300 × 450	M30

Table 2. Meterial properties

Material	Member Type	Grade	Application
Concrete	Columns	M40	Stories 1–20
Concrete	Beams and Slabs	M30	All Storeys
Steel Reinforcement	All Members	Fe500 HYSD	Longitudinal and Transverse

6.1 Hill slope configuration:

A G+20 reinforced concrete building was modelled on a 10° hill slope in ETABS. The variation in foundation levels produces different column heights, causing stiffness irregularity and the short-column effect. The effective column height was determined using:

$$V_B = A_h \times W$$

where Ah is the design horizontal seismic coefficient and W is the seismic weight of the building. The design horizontal seismic coefficient is given by:

$$A_h = (Z/2) \times (I/R) \times (Sa/g)$$

Model B consists of a G+20 reinforced concrete building with 300 mm thick shear walls and dual RC outriggers (450 × 450 mm) located at 0.5H (Storeys 7–8) and 0.7H (Storeys 16–17). The building has plan dimensions of 18 m × 18 m, a total height of 64.3 m, and is located on a 10° hill slope with fixed-base supports. The model was developed in ETABS following IS 456:2000, IS 1893 (Part 1):2016, and IS 16700:2023.

Table-3. Storey height summary

Story	Elevation (m)	Story Height (m)
Base	0.0	—
Storey 1	3.5	3.5
Storey2 -20	6.7 – 64.3	3.2 (typical)
Storey 20 (Top)	64.3	3.2

6.2 Shear wall system

Model B incorporates 300 mm thick reinforced concrete shear walls extending continuously from the foundation to the roof. The shear walls were modelled as shell elements in ETABS and positioned along the building core to provide lateral stiffness and strength against seismic loads. Their primary function is to reduce storey displacement, inter-storey drift, and torsional effects, while increasing the overall stability of the structure. The shear wall system also contributes to carrying axial loads and improving the seismic performance of the building.

6.3 Dual outrigger system

To further enhance lateral resistance, a dual outrigger system was provided in Model B. Reinforced concrete outriggers of 450 × 450 mm were placed at Storeys 7–8 (0.5H) and Storeys 16–17 (0.7H) in accordance with IS 16700 recommendations. The outriggers connect the central shear wall core to the perimeter columns, enabling the transfer of overturning moments and mobilizing the stiffness of the exterior columns. This arrangement reduces lateral displacement, inter-storey drift, and base overturning effects, resulting in improved seismic performance compared with the conventional shear wall system.

Lower outrigger zone: 0.5 × 64.3 =Story 7–8 (elevation 22.7 m – 25.9 m)

Upper outrigger zone: 0.7 × 64.3 = Story 16–17 (elevation 51.5 m – 54.7 m)

6.4 3D Rendering view

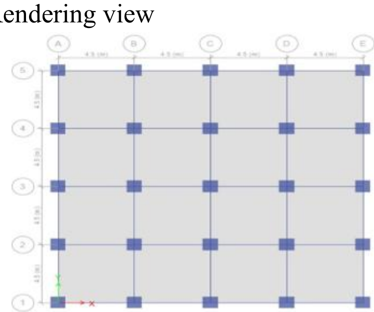


Figure 1: Floor Plan of

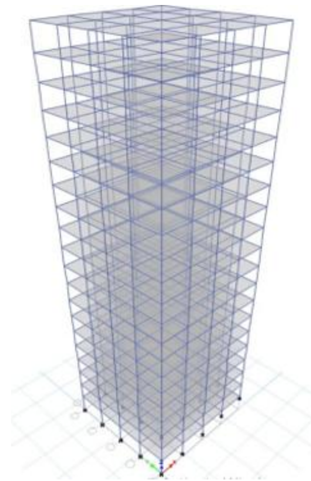


Figure 2: Column C/S at Various Storey Levels (G+2, Story 3–8, Story 9–16, Story 17–20)

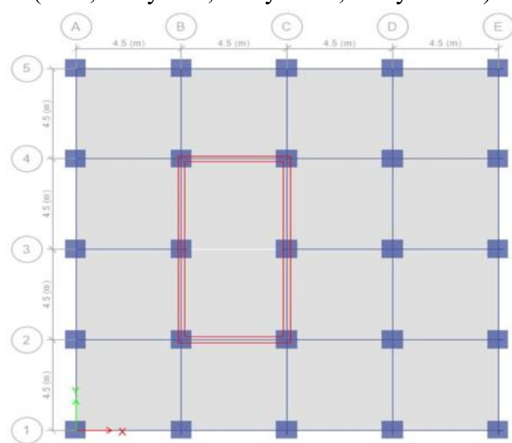


Figure .4: Typical floor plan showing layout of shear walls (300 mm thickness throughout building height)

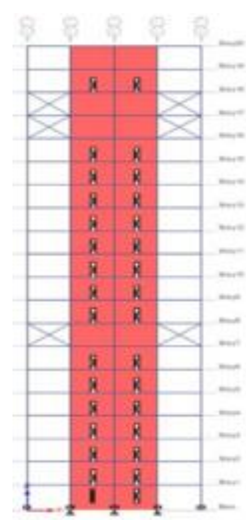


Fig 5: Floor plan of G+20

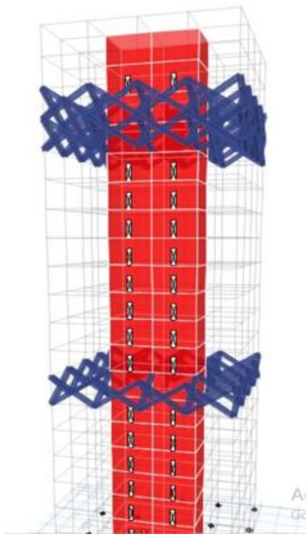


Fig 6:3d view showing outrigger elements at Story 7–8 and Story 16–17 with shear walls


Fig 7: 3d view of the building model on a 10-degree hill slope with outrigger system

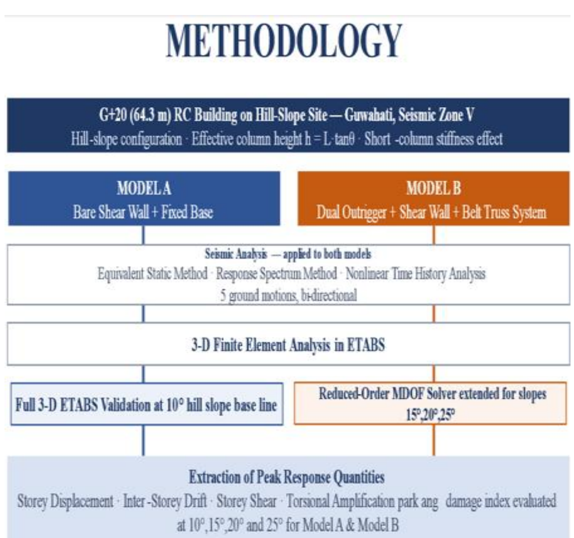
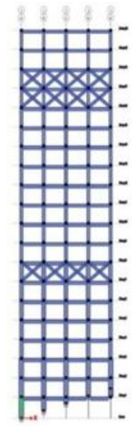
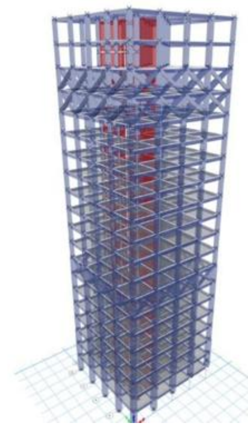
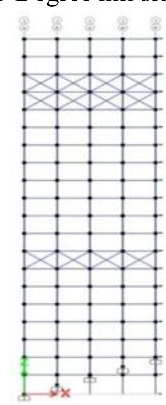


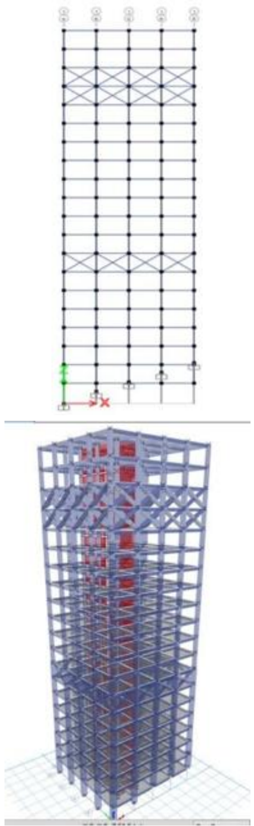
Fig 8: Flow chat of ETABS Analysis




15 Degree hill slope




20 Degree Hill slope



25 Degree Hill slope

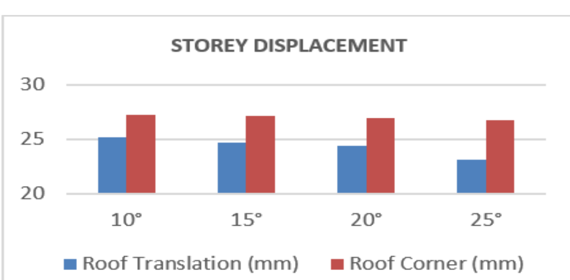
VII. RESULTS AND DISCUSSION

7.1 Model a (bare shear wall)

7.1.1 Storey displacement

Roof displacement slightly decreased with increasing hill-slope angle from 10° to 25°. Roof translation reduced from 25.19 mm to 23.07 mm, while corner displacement reduced from 27.21 mm to 26.72 mm. All values were within the allowable limit.

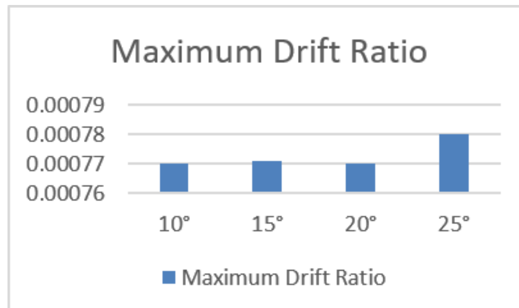
Slope Angle	Roof Translation (mm)	Roof Corner (mm)
10°	25.19	27.21
15°	24.69	27.10
20°	24.41	26.96
25°	23.07	26.72



7.1.2 Inter-storey drift ratio

The maximum drift occurred at Storey 9 for all slope angles. Drift values ranged from 0.000770 to 0.000780, which were well below the permissible limit of 0.004.

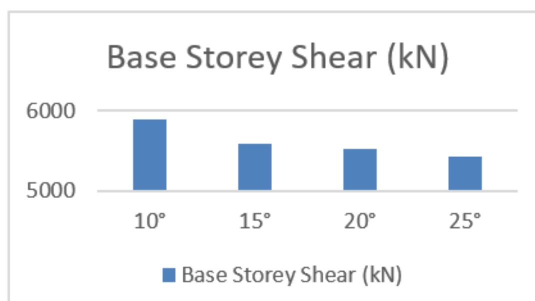
Slope Angle	Maximum Drift Ratio
10°	0.000770
15°	0.000771
20°	0.000770
25°	0.000780



7.1.3 Storey shear

Base storey shear reduced from 5893.4 kN to 5421.9 kN as the slope angle increased from 10° to 25°, indicating a slight reduction in seismic demand.

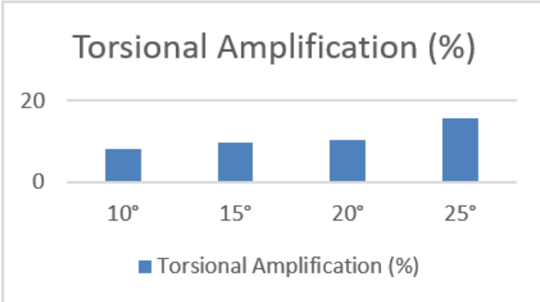
Slope Angle	Base Storey Shear (kN)
10°	5893.4
15°	5589.8
20°	5528.8
25°	5421.9



7.1.4 Torsional amplification

Torsional amplification increased from 8.0% to 15.8% with increasing slope angle, showing higher torsional effects due to slope-induced irregularity.

Slope Angle	Torsional Amplification (%)
10°	8.0
15°	9.8
20°	10.4
25°	15.8

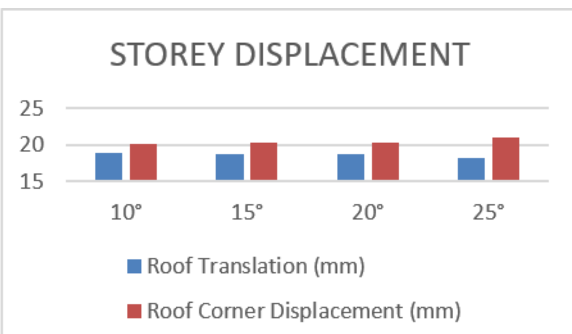


7.2 Model b: dual outrigger + shear wall

7.2.1 Storey displacement

The roof displacement of Model B decreased with increasing hill-slope angle from 10° to 25°. The roof translational displacement reduced from 18.96 mm to 18.18 mm, while corner displacement increased slightly from 20.11 mm to 20.97 mm due to higher torsional effects. All displacement values remained within the allowable limit of 128.6 mm (H/500).

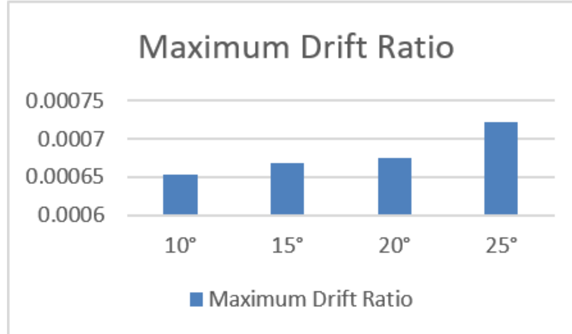
Hill-Slope Angle	Roof Translation (mm)	Roof Corner Displacement (mm)
10°	18.96	20.11
15°	18.81	20.35
20°	18.70	20.40
25°	18.18	20.97



7.2.2 Inter-storey drift ratio

The maximum drift occurred at Storey 9 for all slope angles. Drift values increased slightly from 0.000653 at 10° to 0.000722 at 25°, but remained well below the permissible limit of 0.004 as per IS 1893:2016.

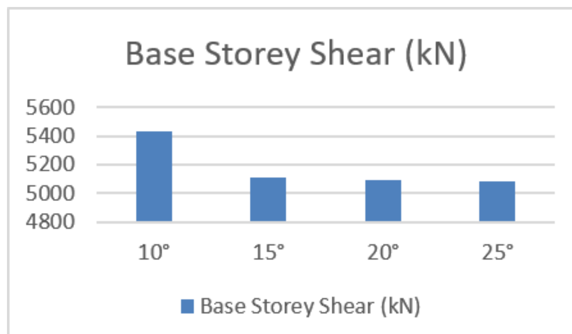
Hill-Slope Angle	Maximum Drift Ratio
10°	0.000653
15°	0.000668
20°	0.000675
25°	0.000722



7.2.3 Storey shear

The base storey shear reduced with increasing slope angle, from 5430.5 kN at 10° to 5084.1 kN at 25°. The results indicate a gradual reduction in seismic force demand with steeper slopes.

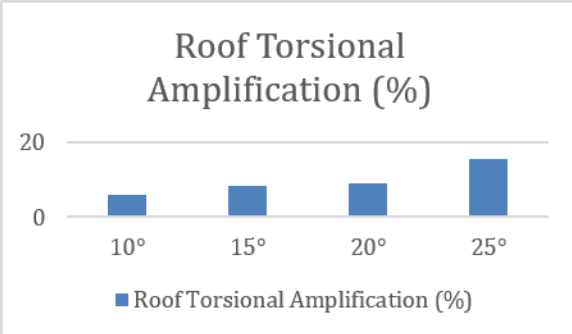
Hill-Slope Angle	Base Storey Shear (kN)
10°	5430.5
15°	5105.8
20°	5093.3
25°	5084.1



7.2.4 Torsional amplification

Roof torsional amplification increased from 6.1% at 10° to 15.4% at 25°, indicating increased torsional response due to slope-induced stiffness irregularity. The structure remained within acceptable performance limits for all slope conditions.

Hill-Slope Angle	Roof Torsional Amplification (%)
10°	6.1
15°	8.2
20°	9.1
25°	15.4

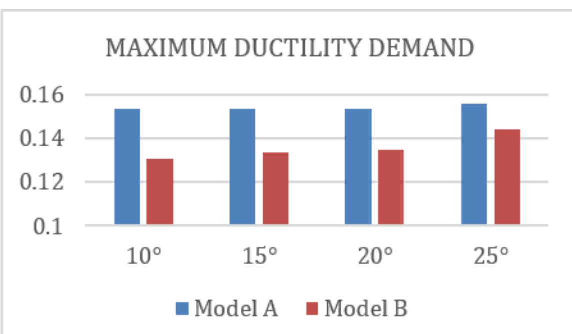


7.3 Damage and response summary – model a (bare shear wall) & model b (dual outrigger + shear wall)

7.3.1 Maximum ductility demand

The maximum ductility demand for all hill-slope angles (10°, 15°, 20°, and 25°) remains below unity, indicating that both Model A and Model B structures remain within the elastic range. Model A shows a maximum ductility demand of 0.156 at 25° slope, while Model B records a lower value of 0.1445, confirming better seismic performance due to the dual outrigger system. The critical storey for maximum ductility demand is observed at Storey 9 for all slope angles.

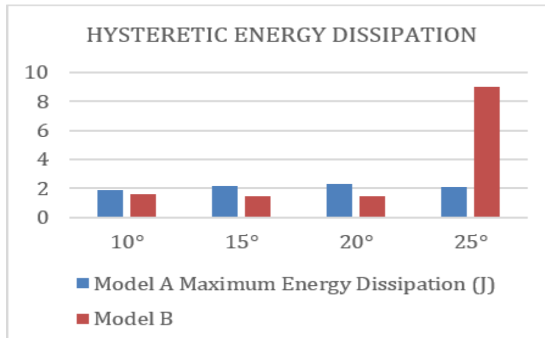
Hill-Slope Angle	Model A	Model B	Critical Storey
10°	0.1536	0.1305	Storey 9
15°	0.1538	0.1337	Storey 9
20°	0.1535	0.1350	Storey 9
25°	0.1560	0.1445	Storey 9



7.3.2 Hysteretic energy dissipation

The hysteretic energy dissipation remains very low for all slope conditions, indicating limited inelastic response and negligible strength degradation. Model A shows slightly higher energy dissipation compared to Model B, while the maximum energy concentration occurs mainly around Storey 9–10. The low energy demand confirms that both structural systems experience predominantly elastic behaviour under seismic loading.

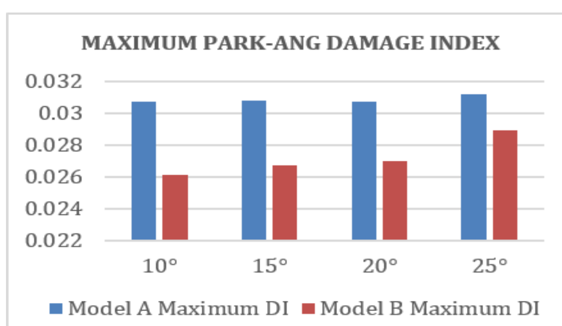
Hill-Slope Angle	Model A Maximum Energy Dissipation (J)	Critical Storey	Model B	Critical Storey
10°	1.86	Storey 11	1.58	Storey 9
15°	2.15	Storey 9	1.50	Storey 9
20°	2.30	Storey 10	1.45	Storey 11
25°	2.08	Storey 10	9.00	Storey 5



7.3.3 Maximum park-ang damage index

The maximum Park-Ang damage index remains within the permissible damage limit (DI < 0.10) for all hill-slope angles. Model A records a maximum DI of 0.0312 at 25° slope, whereas Model B shows a lower maximum DI of 0.0289, demonstrating improved damage resistance of the dual outrigger system. The highest damage index occurs at Storey 9 for both models.

Hill-Slope Angle	Model A Maximum DI	Model B Maximum DI
10°	0.0307	0.0261
15°	0.0308	0.0267
20°	0.0307	0.0270
25°	0.0312	0.0289



7.3.4 Damage state

All storeys of both Model A and Model B remain within the Permissible Limit damage state for slope angles ranging from 10° to 25°. No minor, moderate, severe, or collapse damage levels are observed, confirming adequate structural safety and seismic resilience under the considered ground motions.

7.3.5 critical storey

Storey 9 is identified as the critical storey for both models and all slope angles, as it consistently experiences the maximum ductility demand and Park-Ang damage index. This indicates that the middle-height region of the building governs the seismic response due to the combined effect of lateral deformation and stiffness variation along the height.

Hill-Slope Angle	Model A Critical Storey	Model B Critical Storey
10°	Storey 9	Storey 9
15°	Storey 9	Storey 9
20°	Storey 9	Storey 9
25°	Storey 9	Storey 9

7.3.6 Percentage reduction in peak response -- model b relative to model a

The Dual Outrigger + Shear Wall system (Model B) shows better performance than Model A, achieving reductions of 21.5–26.1% in displacement, 7.4–15.2% in drift, 6.2–8.7% in base shear, 2.5–23.8% in torsional amplification, 7.4–15.0% in damage index, and 7.4–15.0% in ductility demand. This confirms the effectiveness of the outrigger system in reducing seismic response under different hill-slope conditions.

Slope (deg)	Roof Corner Disp. reduction (%)	Max Drift reduction (%)	Base Shear (%)	Torsional Amp. reduction (%)	DI %	Max Ductility (%)
10	26.1	15.2	7.9	23.8	15.	15.0
15	24.9	13.4	8.7	16.3	13.	13.1
20	24.3	12.3	7.9	12.5	12.	12.1
25	21.5	7.4	6.2	2.5	7.4	7.4

VIII. CONCLUSIONS

1. The 3D ETABS models of the G+20 RC building on hill slopes were successfully developed and validated. The dual outrigger system improved structural stiffness, reducing the fundamental period from 1.395 s (Model A) to 1.279 s (Model B).
2. Equivalent Static, Response Spectrum, and Time-History analyses confirmed that both models satisfy IS 1893:2016 requirements, with maximum drift (0.000770) and roof displacement (27.21 mm) remaining within permissible limits.
3. The dual outrigger system significantly improved seismic performance by reducing roof displacement from 27.21 mm to 20.11 mm, demonstrating better control of lateral deformation.
4. The outrigger system effectively reduced hill-slope-induced irregularities such as stiffness eccentricity and torsional response, decreasing torsional amplification from 8.0% to 6.1%.
5. The parametric study for 10°, 15°, 20°, and 25° slopes showed stable structural behaviour. The maximum Park–Ang damage indices (0.0312 for Model A and 0.0289 for Model B) remained below the permissible limit (DI < 0.10), confirming safe seismic performance.

IX. LIMITATIONS OF THIS STUDY

1. The study is limited to seismic evaluation of a G+20 RC building using ETABS and does not include detailed wind-tunnel or CFD investigations.
2. Soil–structure interaction, foundation behaviour, and staged construction effects are not considered.
3. The study focuses on global structural response; detailed RC and steel connection design is beyond the scope.
4. Only selected hill-slope angles are investigated, without economic analysis or structural optimization.

X. FUTURE SCOPE

1. Wind tunnel testing and CFD simulations can be incorporated to study topographic wind effects on hillside high-rise buildings.
2. Soil–structure interaction and detailed stepped foundation/pile foundation modelling can be included for more realistic response prediction.

3. Future studies can consider staged construction analysis, long-term effects, and life-cycle cost evaluation of outrigger systems.

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