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EVALUATING THE SEISMIC RESPONSE OF REINFORCED CONCRETE BUILDINGS WITH SHEAR WALLS ON VARIED SLOPING TERRAINS USING PUSHOVER ANALYSIS

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SUMMARY

This study investigates the seismic performance of a four-story reinforced concrete frame building with irregularities, situated on sloping ground. Recognizing the increasing prevalence of construction on slopes due to population growth and urban expansion, this research employs a step-back model on the sloping terrain at inclinations of 0°, 10°, and 20°. A three-dimensional model of the rectangular building was developed and analysed using SAP2000 software, implementing pushover analysis as per ATC-40 guidelines. The analysis focuses on the impact of sloping ground on structural forces, specifically examining horizontal reactions and bending moments in columns. Preliminary findings indicate that shorter columns experience higher forces due to increased stiffness, resulting in elevated shear and bending moments. Consequently, these columns require design modifications to accommodate the amplified forces. Furthermore, the study examines key dynamic characteristics, including hinge formation, base shear, target displacement, and maximum column moments, comparing results between level and sloping ground conditions.

Key words: *pushover analysis, sloping ground, shear wall, step-back building, performance point, sap2000.*

INTRODUCTION

Earthquakes can lead to the destruction or collapse of various structures, both natural and man-made. Establishing earthquake-resistant structures is essential to safeguard against seismic activity for new and existing buildings. The implementation of relevant regulations is crucial in protecting these structures from earthquake-induced damage. The seismic response of a structure is complex, influenced by factors such as ground motion, material behaviour, foundation type, and soil topology. Identifying the vulnerability of a structure to damage during and after an earthquake is necessary to meet safety criteria. Some previously applied techniques for earthquake resistance have proven effective, and the development of new earthquake-resistant techniques holds significant potential for the future. Seismic analysis methods are presented in the table 1 below.

Table 1. Methods of Seismic Analysis

Structure loading	**Linear** **E, A, G etc. are constant, K is constant**	**Nonlinear** **E=constant, EI and K not constant**
Static	Equivalent static Analysis	Pushover Analysis
Dynamic	Response Spectrum Analysis (or Mode Spectral Analysis) Modal Response History (Time History) Analysis Linear Response History (Time History) Analysis	Nonlinear Modal Response History (Time History) Analysis Nonlinear Response History (Time History) Analysis (Direct Integration non-linear RHA)

Buildings must be designed with sufficient strength, high ductility, and integrity to withstand severe ground motions during earthquakes. Societal factors, such as population density, earthquake timing, and community preparedness, also play crucial roles. Previously, strategic risk-taking and loss-minimization efforts were based on observational knowledge of various building types' earthquake performance.

During seismic events, the strengths, weaknesses, desirable material attributes, and construction techniques, as well as site selection, can be readily identified [18]. The proposed research investigates the behaviour and design of structures on sloping terrain. Engineered construction in sloping areas is constrained by topography, leading to the use of set-back, step-back, or step-back setback structural forms. The earthquake response of buildings is influenced by the distribution of mass and stiffness in both the horizontal and vertical planes, which differ in structures on sloping ground (Federal Emergency Management Agency, 1997). Consequently, a performance-based design philosophy is necessary, which can be partially addressed through pushover analysis.

Shear walls are commonly employed in tall building construction, both residential and commercial, as the current trend is toward taller structures [3][15]. This may help reduce the consequences of lateral stresses from wind, earthquake, and blast loads. Shear walls are vertical elements that generally extend from the foundation to the full building height [6]. The Indian Standard Ductile Detailing Code for RC members provides special design guidelines for the ductile detailing of shear walls [24]. Designers often face the challenge of providing sufficient strength and stability to withstand lateral stresses. Shear walls provide lateral support for high-rise buildings, helping to minimize lateral sway. Due to their orientation, shear walls can offer extra strength and rigidity along their path. Reinforced Concrete Shear Walls are commonly incorporated into building structures [9]. Shear walls can effectively control inter-story drift and achieve satisfactory energy dissipation capacity. Shear walls are generally stronger when they have no openings. [1][2]

Researchers have conducted comprehensive seismic analyses of reinforced concrete (RC) building structures using pushover analysis techniques. Sharad Sharma's research involved static pushover and response spectrum analyses on five buildings, including three step-back and two step-back-setback configurations with varied support conditions. The study employed equivalent springs to analyze different soil conditions, comparing response characteristics for fixed base and soil spring scenarios [20]. H. Chaulagain et al. studied the seismic response of four 3-story RC residential buildings under non-linear static pushover analysis with different load paths. They compared the results of adaptive pushover and non-linear dynamic time history analyses, finding a correlation between the static and dynamic methods [4]. Akshay V. Raut evaluated the behaviour of a G+3 RC frame structure in Zone II using the nonlinear static procedure in SAP2000 [5]. The capacity spectrum analysis revealed the building's performance levels, and the hinge formation indicated the failure mechanism of the components. Mohammad Azaz conducted a pushover analysis on a G+10 RC building in the x and y directions using SAP2000, assessing the structural performance for seismic activities. The progressive formation of plastic hinges in the beams and columns was observed from the pushover curve [21]. Hareen and Mohan studied the inelastic torsional response of asymmetric ductile RC buildings with a soft first story, using pushover methods and bi-directional non-linear time history analysis. [7].

Shaik Akhil Ahamad and K.V. Pratap investigated the structural behaviour by varying the building's stiffness along the height across different seismic zones in India. They performed dynamic analysis to optimize the placement of shear walls and compared the seismic response with and without shear walls, finding that the building with shear walls at the four ends exhibited superior performance [8] [12]. Qudsia Bhavikatti explored the seismic analysis of a building on sloping ground with inclination angles of 16, 20, and 24 degrees, considering soil-structure interaction and infill [22]. Tejaswani ML and Sheetal Naik conducted a comparative study of seismic analysis methods for a G+15 high-rise building in seismic zones II and III [10]. A.C. Suryawanshi and V.M. Bogar carried out a seismic analysis of a G+19 story RCC framed building on sloping ground, considering soil-structure interaction [11]. Kumar Sanjay and D. Rachcha studied the effect of soil-structure interaction on the seismic performance of a step-back building resting on sloping ground with inclinations ranging from 10 to 40 degrees, using ETABS software. Response spectrum analysis was conducted to investigate the impact of soil-structure interaction on the seismic performance of the RCC framed building with a step-back system for different slope angles. The buildings were also analysed for the inclusion [23].

Various research using pushover analysis to address performance-based structure design have been described in the literature. Despite the fact that a few studies have been published in the areas of pushover analysis and performance-based design, research on pushover on slope is sparse. The goal of this study is to perform a pushover analysis on sloping ground with and without shear wall by using the structural analysis tool SAP2000. Reinforced concrete shear wall is design as per IS456:2000 from fixed base to full height of the building [13].

1.1. Significance and Novelty of the Work

This research critically evaluates the seismic performance of buildings on sloping ground through pushover analysis, addressing a significant research gap. While previous studies have explored pushover techniques, investigations into structures on sloping terrain remain limited. By comprehensively assessing building performance—including comparative analyses with and without shear walls—the study aims to identify weak structural elements and device some strategies to overcome the identify vulnerabilities and develop strategies for enhancing seismic resilience. The research provides crucial insights into the structural behavior and response of buildings in topographically challenging environments, offering valuable methodological contributions to earthquake engineering.

1.2. Objective of the Study

- Evaluate structural performance under slope inclinations of 0°, 10°, and 20° using Pushover Analysis
- Compare the structural performance with and without the inclusion of a shear wall.
- Identify the weaker elements of the building and propose modifications to enhance its overall performance.
- Analyse the observed performance to derive secondary objectives for improving the seismic resilience of the building.

METHODOLOGY

Pushover analysis is a nonlinear static method where loads or displacements are gradually increased until the structure reaches a collapse mechanism. This enables evaluating the structure's capacity, demand, and performance characteristics. The capacity spectrum reflects the structure's fundamental modal response, assuming the primary vibration mode dominates behaviour. The demand spectrum is estimated using a spectral reduction approach, lowering the elastic damped design spectrum. The performance point is the intersection of the capacity and demand spectra.

The Capacity Spectrum Method is a seismic analysis technique that compares structural capacity to ground motion demands by expressing both in spectral acceleration and displacement terms. The method assumes the peak nonlinear response equals the modal displacement of an equivalent elastic system with an effective period based on secant stiffness (figure 5 & 6).

As load increases, structural elements yield sequentially, dynamically changing system stiffness. The performance point emerges at the intersection of capacity and demand curves, characterized by three performance levels: Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) in figure 9 & 10. This approach enables engineers to predict structural behavior and potential response during seismic events, facilitating more resilient design strategies that prioritize structural integrity and occupant safety in figure 1.

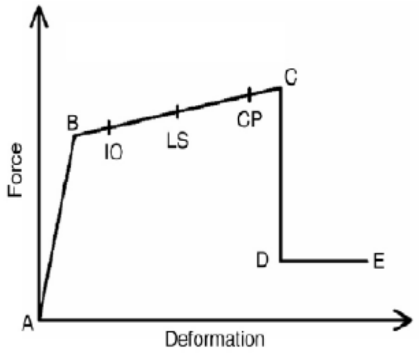


Figure 1. Building Performance Points

MODELLING

A four-story building was modelled on sloping ground using SAP2000. The slope angles considered were 0°, 10°, and 20°. A rectangular building layout with a 5x4 bay configuration was adopted, with each bay measuring 6 meters in both the x and y directions. The shear walls were designed based on the model proposed by Hareen CH.B.V. and Mohan S.C., and the building specifications were also taken from the same reference. Seismic analysis was conducted using the Nonlinear Static Pushover method in SAP2000, in accordance with the ATC40 guidelines [14].

Assumptions Made in the Study

The study made several key assumptions to investigate the seismic behaviour of buildings on sloping ground using pushover analysis. The researchers modelled a four-story reinforced concrete building with a rectangular layout and a 5 × 4 bay configuration, where each bay measured 6 meters in both the x and y directions. The slope angles considered were 0°, 10°, and 20° in figure 2.

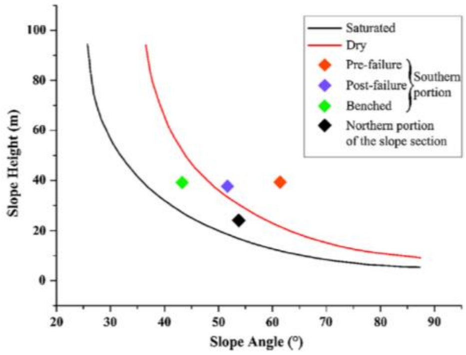


Figure 2. Critical Slope Height Versus Slope Angle Relation for Soil Slope Geometry (after Hoek and Bray 1981) [25][16]

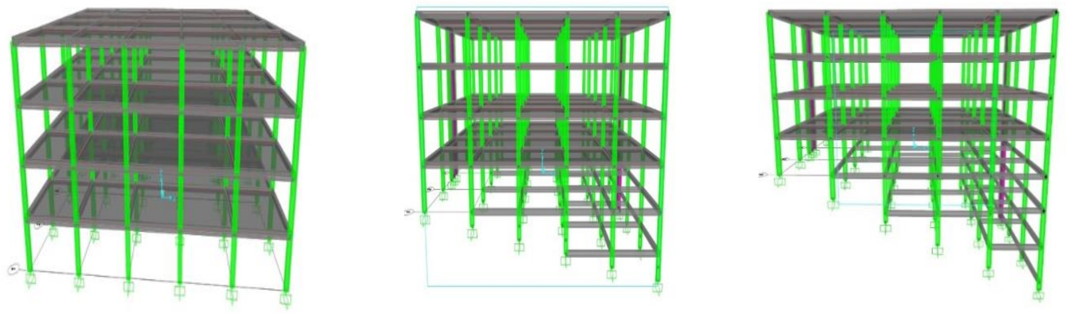
The study utilized step-back building structures to maintain the consistency in the structural configuration of the structure in the flat soil, which are common in hilly regions and on sloping ground.

Step-back structures are characterized by successive reductions in the building footprint at higher floors, creating setbacks. This architectural design is often used to address stability and safety concerns on sloping terrain. And

Nonlinear behavior was expected to occur within the frame elements at the concentrated points or plastic hinges, which were assigned based on the ASCE 41-13 criteria. Standard PMM hinges at both ends of the moment frame columns and standard M3 hinges at both ends of the moment frame beams were assigned as described in ATC-40. These assumptions allowed the researchers to effectively model the nonlinear response of the building under seismic loading on sloping ground in figure 3 [17–19]. Building description are shows in table 2

a) 3D model with Shear wall

b) Plan



c) Building 3D model without Shear wall

d) 10° Slope

e) 20^0 Slope

Figure 3. Building Plan, 3D Model and Sloping

Table 2. Building Description

Size Of Building	30m × 24m
Bays	5 × 4
Bay Size	6m × 6m
Storey Height	3.5m
Slab Thickness	115mm
Wall Thickness	180mm
Beam Size	300mm × 450mm
Column Size	300mm × 450mm
Sloping Ground Angles	0^0, 10°, 20°

RESULT AND DISCUSSION

In SAP 2000, nonlinear behaviour is expected to occur within the frame element at the concentrated points or plastic hinges. Hinges are assigned in accordance with ASCE 41-13, which is typically based on the criteria of FEMA 273/356 or ATC-40. These standard hinge characteristics depend on the cross-section properties. The standard PMM hinges at both ends of the moment frame columns and the standard M3 hinges at both ends of the moment frame beams were assigned, as described in ATC-40.

The Pushover Curve creation includes an assessment of the force distribution along the height of the structure. The static pushover analysis defines two additional load cases: a gravitational load case and a lateral load distribution in the X-direction. The load application is defined as displacement-controlled, and the load case is specified for pushover analysis (Figure 7 & 8).

The current analysis shows that the formation of plastic hinges in the building frame exhibits a similar pattern for different types of foundation media. In the X-orientation, the hinge formation begins with the beams at the ends of the shortest column frames. During the initial hinge formation, the first few hinges are deployed in the shortest rows in the Y-direction. The hinge formation starts with the shortest columns and extends to the longest frames at the end. The shortest rows of hinges have rotations corresponding to the immediate occupancy level and generally attain all types of support state collapse prevention levels. In some cases, the hinges in these columns reach the collapse prevention level after the immediate occupancy level, skipping the life safety zone (Figure 11). The data obtained from the pushover analysis and the sequence of formation and hinge patterns of the step-back buildings are presented.

Performance Points

Table 3. Performance Points Without Shear Wall

Building Type	Values of V (kN)	V % Change	Values of δ_{PP} (mm)	δPP % Change
0^0	3858.15	-	93	-
10^0	3757.43	-2.61%	96	+3.23%
20^0	3453.83	-8.08%	99	+3.13%

Table 4. Performance Points with Shear Wall

Building Type	Values of V (kN)	V % Change	Values of δ_{PP} (mm)	δPP % Change
0^0	5353.57	-	67	-
10^0	5282.84	-1.32%	89	+32.84%
20^0	4891.31	-7.41%	98	+10.11%

As the ground slope increases, notable changes occur in the structure's performance point (Table 3 & 4):

Base Shear Variation

- The base shear exhibits complex modifications depending on the structure's regularity and slope angle.
- The required base shear to reach the performance point decreases with increasing inclination, indicating a reduction in the overall building stiffness.

Structural Displacement

- With changes in the slope angle, structural displacement exhibits the following patterns:
- In regular structures, the overall story displacement tends to decrease.
- Differential movement occurs between the taller and shorter sides of the structure.
- The shorter side of the structure experiences a concentration of stiffness on steeper slopes.

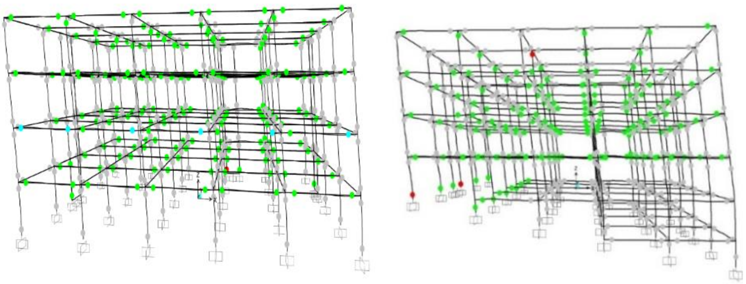
Structural Vulnerability

The performance point reveals critical insights into structural vulnerability:

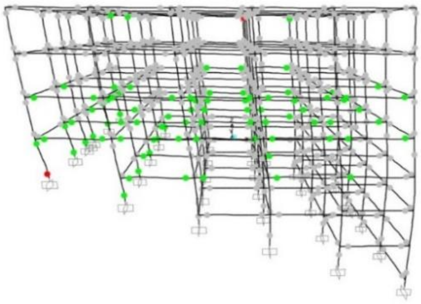
- Regular structures exhibit less vulnerability with incremental slope angles (figure 4).
- Columns on the higher side of the slope experience reduced bending moments.

- The structure's seismic performance becomes more efficient with carefully managed slope variations.

Plastic Hinges and Instability Progress



Plain Ground b) 10^0 slope Building



20^0 Sloping Building

Figure 4. Plastic Hinges Formation

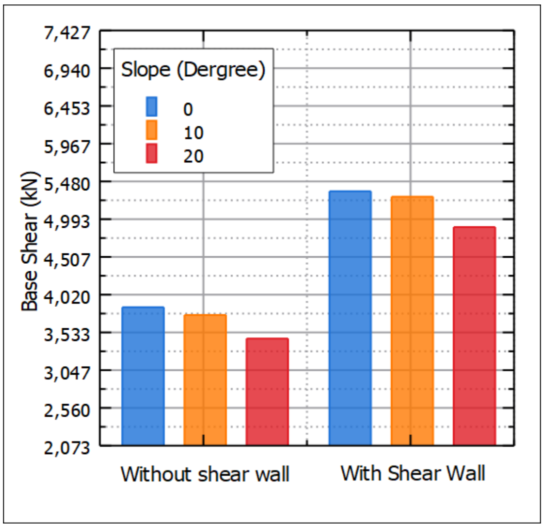


Figure 5. Base Shear with Respect to Slope of the Building as per Capacity Spectrum Method

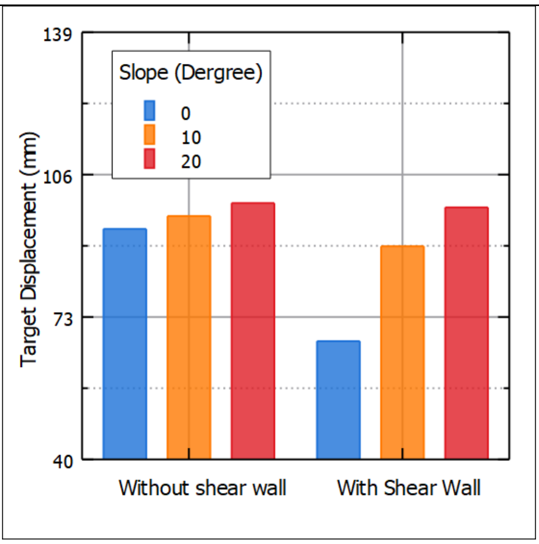


Figure 6. Target Displacement with Respect to Slope of the Building as per Capacity Spectrum Method

Pushover Curve

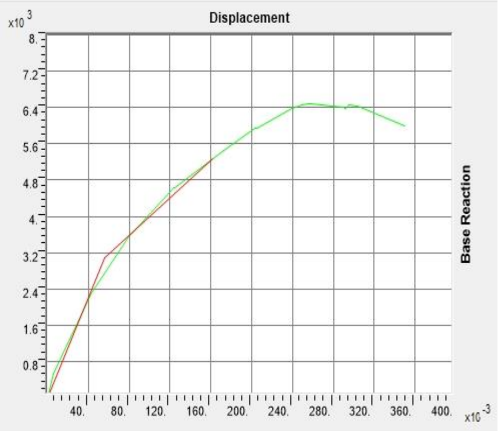


Figure 7: Pushover Curve Without Shear Wall

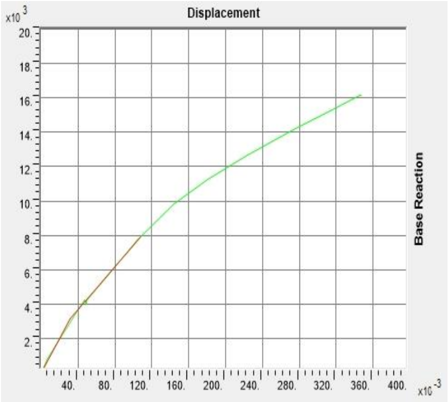


Figure 8: Pushover Curve with Shear Wall

Capacity curve

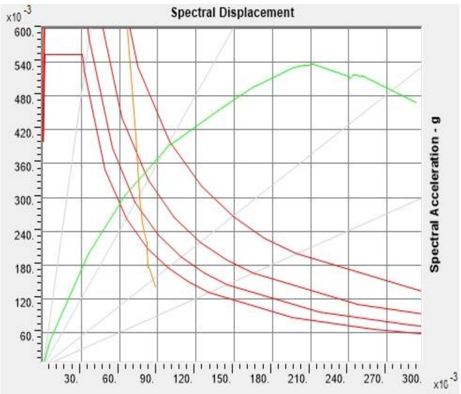


Figure 9: Capacity Curve Without Shear Wall

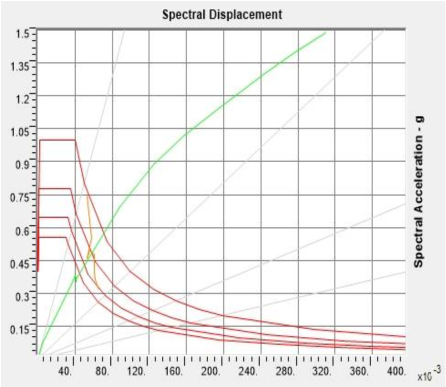


Figure 10: Capacity Curve with Shear Wall

Exterior Column Moment

Table 5. Moments on Exterior Column with Shear wall at Target Displacement

SLOPE	0^0 Slope		10^0 Slope		20^0 Slope	
COLUMN	M2 (kN-m)	M3 (kN-m)	M2 (kN-m)	M3 (kN-m)	M2 (kN-m)	M3 (kN-m)
C1	12.93	28.53	7.51	159.04	7.54	176.32
C2	30.20	37.03	10.65	183.96	7.41	194.27
C3	14.63	24.41	5.92	143.17	2.39	156.22
C4	23.79	34.85	7.84	171.37	4.50	189.66
C5	23.63	25.47	10.45	119.89	6.80	148.77
C6	7.66	45.23	6.86	60.27	13.22	88.84
C7	6.97	44.33	23.66	137.61	15.58	148.83
C8	11.71	44.44	27.22	137.07	17.88	54.49
C9	17.25	45.23	31.85	132.1	20.72	95.74
C10	18.46	44.66	37.23	59.15	22.26	100.98

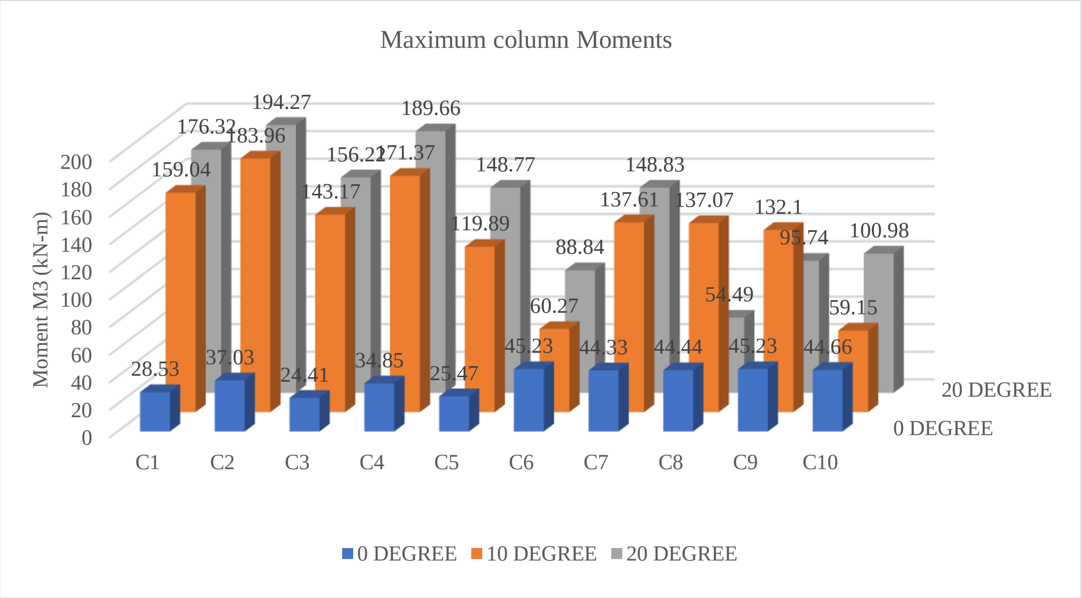


Figure 11. Maximum Column Moments

Real-World Structural Vulnerability

Earthquake-Induced Vulnerabilities

Structures situated on sloping terrain exhibit heightened susceptibility to seismic events due to several key factors:

1. Displacement Dynamics

   - As the slope angle increases, the overall story displacement tends to decrease (Table 5)
   - The top stories experience maximum displacement compared to the bottom stories
   - Differential movement between the taller and shorter sides of the structure creates additional stress points

2. Structural Performance Modifications

   - The modal period decreases with increasing slope angle

- The storey acceleration reduces as the slope angle increases
- Irregular structures demonstrate more critical seismic responses compared to regular structures

Practical Implications

Design Considerations

The research highlights critical design strategies for structures on sloping terrain:

1. Structural Irregularity Management
    - Vertical irregularity poses more significant risks than plain irregularity
    - Careful configuration of building frames becomes crucial
2. Seismic Resilience
    - Structures on sloping ground require more sophisticated seismic design approaches
    - Additional reinforcement may be necessary, especially for irregular structures

Risk Mitigation Strategies

Engineers must consider:

- Specialized design techniques to manage differential ground movement
- Comprehensive analysis of structural response under various slope conditions

CONCLUSION

The following conclusions are drawn from the above results and observations:

1 The base shear of a structure on sloping terrain exhibits an inverse relationship with the ground's slope angle. As the slope angle becomes less steep, the base shear intensity increases correspondingly.

2 Shear walls significantly influence the seismic resilience of reinforced concrete structures, substantially enhancing building performance when strategically incorporated.

3 Structures analyzed without shear walls demonstrate lower base shear resistance and higher target displacement values, indicating reduced structural stability.

4 Implementing shear walls dramatically transforms structural dynamics. These walls increase base shear capacity while simultaneously reducing target displacement. The maximum base shear resistance is most prominently observed at the performance point with shear wall integration.

5 Structural response parameters, particularly story displacement measurements, exhibit an inverse correlation with slope angle, escalating as the ground's inclination decreases.

6 The bending moment experienced by building frames intensifies proportionally with increasing ground slope.

7 Despite columns having limited ductility, strategically designed shear walls can substantially mitigate potential structural damage. This protective mechanism is evidenced by the reduced number of columns experiencing critical damage states.

8 Shear walls provide critical structural support against seismic loads, with their effectiveness directly linked to their hysteretic energy dissipation and overall ductility capabilities.

9 Inadequately reinforced shear walls fail to improve a building's seismic performance, even when meeting basic dimensional requirements. Their effectiveness hinges on precise strength and ductility alignment with established engineering standards.

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