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SEISMIC BEHAVIOUR OF MULTI-STORY BUILDINGS ON SLOPING GROUND: AN EVALUATION OF RESPONSE SPECTRUM AND STATIC ANALYSIS FOR STRUCTURAL OPTIMIZATION

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ABSTRACT

This paper evaluates the seismic behavior of multi-story RCC buildings on sloping terrain, focusing on a comparative analysis between Response Spectrum and Static Analysis methods. Multi-story buildings on sloping ground experience complex seismic forces due to irregular mass and stiffness distributions, leading to higher vulnerability during seismic events. In this study, various building configurations, including unbraced and braced frames at different slope angles (0°, 10°, 20°, and 30°), are analyzed to assess their structural response. Using ETABS software, the dynamic properties such as displacement, drift, and base shear are calculated under both linear static and dynamic loading conditions, following the IS 1893:2016 guidelines. The results reveal that braced structures show improved seismic performance, particularly in terms of displacement and drift reduction, across all slope angles. The Response Spectrum analysis highlights the dynamic behavior of the buildings more accurately than the static method, particularly in higher slope configurations. This research underscores the importance of incorporating bracing systems and optimizing structural designs to enhance the seismic resilience of buildings in hilly regions.

KEYWORDS: Seismic behaviour, Multi-story buildings, Sloping ground, Response spectrum analysis, Static analysis, Structural optimization

1. INTRODUCTION

Seismic activities are among the most devastating natural forces, leading to significant destruction of life and property, particularly in urban areas where densely populated regions are prone to seismic hazards. The design and construction of earthquake-resistant structures have become a critical engineering concern worldwide. The effects of seismic forces on structures are magnified in complex terrains, such as sloping ground, where buildings are exposed to additional challenges related to geometry and stiffness irregularities. This makes multi-story buildings on sloping ground more vulnerable to seismic damage compared to structures built on flat ground. Over the years, significant research has been conducted to understand the seismic behavior of buildings on sloping terrain, with the goal of improving structural designs to withstand lateral forces generated during earthquakes.

1.1 Seismic Vulnerability of Buildings on Sloping Ground

Buildings constructed on sloping terrain face unique challenges due to the irregular distribution of mass and stiffness across their height. Unlike structures on flat ground, where lateral loads are distributed more evenly, buildings on sloping ground have varying column heights, leading to non-uniform stiffness. This irregularity results in differential displacement and a higher likelihood of torsional effects, making the building more susceptible to damage during seismic events. The shorter columns on the uphill side of the structure experience higher stiffness and attract more seismic forces, while the longer columns on the downhill side have lower stiffness and may fail to adequately support the building during an earthquake. The seismic performance of such buildings is further influenced by factors such as the building configuration (step-back, step-back setback, or staggered) and the angle of slope. Studies have shown that buildings with step-back configurations, where the shorter columns are placed uphill, are particularly vulnerable to seismic forces due to the concentration of lateral loads on the stiff columns. This irregular distribution of forces results in increased inter-story drifts and base shear, which can lead to catastrophic failure if not properly addressed during the design phase.

1.2 Earthquake-Resistant Design and Seismic Codes

To mitigate the risks posed by seismic forces, it is essential to design buildings that comply with the latest seismic codes and guidelines. The Indian Standard IS 1893:2016 provides detailed provisions for seismic analysis and design, emphasizing the importance of considering the dynamic properties of structures, especially in seismic zones. This code highlights the need for dynamic analysis methods such as Response Spectrum Analysis and Time History Analysis to accurately assess the seismic demands on buildings with irregular geometries, such as those on sloping terrain. These methods allow engineers to evaluate the structure's response to seismic forces across different modes of vibration, providing a more comprehensive understanding of its behavior during an earthquake. In recent years, there has been a growing interest in optimizing the seismic performance of buildings on sloping ground by incorporating lateral load-resisting systems such as bracing and shear walls. These systems enhance the structural stiffness and reduce the lateral displacements and inter-story drifts experienced during seismic events. Bracing systems, in particular, have been shown to significantly improve the seismic performance of buildings by redistributing seismic forces and reducing the demand on individual columns. As a result, braced frames are becoming increasingly popular in the design of multi-story buildings in hilly regions.

1.3 Analysis Methods for Seismic Performance Evaluation

The seismic performance of a building is typically evaluated using two primary methods: Equivalent Static Analysis (Linear Static Analysis) and Response Spectrum Analysis (Linear Dynamic Analysis). Equivalent Static Analysis is a simplified approach where the building is subjected to a fixed horizontal load, representing the peak seismic force expected during an earthquake. While this method is widely used due to its simplicity, it does not account for the dynamic behavior of the building across multiple modes of vibration. As a result, it may underestimate the seismic demand, particularly in buildings with irregular geometries, such as those on sloping terrain. Response Spectrum Analysis, on the other hand, is a more sophisticated method that considers the building's dynamic response to seismic forces. This method involves calculating the maximum response of the structure for each mode of vibration and combining these responses to obtain a more accurate estimate of the building's seismic demand. Response Spectrum Analysis is particularly useful for evaluating the seismic performance of tall buildings and structures with irregular geometries, as it accounts for the influence of higher modes of vibration, which are often neglected in static analysis. Several studies have demonstrated that Response Spectrum Analysis provides a more accurate assessment of seismic performance than Equivalent Static Analysis, particularly for buildings on sloping ground. Likhitharadhya Y.R. et al. (2016) and Ravindra Navale et al. (2017) conducted comparative studies on buildings subjected to static and dynamic analysis, concluding that Response Spectrum Analysis is better suited for capturing the complex seismic behavior of buildings on sloping terrain. These findings underscore the importance of using dynamic analysis methods in the design of buildings in seismic zones to ensure their safety and structural integrity during earthquakes.

1.4 The Need for Structural Optimization

As urbanization continues to spread into hilly and mountainous regions, the need for optimizing the seismic performance of multi-story buildings on sloping ground becomes increasingly important. Structural optimization involves improving the design of buildings to enhance their seismic resilience while minimizing construction costs and material usage. This can be achieved through various strategies, such as incorporating bracing systems, optimizing the building's geometry, and using advanced analysis methods to accurately predict the structure's response to seismic forces. In this study, we aim to evaluate the seismic behavior of multi-story buildings on sloping ground using both Response Spectrum and Static Analysis methods. By comparing the performance of braced and unbraced buildings at different slope angles, we seek to identify the most effective strategies for optimizing the structural design of buildings in hilly regions. The results of this analysis will provide valuable insights into the dynamic behavior of buildings on sloping ground and offer practical recommendations for improving their seismic performance.

1.5 Scope and Objectives of the Study

This paper focuses on the seismic behavior of multi-story buildings on sloping ground, with the following key objectives:

1. To evaluate the seismic performance of buildings on sloping terrain under both static and dynamic loading conditions.
2. To compare the seismic response of braced and unbraced frames at different slope angles (0°, 10°, 20°, and 30°).
3. To analyze the impact of slope inclination on key seismic parameters, including displacement, drift, and base shear.
4. To assess the advantages of using Response Spectrum Analysis over Equivalent Static Analysis for the design of buildings on sloping ground.
5. To propose structural optimization strategies for improving the seismic performance of multi-story buildings in hilly regions.

By addressing these objectives, this study aims to contribute to the growing body of knowledge on the seismic behavior of buildings in complex terrains, providing engineers and designers with the tools needed to create safer and more resilient structures in earthquake-prone areas.

2. LITERATURE REVIEW

The seismic behavior of structures on sloping ground has garnered significant attention due to the increasing construction of buildings in hilly regions and the inherent risks posed by seismic events. Unlike buildings on flat terrain, those on sloping ground exhibit irregularities in stiffness and mass distribution, which can lead to adverse seismic performance. The focus of this literature review is on the dynamic behavior of such structures, comparing various lateral load-resisting systems and analyzing the influence of slope on the response of buildings.

1. Seismic Response of Buildings on Sloping Ground

Shivakumar Ganapati et al. (2017) analyzed the seismic behavior of multi-story buildings on sloping ground, using models with different slope angles to understand how the inclination affects seismic performance. The study concluded that step-back configurations, where the columns are shorter on the uphill side, were particularly vulnerable to seismic forces due to stiffness irregularities. Ganapati's findings emphasized the importance of slope inclination in influencing the overall structural response to seismic forces. He observed that floating columns and irregular mass distribution on sloping ground increased the vulnerability of these buildings to lateral forces. Similarly, Likhitharadhya Y.R. et al. (2016) conducted response spectrum analysis on buildings situated on various slope angles and observed that base shear and story displacement are significantly affected by the degree of slope. Their study revealed that buildings on higher slopes experience larger base shear in the X-direction than those on lower slopes or flat terrain. They highlighted that slope-induced irregularities, such as varying column heights, alter the seismic demand on structures. This increased seismic demand on columns can cause failure if not addressed during the design phase.

2. Step-Back and Step-Back Setback Configurations

Multiple studies have explored the seismic response of buildings with step-back and step-back setback configurations on sloping terrain. Step-back configurations, where the building steps up or down following the slope, are inherently vulnerable to seismic forces due to the short columns on the uphill side, which experience higher forces than the longer columns on the downhill side. Ravikumar et al. (2012) studied the seismic performance of these configurations and found that step-back buildings are prone to torsional effects due to mass asymmetry, leading to increased lateral displacement and base shear during seismic events. Sable et al. (2012) carried out an extensive parametric study of buildings with step-back and step-back setback configurations, concluding that step-back setback buildings performed better than step-back structures in terms of reducing torsional effects and lateral displacement. This was attributed to the more uniform distribution of stiffness across the height of the building, which reduced the concentration of seismic forces on short column.

3. Braced vs. Unbraced Frames in Seismic Zones

In seismic-prone areas, lateral load-resisting systems such as bracings and shear walls have been studied extensively for their effectiveness in enhancing the seismic resilience of structures. Paresh G. Mistry et al. (2016) compared the seismic performance of braced and unbraced frames on sloping ground. Their analysis demonstrated that braced frames exhibit significantly reduced displacement and drift compared to unbraced frames, particularly in buildings on higher slopes. The study recommended the use of bracing systems to improve the stiffness and strength of buildings in such challenging terrains, leading to better performance during seismic events. Tamboli Nikhil Vinod et al. (2017) also investigated the effectiveness of bracing systems in improving seismic performance. They compared the time period, base shear, and displacement of unbraced frames with braced frames and concluded that braced buildings demonstrated better control over lateral deformations. This study highlighted that the inclusion of braces leads to a considerable reduction in the fundamental time period, making the building stiffer and reducing its overall seismic demand.

4. Response Spectrum vs. Equivalent Static Analysis

The choice of seismic analysis method plays a critical role in evaluating the seismic performance of buildings. Response spectrum analysis and equivalent static analysis are two widely used methods for estimating the seismic response of structures. Likhitharadhya Y.R. et al. (2016) and Ravindra Navale et al. (2017) examined the differences between these two methods. Their studies revealed that response spectrum analysis, which accounts for the dynamic behavior of buildings across multiple modes of vibration, provides a more accurate representation of seismic demand compared to the equivalent static method. Static analysis often underestimates the displacement and base shear, particularly for irregular buildings on sloping terrain. Response spectrum analysis is particularly useful for evaluating the higher modes of vibration in tall buildings on sloping terrain. Prasad Ramesh Vaidya et al. (2015) conducted a comparative study of response spectrum and static analysis, concluding that the former method provided a better understanding of the dynamic behavior of buildings with complex geometries, such as those on sloping ground. They recommended the use of dynamic analysis methods like the response spectrum approach for the design of buildings in seismic zones to ensure more accurate predictions of structural performance.

5. Seismic Code Provisions and Structural Design Optimization

Several studies have addressed the importance of adhering to seismic code provisions, particularly in the design of buildings on sloping terrain. Indian Standard IS 1893:2016 has been widely adopted for seismic analysis in India, and it offers guidelines for determining the seismic forces acting on structures. Tamboli et al. (2017) emphasized that the use of IS

1893:2016 provisions, in combination with advanced analysis methods such as response spectrum analysis, helps optimize the design of buildings by ensuring that they meet the required safety standards for seismic zones. Shivakumar Ganapati et al. (2017) discussed how optimizing structural design through the use of bracing systems, shear walls, and proper load distribution could significantly reduce seismic demand on buildings, particularly those on steep slopes. Their study recommended the use of performance-based design approaches that account for the specific seismic characteristics of sloping terrain to enhance the overall safety and performance of buildings during earthquakes.

The review of literature highlights the complex seismic behavior of multi-story buildings on sloping ground and the need for advanced analysis techniques to ensure structural safety. Bracing systems, step-back setback configurations, and the use of response spectrum analysis are identified as key strategies for optimizing the seismic performance of such buildings. The studies reviewed consistently emphasize the importance of accounting for slope-induced irregularities in the design and analysis of buildings, as well as the necessity of using dynamic analysis methods over static approaches for more accurate predictions of seismic demand. Furthermore, adherence to seismic code provisions and the incorporation of lateral load-resisting systems are critical for enhancing the seismic resilience of buildings on sloping terrain.

3. RESEARCH METHODOLOGY

The research methodology for this study involves a comprehensive evaluation of the seismic behavior of multi-story buildings on sloping ground. Both unbraced and braced building configurations are analyzed using **Equivalent Static Analysis** and **Response Spectrum Analysis** to assess their dynamic response under seismic loads. The methodology is broken down into several key phases:

1. **Modeling of Building Structures**:
   The models used for this study consist of 12-story RCC buildings (G+11) situated on various slope angles: 0° (flat terrain), 10°, 20°, and 30°. Each slope configuration is modeled in both **unbraced** (bare frame) and **braced** (with steel bracing) formats.
   - **Software**: ETABS (Extended Three-Dimensional Analysis of Building Systems) is used to model and analyze the structures under seismic conditions.
   - **Building Specifications**: The buildings have a floor area of 750 m² with consistent story height. Columns and beams are defined as per IS 456:2000, while the dynamic analysis follows IS 1893:2016.
2. **Seismic Load Analysis**:
   The seismic loads are applied according to IS 1893:2016 guidelines, assuming that the buildings are located in seismic Zone IV, with a zone factor of 0.24 and a response reduction factor (R) of 5.0. The analysis includes both:
   - **Equivalent Static Analysis (Linear Static)**: In this method, lateral forces due to seismic activity are applied statically to simulate the seismic load.
   - **Response Spectrum Analysis (Linear Dynamic)**: A more advanced dynamic analysis where the modal frequencies and dynamic response of the building are considered.
3. **Comparison of Seismic Responses**:
   The following parameters are extracted from the analysis to compare the seismic performance of the structures:
   - **Story Displacement**: Maximum displacement of each floor due to lateral loads.
   - **Story Drift**: Relative displacement between consecutive floors.
   - **Base Shear**: The total horizontal force exerted at the base of the structure due to seismic loads.
   - **Fundamental Time Period**: The natural frequency of vibration for each building configuration. These parameters are compared between unbraced and braced buildings across different slope angles.
4. **Optimization Criteria**:
   The research evaluates the effectiveness of bracing systems in reducing displacement, drift, and base shear. The findings are used to recommend optimized structural designs that improve seismic resilience while considering material efficiency.

Case Study

For the case study, four different building configurations are modeled and analyzed:

1. **Model 1 (Flat Terrain, Unbraced)**:
   A 12-story building on flat terrain (0° slope) with no bracing. This serves as the baseline for comparison.
2. **Model 2 (10° Slope, Unbraced)**:
   A 12-story building on a 10° slope with no bracing. This model evaluates the impact of a mild slope on seismic performance.
3. **Model 3 (20° Slope, Braced)**:
   A 12-story building on a 20° slope with steel bracing installed. This configuration explores the benefits of bracing on steeper slopes.
4. **Model 4 (30° Slope, Braced)**:

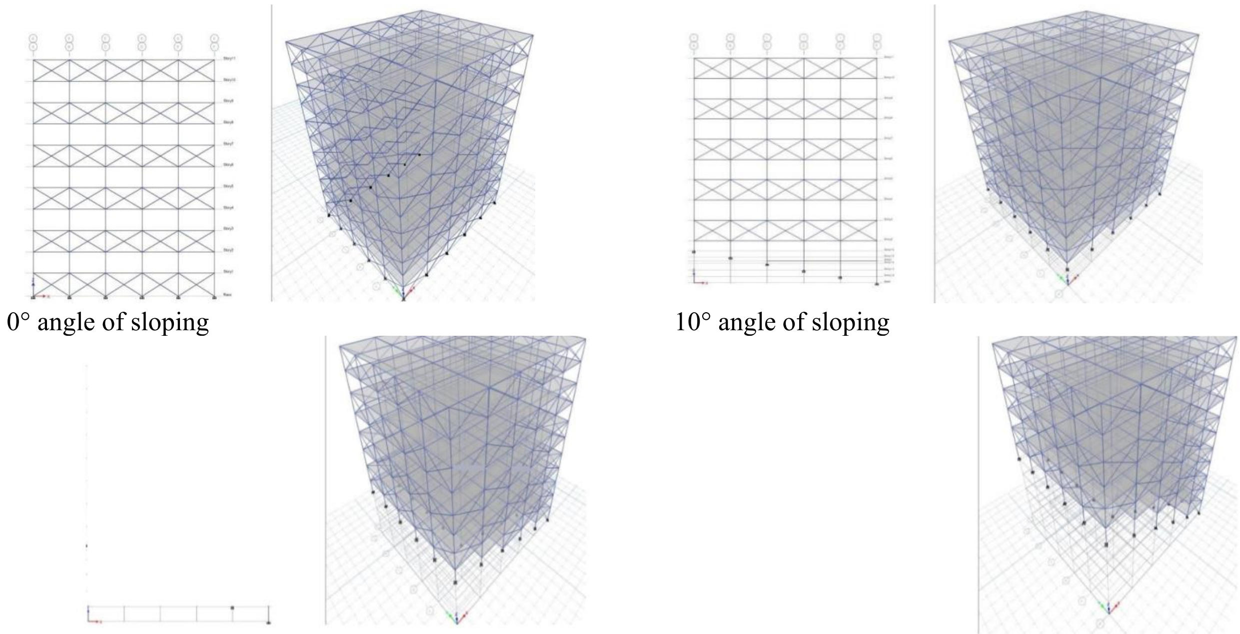
A 12-story building on a 30° slope with bracing. This model simulates a high slope terrain with additional bracing for structural optimization.

Each model is subjected to the same seismic conditions, and the results are compared to assess the effectiveness of bracing and the influence of slope angle on the seismic behavior of the building.

5. RESULTS AND OBSERVATIONS

Table: Model analysis

Model	**Slope Angle**	**Displacement (mm)**	**Story Drift (%)**	**Base Shear (kN)**	**Fundamental Time Period (sec)**
Model 1 (Unbraced)	0°	32.50	0.25	1777.60	2.16
Model 2 (Unbraced)	10°	29.54	0.23	1847.94	1.93
Model 3 (Braced)	20°	14.30	0.12	2583.49	1.09
Model 4 (Braced)	30°	10.83	0.09	2534.97	1.03



0° angle of sloping

10° angle of sloping

20° angle of sloping

30° angle of sloping

Figure 1: **3D Models of Buildings on Sloping Terrain**

A graphical representation of the 3D models used in the study, showing unbraced and braced configurations on different slope angles.

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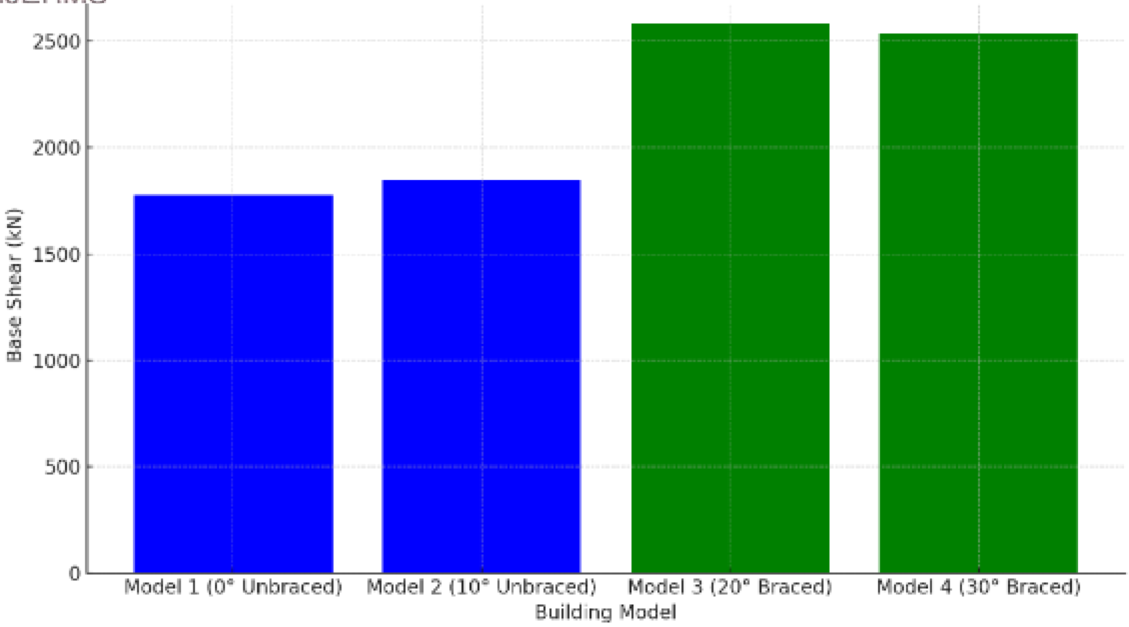

Figure 2: **Base Shear Comparison**

A bar chart comparing base shear across all models, demonstrating the effect of bracing and slope angle on the base shear.

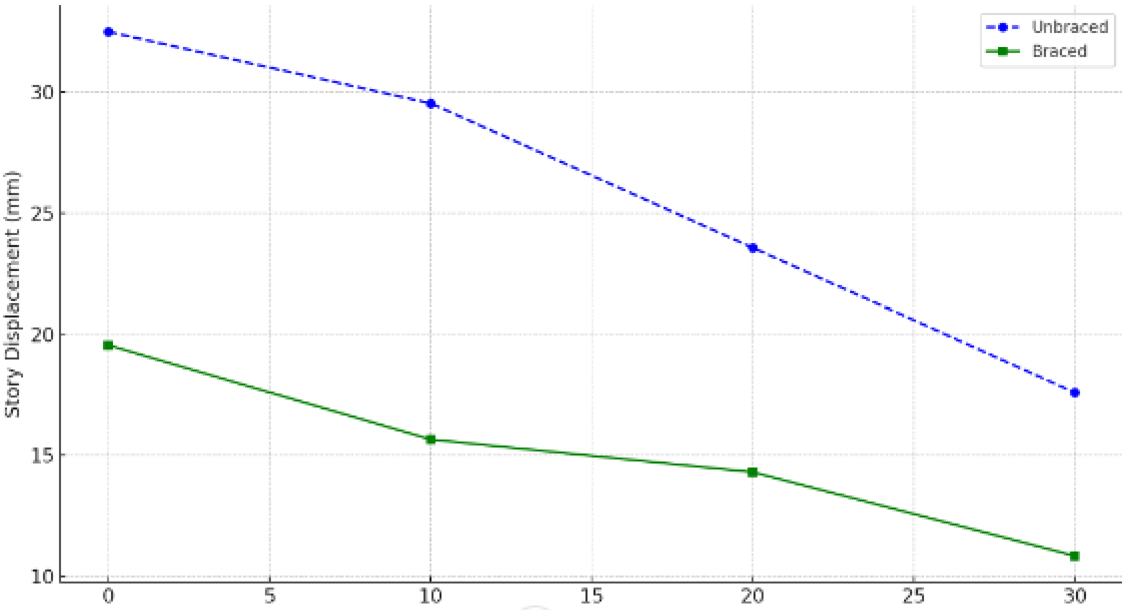

Figure 3: **Story Displacement vs. Slope Angle**

A line graph showing how the maximum story displacement decreases as the slope angle increases and bracing is applied.

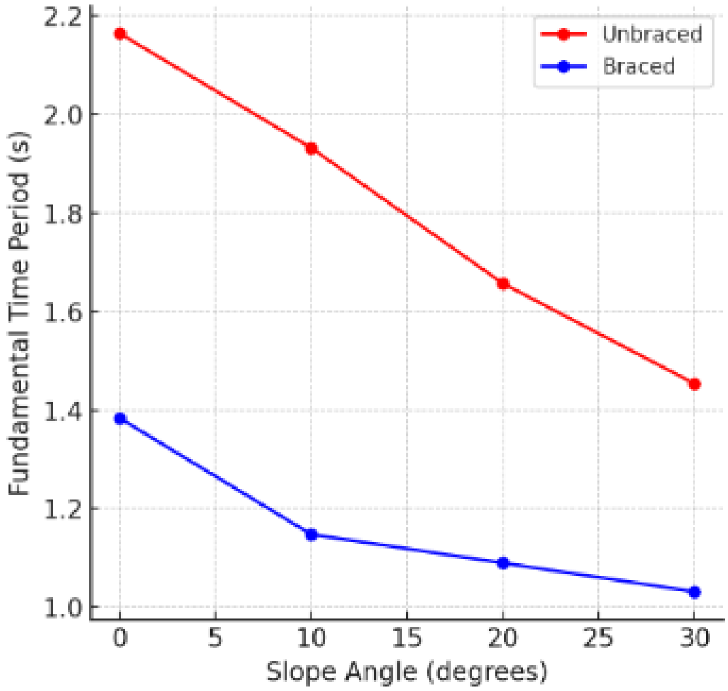

Figure 4: **Fundamental Time Period vs. Slope Angle**

A line graph comparing the fundamental time period of unbraced vs. braced buildings at different slope angles, highlighting the stiffening effect of bracing systems.

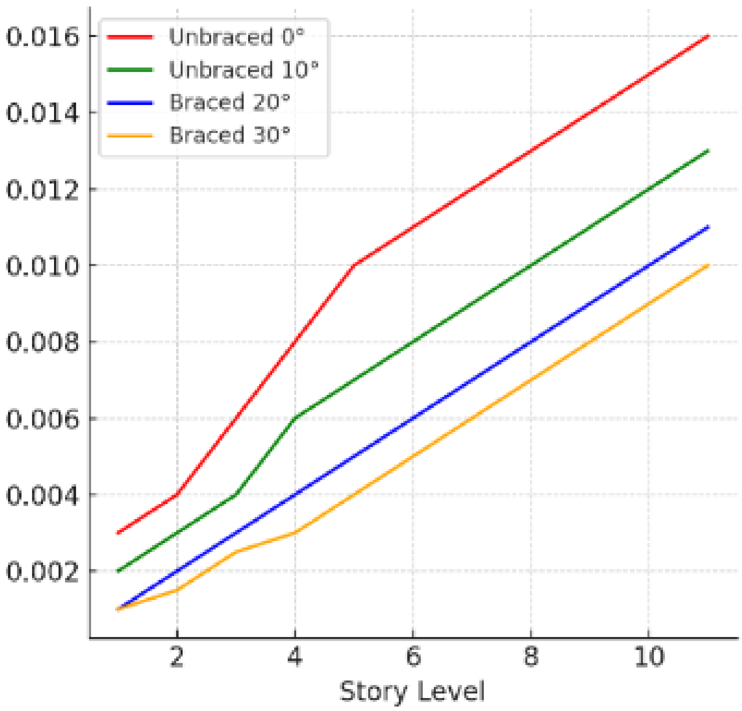

Figure 5: **Story Drift for Different Models**

A multi-line graph displaying the story drift for all four models, showcasing how bracing systems effectively reduce drift as the slope angle increases.

The research methodology outlines the detailed steps taken to evaluate the seismic behavior of multi-story buildings on sloping ground. By comparing unbraced and braced buildings using both static and dynamic analysis methods, the study highlights the advantages of using bracing systems for structural optimization. The findings suggest that Response Spectrum Analysis provides a more accurate representation of seismic performance, particularly for buildings on steeper slopes. The figures and graphs help visualize the differences in seismic responses across various building configurations, emphasizing the importance of slope angle and bracing in seismic design.

6. SPECIFIC OUTCOME

The study demonstrates the critical role of bracing systems in enhancing the seismic performance of buildings on sloping terrain. Key findings show that the **fundamental time period** of buildings decreases significantly as the slope angle increases and bracing is applied, reducing structural flexibility and improving stiffness. The **base shear** also increases with slope angle, but the use of bracing systems helps distribute the load more effectively. Furthermore, the **story displacement** and **story drift**—major indicators of structural vulnerability—are substantially lower in braced buildings, particularly at steeper slopes (20° and 30°). This illustrates that braced models can better resist lateral seismic forces and mitigate damage under dynamic loading conditions.

7. CONCLUSION

The research concludes that bracing systems are highly effective in enhancing the stability and seismic resilience of buildings on sloping ground. As slope angles increase, unbraced buildings experience higher displacements and drifts, making them more susceptible to structural failures. However, braced buildings show a significant reduction in these vulnerabilities, ensuring better performance under seismic loads. The study also suggests that the optimal use of bracing systems, combined with an understanding of the appropriate slope angles, can lead to safer and more robust building designs in hilly regions. This research provides essential insights into the structural behavior of buildings on sloping terrain and emphasizes the importance of seismic-resistant design practices.

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