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A Performance-Oriented Seismic Study of Vertically Irregular RC Structures on Hilly Terrains

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Abstract - This study investigates the seismic performance of reinforced concrete (RC) multistorey buildings constructed on sloping ground. Analytical approaches including Equivalent Static, Response Spectrum, Time-History, and Nonlinear Pushover analyses were carried out using ETABS for G+10 storey buildings with both regular and irregular (step-back, setback, and step-back–setback) configurations. The results reveal that slope-induced irregularities significantly affect seismic response, leading to higher storey displacements, drifts, and base shear compared to flat-ground structures. Short columns on the uphill side were found to be highly vulnerable due to stiffness concentration, attracting larger seismic forces and causing premature failures. Among the studied configurations, step-back–setback systems demonstrated relatively better performance. The findings emphasize the necessity of slope-specific seismic design, enhanced detailing of short columns, and consideration of height restrictions for structures on steep slopes.

Key Words: Seismic analysis, RC framed buildings, sloping ground, storey drift, base shear, pushover analysis, earthquake engineering.

1. INTRODUCTION

Multistoried reinforced concrete (RC) framed buildings are increasingly constructed in hilly regions due to rapid urbanization, rising land costs, and limited availability of level ground. Such buildings often adopt **setback**, **step-back**, or combined configurations, depending on the slope of the terrain. While setback structures are common on level ground, step-back and step-back–setback configurations dominate on hilly slopes. These irregular geometries introduce torsional effects, stress concentrations, and discontinuities, particularly under earthquake excitation, thereby necessitating detailed seismic analysis as per current building codes.

In hilly terrains, buildings are typically asymmetric in both plan and elevation, supported by columns of varying heights. Shorter columns, being stiffer, attract higher seismic forces, making them more vulnerable to damage during earthquakes. Additionally, non-uniform soil profiles on slopes lead to variations in bearing capacity, cohesion, and settlement, further compromising stability. Lateral earth pressure and slope instability exacerbate these vulnerabilities, often leading to structural failures.

To address seismic demands, simplified nonlinear static procedures (NSP), such as those outlined in FEMA-273/356 and ATC-40, are widely employed. These methods simulate the inelastic behavior of structures by subjecting them to monotonically increasing lateral forces until a target displacement is achieved. The unpredictability and destructive nature of earthquakes necessitate such advanced analytical approaches to mitigate loss of life and property.

Several studies have emphasized the seismic vulnerability of irregular structures, highlighting the importance of regularity and symmetry in both plan and elevation. Despite adherence to code requirements, buildings with irregular configurations often exhibit poor seismic performance compared to their regular counterparts. Consequently, understanding the influence of slope-induced irregularities on the seismic behavior of RC buildings has become a crucial area of research.

A. SEISMIC BEHAVIOUR OF BUILDINGS ON SLOPES IN INDIA

In India, large portions of the north and northeastern regions lie in **Seismic Zones IV and V**, where urban expansion has led to the widespread construction of RC framed buildings on slopes. These structures are highly irregular, torsionally coupled, and prone to column height variations. Past earthquakes have shown that short columns suffer disproportionately higher damage due to increased stiffness compared to taller columns in the same storey. Such behavior underscores the necessity for slope-specific seismic design considerations.

B. CONFIGURATION OF BUILDINGS ON HILL SLOPES

Buildings on slopes exhibit unique configurations, with successive floors stepping back towards the hill, resulting in unequal column heights and stiffness irregularities in both cross-slope and along-slope directions. This irregular stiffness distribution leads to significant torsional effects and shear concentration in short columns, often causing premature failures. Other common configurations include buildings founded at multiple levels on steep slopes, which further complicate torsional response and structural stability.

1.1 OBJECTIVES OF THE STUDY

The present study aims to evaluate the seismic performance of hypothetical multistory RC framed buildings resting on sloping ground with the following objectives:

1. To generate three-dimensional building models for both elastic and inelastic analyses.
2. To determine deflections and storey drifts using Response Spectrum and Pushover analysis.
3. To establish performance levels of buildings under static and dynamic seismic loading.

4. To study the influence of varying ground slopes on overall structural behavior.
5. To investigate the effect of vertical irregularities on the natural period and seismic performance.
6. To assess the distribution of damage under earthquake loading conditions.

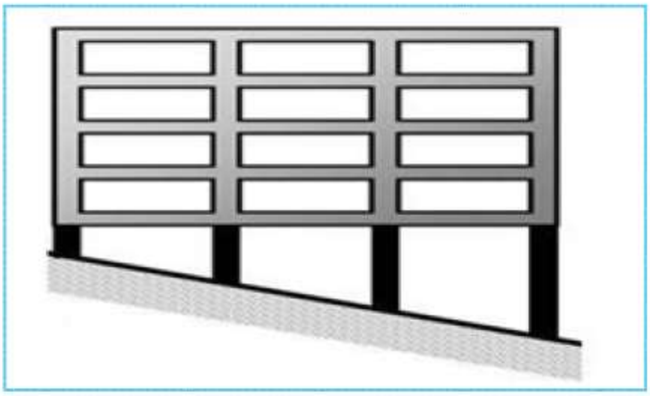

Fig.1 Building Frame with Short Columns

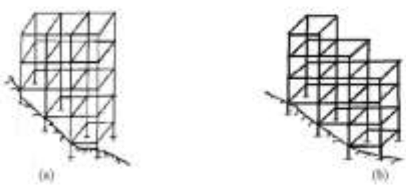

Fig.2 (a) Buildings step back towards the hill slope, (b) Buildings also set back

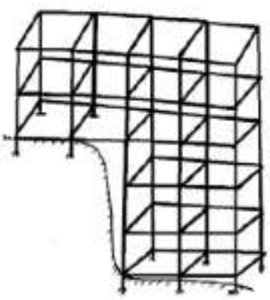

Fig.3 Building Configurations at Vertical Cuts/Steep Slopes

2. LITERATURE REVIEW

Numerous studies have been conducted to evaluate the seismic performance of buildings on sloping ground, focusing on irregularities in mass, stiffness, and geometry. These investigations highlight the increased vulnerability of structures constructed on hilly terrains compared to those on flat ground.

Chen and Constantinou (1998) proposed a practical system that introduced flexibility at the sloping ground storey by incorporating Teflon sliders and ductile columns for energy dissipation. Their analysis demonstrated improved stability of structures under seismic loading. Chandrasekaran and Rao (2002) analyzed multi-storied RCC buildings on varying slopes (5°, 10°, and 15°) and compared seismic forces, nodal displacements, and stresses using IS 1893–2002.

Birajdar (2004) carried out seismic analyses on 24 RC buildings with different configurations—step-back, setback, and step-back–setback. Using three-dimensional response spectrum analysis, the study concluded that step-back–setback buildings performed better on sloping ground due to improved stability. Similarly, Kadid and Boumrkik (2005) applied pushover analysis on 5-, 8-, and 12-story buildings, demonstrating that properly designed frames could perform well under seismic conditions.

Abu (2010) employed the Site Response Spectrum method to generate seismic response spectra for Zone III and IV regions in India. The study revealed that slope angle significantly influenced displacement patterns in buildings. Saptadip (2010) used STAAD.Pro to evaluate 2D frames with varying heights and bay lengths, establishing a correlation between slope angles and internal forces in structural members.

Balaji (2011) performed nonlinear analyses of symmetric and asymmetric structures on plane and sloping grounds using SAP2000 and STAAD.Pro. The study emphasized that asymmetric configurations with irregular bays were more vulnerable. Mohammed and Farooque (2012) highlighted the poor seismic resistance of short columns in hilly structures and evaluated the effect of shear walls through linear and nonlinear methods, including pushover analysis.

Ramin (2013) compared displacement behavior in buildings on flat and sloping lots using STAAD.Pro, concluding that slope-ground buildings exhibited higher resistance to displacements. Ramancharla (2013) studied slope angles of 15°, 30°, and 45° with varying shear wall placements, emphasizing the necessity of slope-specific design strategies.

Rajeeva and Tesfamariam (2012) developed fragility-based seismic vulnerability models considering soft storey and construction quality. Their probabilistic demand models revealed significant sensitivity to such irregularities. Sarkar et al. (2010) introduced a "regularity index" to quantify vertical irregularities in stepped buildings and provided an empirical formula for fundamental time period estimation.

Karavasilis et al. (2008) investigated steel frames with vertical mass irregularity, finding that inelastic demand distribution was influenced by storey count and mass location. Athanassiadou (2008) reported that irregular frames, despite being less ductile, exhibited seismic performance comparable to regular ones under design-level earthquakes.

Lee and Ko (2007) tested 17-story scaled RC wall models with different irregularities and observed that energy dissipation was predominantly influenced by overturning effects rather than wall placement. Devesh et al. (2006) highlighted increased seismic demands in setback structures with mass and stiffness irregularities.

Shahrooz and Moehle (1990) conducted experimental and analytical studies on setback structures, identifying dynamic response deficiencies and proposing design improvements. Valmundsson and Nau (1997) compared earthquake responses of irregular frames with Uniform Building Code (UBC) provisions, emphasizing the limitations of Equivalent Lateral Force methods.

Das (2000) and Sadjadi et al. (2007) reinforced the importance of nonlinear methods, while Kim and Elnashai (2009) demonstrated reduced shear capacity due to vertical motions in earthquakes. Duan et al. (2012) verified that Chinese GB50011-2010 provisions adequately addressed inelastic behavior but indicated susceptibility to soft-storey mechanisms.

Poonam et al. (2012) emphasized the detrimental role of weak or soft first storeys and mass irregularities, urging advanced design measures. Other studies, including those by Chopra and Goel (2001, 2002), Miranda and Garcia (2002), and FEMA guidelines (1997, 2000), have established pushover and performance-based methods as effective tools for seismic evaluation.

Collectively, these investigations highlight that structural irregularities induced by slope, mass distribution, and stiffness discontinuities significantly increase seismic vulnerability. Proper placement of shear walls, simplified configurations, and nonlinear evaluation methods are crucial for ensuring seismic resilience of RC buildings on hilly terrains.

3. METHODS OF ANALYSIS

The seismic performance of buildings depends strongly on the structural configuration, ground conditions, and analysis methodology. Structures resting on sloping ground introduce irregularities in stiffness, mass distribution, and load transfer, thereby requiring advanced analytical methods to accurately evaluate their seismic response.

A. Analytical Approaches

Seismic codes, including IS 1893:2002, recommend different analytical procedures depending on the regularity of the structure. For simple, regular configurations, **equivalent static analysis** is considered adequate. However, irregular buildings, particularly those on sloping ground, require **dynamic methods** such as **response spectrum** or **time-history analysis**.

1. **Equivalent Static Analysis**
   This approach simplifies seismic loading as equivalent lateral forces based on seismic weight, zone factor, importance factor, and fundamental time period of the structure. While effective for regular, low-rise buildings, this method often underestimates demands in irregular or tall structures.
2. **Response Spectrum Method**
   This method evaluates maximum response of a single-degree-of-freedom system subjected to seismic excitation. Response spectra corresponding to local soil conditions and seismic zones are applied to multi-storey frames to estimate displacements, storey shears, and time periods. It provides a more realistic representation of dynamic effects than static analysis.
3. **Time-History Analysis**
   This method computes structural response at successive time intervals using actual or synthetic ground motion records. It captures both linear and nonlinear behavior with high accuracy but requires significant computational effort. In this study, the Bhuj earthquake record (magnitude 7.7, PGA = 0.106 g) was used for simulation.
4. **Nonlinear Static (Pushover) Analysis**
   A performance-based method where lateral loads are monotonically increased until a target displacement is reached. Plastic hinge properties are introduced (FEMA-356 guidelines) to simulate inelastic behavior. Pushover analysis provides insights into capacity, ductility, and performance levels under seismic demand.

B. Modeling of Structures

Three-dimensional models of **G+10 storey RC buildings** were developed using ETABS. Both **rectangular configurations** and irregular layouts (setback, step-back, and step-back–setback) were considered. Input parameters included:

- Storey height: 3 m each
- Column dimensions: 450 × 230 mm
- Beam dimensions: 230 × 300 mm
- Shear wall thickness: 230 mm
- Materials: M25 grade concrete, Fe-500 steel
- Soil type: Type II (medium)
- Seismic Zone: II (as per IS 1893:2002)
- Wind speed: 44 m/s (Hyderabad region, IS 875:1987)

Loads were applied as per IS 875 (Part 1 and 2) for dead and live loads, and IS 1893 (Part 1):2002 for seismic forces. Wind loads were computed considering risk factor, terrain category, and topography effects.

C. Comparative Framework

The analysis was performed on three building models located on slopes of **0°, 5°, 10°, and 15°**. Comparative evaluation was carried out in terms of:

- **Storey displacement**
- **Storey drift**
- **Base shear**
- **Axial force and bending moments** in columns
- **Shear distribution** across storeys

This comprehensive methodology enables a realistic assessment of the seismic vulnerability of multistoried RC buildings on hilly terrains, incorporating both linear and nonlinear performance measures.

4. RESULTS AND DISCUSSIONS

Seismic analyses were performed on G+10 reinforced concrete (RC) buildings resting on varying slopes (0°, 5°, 10°, and 15°). The evaluation focused on storey displacement, drift, shear distribution, and base shear under earthquake loading. Results were obtained using **Equivalent Static**, **Response Spectrum**, **Time-History**, and **Pushover** analyses.

A. Storey Displacement

Figure 4.5–4.9 and Table 4.1 illustrate storey displacements for different slope angles. Buildings on sloping ground exhibited higher lateral displacements compared to flat-ground structures. The maximum displacement occurred at the roof level, with displacement values increasing proportionally with slope angle. However, beyond 15°, displacement values showed a tendency to stabilize due to redistribution of stiffness.

B. Storey Drift

Tables 4.2–4.5 and Figures 4.10–4.11 present storey drift variations. Maximum drift occurred at lower and middle storeys. Structures on slopes exhibited significantly higher drifts compared to flat-ground buildings, particularly at 5° slope. Drifts reduced slightly at 10° and 15°, indicating stiffness concentration in short uphill columns. IS 1893 drift limits (0.004 times storey height) were approached in some cases, highlighting potential performance concerns.

C. Storey Shear

Storey shear values (Tables 4.6–4.9, Figures 4.12–4.13) revealed that as slope increased, **base shear demand** also increased, with the maximum observed at 15°. The distribution of shear across storeys was nonlinear, with short columns at uphill sides attracting disproportionately high forces. This behavior underscores the vulnerability of short columns to brittle failures.

D. Pushover Analysis

Nonlinear static analysis indicated that short columns on higher elevations yielded earlier than longer columns. Plastic hinge formation was concentrated at ground and intermediate levels, suggesting the need for enhanced detailing in critical members. Performance levels ranged between **Immediate Occupancy (IO)** and **Life Safety (LS)**, depending on slope angle and configuration.

E. Discussion

1. **Effect of Slope** – Increasing slope angles intensified irregularity, resulting in higher base shear, storey displacement, and drift concentration.
2. **Short Column Effect** – Columns on the uphill side, being shorter and stiffer, attracted larger forces, often exceeding their capacity.
3. **Configuration Influence** – Step-back–setback buildings demonstrated relatively better seismic performance compared to purely step-back systems, due to improved load distribution.
4. **Performance Trends** – Structures on 15° slopes were prone to collapse beyond four storeys, indicating height restrictions may be necessary for safety.
5. **Directional Behavior** – Base shear was consistently higher in the longitudinal direction compared to the transverse, confirming torsional irregularity as a dominant factor.

Overall, results emphasize that geometric irregularities caused by slopes critically affect seismic response, making slope-specific seismic design and detailing indispensable.

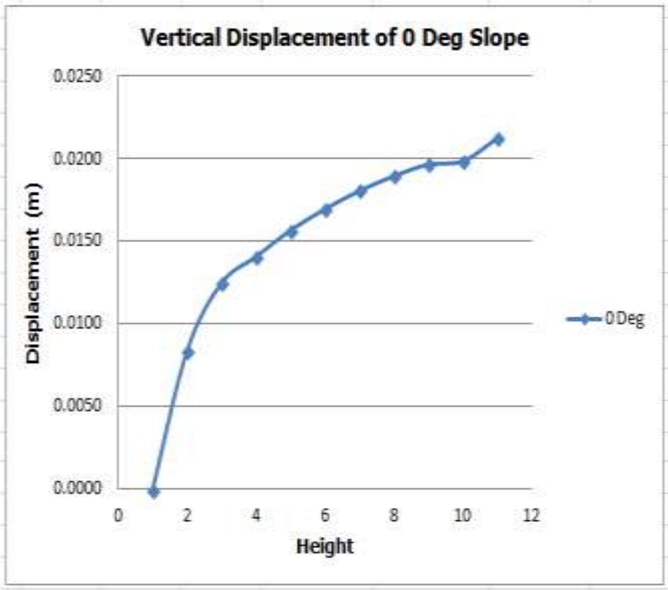

Fig.4 Story Shear Graph with Varying Slopes along Y-Direction.

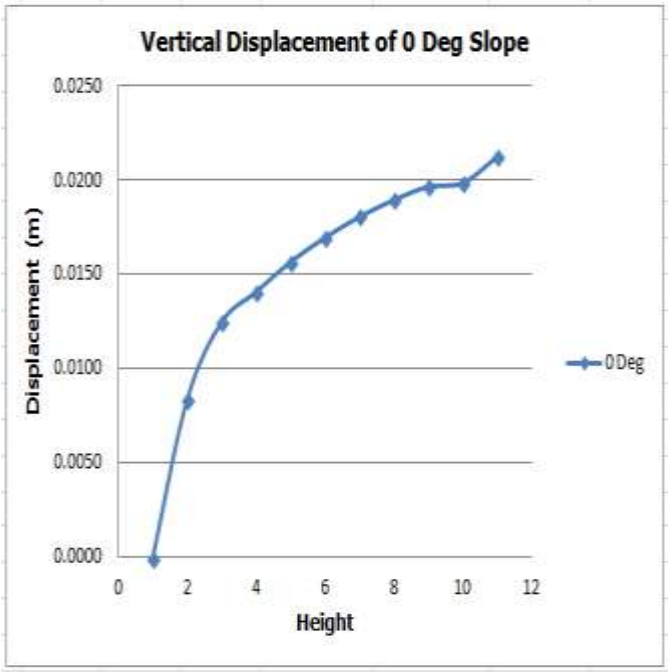

Fig.5 Story Displacement Graph with 0 Deg Slope

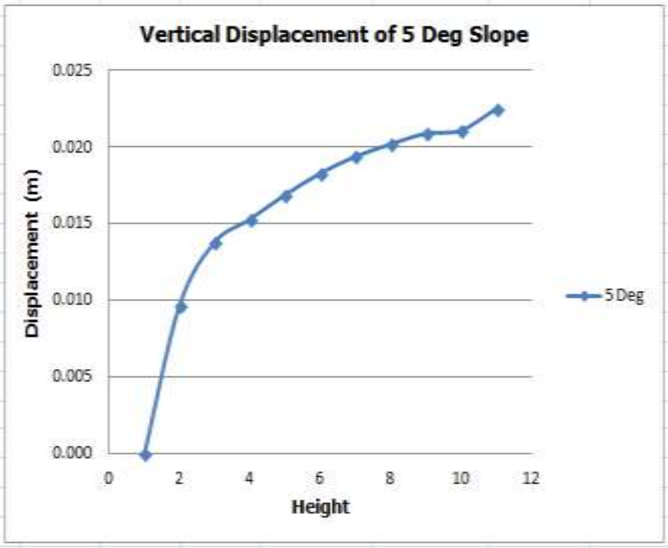

Fig.6 Story Displacement Graph with 5 Deg Slope

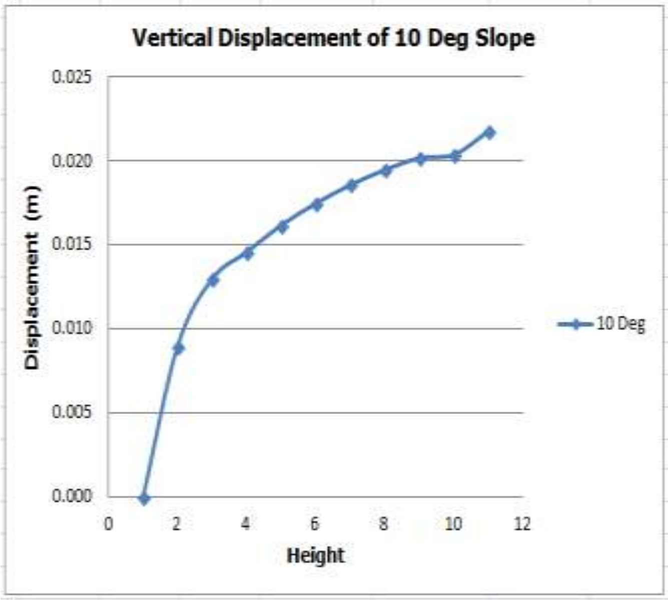

Fig.7 Story Displacement Graph with 10 Deg Slope

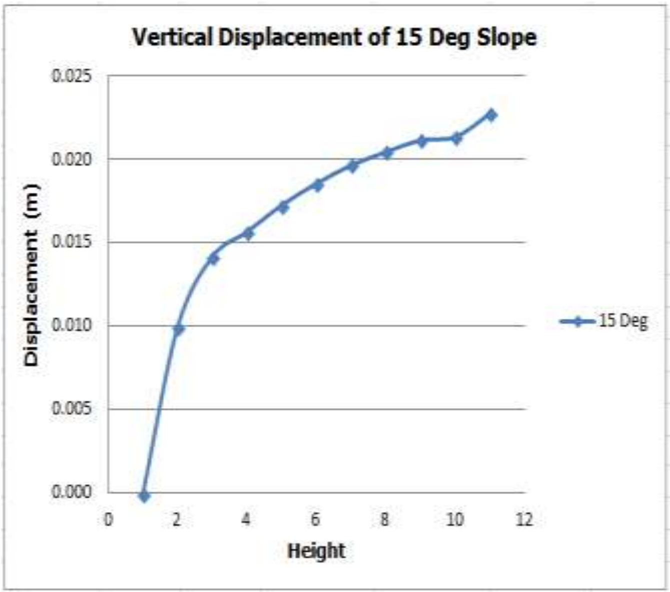

Fig.8 Story Displacement Graph with 15 Deg Slope

5. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

The seismic performance of multistorey RC framed buildings on sloping ground was investigated through linear static, dynamic, and nonlinear analyses. Based on the results, the following conclusions are drawn:

1. **Short Column Vulnerability** – In step-back and setback frames, columns located on the higher elevation of the slope are significantly stiffer and attract greater seismic forces, making them the most critical elements. Special detailing is required to prevent brittle failures.
2. **Effect of Building Height** – Base shear and displacement increase with building height. On steep slopes (15°), structures beyond four storeys approach collapse conditions, suggesting practical height limitations for safety.
3. **Storey Drift Characteristics** – Storey drifts were found to increase with both slope angle and building height. Maximum drift occurred at lower storeys, which could lead to soft-storey mechanisms if not properly designed.
4. **Influence of Slope Angle** – As slope angle increases, **base shear increases** while **target displacement decreases**. This indicates greater force demand but reduced overall ductility in sloping ground buildings.
5. **Directional Behavior** – Base shear was consistently higher in the longitudinal direction compared to the transverse direction, confirming the presence of torsional irregularities.
6. **Performance Levels** – Nonlinear pushover analysis revealed performance levels ranging between Immediate Occupancy (IO) and Life Safety (LS). Collapse Prevention (CP) conditions were approached in taller structures on steeper slopes.

B. Recommendations

1. **Design of Short Columns** – Enhanced reinforcement detailing, confinement, and use of ductile design provisions (IS 13920) should be prioritized for short columns.
2. **Height Restrictions** – On slopes exceeding 15°, building height should be limited to four storeys to ensure structural safety.
3. **Regularity in Configuration** – Step-back–setback configurations perform better compared to purely step-back structures. Designers should adopt more regular and symmetric layouts wherever possible.
4. **Advanced Analytical Methods** – Nonlinear dynamic methods (time-history and pushover analysis) should be used in addition to static approaches for buildings on sloping terrain.
5. **Seismic Detailing and Code Compliance** – Seismic detailing per IS 1893:2002 and IS 13920 should be strictly implemented, with special attention to torsional irregularities.
6. **Future Studies** – Further research may focus on soil–structure interaction, site-specific ground motion

effects, and use of base-isolation techniques for hilly terrain structures.

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