

Seismic Performance of Buildings on Sloping Terrain: A Review of Structural Behavior and Design Consideration

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ABSTRACT- A comprehensive literature review has been conducted to examine the seismic behavior of structures situated on sloping ground. The review encompasses various building configurations, analytical methodologies, and soil-structure interactions. The studies analyzed include reinforced concrete and steel structures of varying heights, incorporating different bracing systems and slope angles. The findings indicate that step-back setback configurations generally exhibit superior seismic resistance compared to step-back buildings. Additionally, the incorporation of shear walls significantly enhances structural performance. The research underscores the critical importance of considering soil-structure interaction (SSI) and topographic effects in seismic analysis, as these factors can substantially alter building responses. Factors such as slope angle, building height, and soil conditions have been identified as significant influencers of seismic parameters, including base shear, displacement, and fundamental time period etc. The review also highlights the vulnerability of shorter columns on steeper slopes and evaluates the effectiveness of various bracing systems in improving seismic performance. These insights contribute to the advancement of more resilient and economically viable structural designs for buildings situated on sloping terrain in seismically active regions.

Keywords: – Sloping ground, Seismic analysis, Soil Structure Interaction (SSI), Topographic effects, Response spectrum analysis, Time History method, Pushover analysis, Equivalent static method, Slope angle variations.

1. INTRODUCTION

The seismic behavior of structures built on sloping terrain is a critical concern in earthquake-prone regions. Unlike buildings on flat ground, structures on inclined surfaces experience complex dynamic interactions due to variations in slope angle, soil composition, and structural configurations. These factors significantly influence seismic parameters such as base shear, displacement, and

fundamental time periods, affecting overall structural stability.

Extensive research has been conducted to analyze the impact of different building configurations, including step-back, step-back setback, and setback structures, on seismic performance. Studies indicate that step-back setback buildings generally exhibit superior resistance to seismic forces compared to conventional step-back structures. Additionally, the presence of shear walls and bracing systems has been found to enhance lateral stability, reducing displacement and torsional effects.

Another crucial factor influencing seismic response is soil-structure interaction (SSI), which alters load distribution and energy dissipation during an earthquake. Variations in soil properties can amplify seismic forces, making it essential to account for topographic effects and foundation stability in structural design. Shorter columns on steeper slopes are particularly vulnerable, highlighting the need for optimized engineering solutions tailored to sloping terrains.

This study aims to evaluate the influence of slope angles, soil conditions, and structural configurations on the seismic response of buildings. By integrating advanced analytical techniques such as response spectrum analysis, time history methods, and pushover analysis, this research seeks to enhance the understanding of seismic performance and contribute to the development of safer, more resilient structures in hilly and mountainous regions.

2. LITERATURE REVIEW

- I. Birajdar, B. G., and S. S. Nalawade. "Seismic analysis of buildings resting on sloping ground." 13th world conference on earthquake engineering. No. 1472. 2004.

This research paper investigates the seismic performance of three distinct building configurations—Step-back, Step-back Setback, and Setback—constructed on both sloping and plain ground. A response spectrum analysis, conducted in accordance with IS 1893 (Part 1): 2002 guidelines, evaluates key seismic parameters including base shear, fundamental time period, and top-storey displacement. The

analysis considers buildings ranging in height from 4 to 11 storeys (15.75 m to 40.25 m) situated on sloping ground with a 27° incline, as well as comparable structures on level terrain.

The results indicate that Step-back buildings are the most vulnerable under seismic loading, primarily due to significant torsional effects and uneven shear distribution. In contrast, Step-back Setback configurations demonstrate improved seismic behavior by minimizing torsional moments, making them a more dependable design option for sloped sites. Setback buildings on plain ground exhibit structural stability and are less influenced by seismic forces; however, implementing such designs on sloped terrain often requires substantial leveling work, which may increase construction costs.

Overall, for seismic design in hilly regions, Step-back Setback configurations offer an effective balance between structural performance and practical feasibility.

II. Deep, V. Mani, and P. Polu Raju. "Pushover analysis of RC building: comparative study on seismic zones of India." Int. J. Civil Eng. Technol 8.4 (2017): 567-578.

This study presents a comparative pushover analysis of reinforced concrete (RC) buildings with different structural configurations to evaluate their seismic performance. Using ETABS software, three models were developed: a bare frame, a frame with masonry infill, and a frame with shear walls. Nonlinear static analysis was conducted in accordance with IS 1893:2002 to assess seismic response under gravity and lateral loads. The analysis focused on key parameters such as base shear capacity and roof displacement.

The conclusion showed that the model with shear walls exhibited the highest base shear and lowest displacement, indicating superior seismic performance and structural stability. The model with masonry infill provided improved strength over the bare frame but introduced irregularities in force distribution, which could affect reliability during seismic events. In contrast, the bare frame model demonstrated the poorest performance, with the highest displacements and lowest lateral load resistance. Overall, the inclusion of shear walls significantly enhances the structural resilience of RC buildings in seismic zones, making them the most effective option among the configurations studied. Masonry infill offers moderate benefits but may complicate structural behavior under dynamic loading. These findings underscore the importance of selecting appropriate lateral load-resisting systems, particularly for buildings in earthquake-prone areas.

III. Sanjay, Phatale Swarup, and S. R. Parekar. "Seismic analysis of Step-back building resting on sloping ground considering different types of Bracing system." International Journal for Modern Trends in Science and Technology 5.07 (2019).

This study analyzes the seismic performance of step-back buildings constructed on sloping ground using various bracing systems, including X, V, Inverted V, Diagonal, and a Bare Frame configuration. Response spectrum analysis was performed using ETABS software to assess key seismic parameters such as storey displacement, inter-storey drift, base shear, and fundamental time period. All models were designed with identical geometry and material properties and placed on a 26-degree inclined slope in Seismic Zone V.

The results revealed that the bare frame exhibited the highest top-storey displacement (33.86 mm), while the Inverted V and X bracing systems significantly reduced displacement to 16.26 mm and 16.58 mm, respectively, due to their enhanced lateral stiffness. Inter-storey drift was highest at the sixth storey in the bare frame model and lowest in structures with Inverted V and X bracing, which effectively distributed seismic forces and minimized deformation.

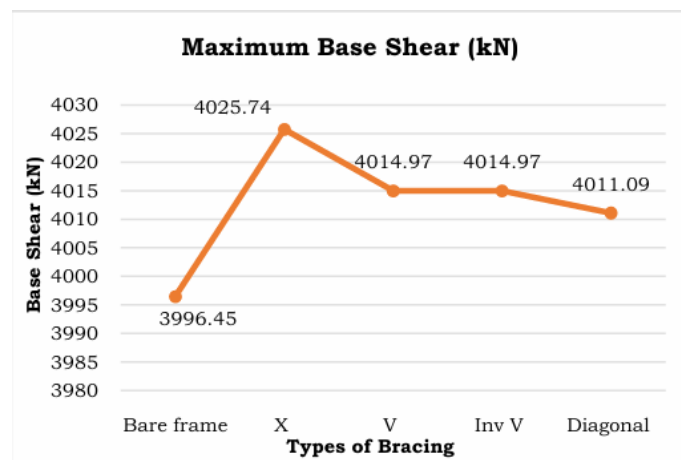


Figure 1: Maximum base shear vs Types of bracing.

In terms of base shear, the X-braced frame showed the highest value (4025.74 kN), reflecting its superior stiffness and energy absorption capacity, while the bare frame recorded the lowest (3996.45 kN). Regarding the fundamental time period, the bare frame had the longest duration, indicating lower stiffness, whereas V bracing resulted in the shortest time period. Overall, the X and Inverted V bracing systems proved to be the most effective for enhancing seismic performance in step-back buildings on sloping terrain, offering increased stiffness, reduced displacements and drift, and improved overall structural response to seismic forces.

IV. Patel, Mohammed Umar Farooque, A. V. Kulkarni, and Nayeemulla Inamdar. "A Performance study and seismic evaluation of RC frame buildings on sloping ground." IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) e-ISSN (2014): 2278-1684.

This study investigates the seismic performance of reinforced concrete (RC) frame buildings constructed on sloping ground, where irregularities in geometry and mass distribution significantly affect structural behavior during earthquakes. Using structural modeling and analysis tools, various building configurations differing in height and step-back or setback-step-back arrangements were evaluated under seismic loading conditions.

The study concludes that buildings on sloping ground experience increased lateral displacement, storey drift, and base shear compared to those on flat ground. Among the evaluated configurations, setback-step-back buildings were found to be the most vulnerable due to irregular column lengths and mass distribution, leading to concentrated stress and poor energy dissipation. The results emphasize the need for careful design and detailing of RC frame structures on slopes, with particular attention to vertical irregularities, to enhance their seismic resilience and ensure structural safety.

V. Gaikwad, Apurva Arjun, and Atul B. Pujari. "Seismic analysis of low rise, Mid-rise and High-Rise RCC structure on sloping Ground." International Research Journal of Engineering and Technology 6.7 (2019): 1357-1365.

This study analyzes the seismic behavior of low-rise (G+5), mid-rise (G+10), and high-rise (G+15) RC structures placed on both plain and sloping ground at varying slope angles using ETABS software. The analysis is conducted using Equivalent Static Method, Response Spectrum Method, and Time History Method to evaluate parameters such as storey displacement, base shear, storey drift, time period, and modal participation factors. Results indicate that structures on sloping ground exhibit greater maximum displacement compared to those on flat terrain, which can lead to critical structural conditions.

Ground Profile	Base Shear (KN)					
	5 Storey		10 storey		15 Storey	
	X dir	Y dir	X dir	Y dir	X dir	Y dir
Plain Ground	612.341	612.341	332.855	332.855	223.782	223.782
10°	631.666	631.666	352.416	349.324	230.292	229.131
20°	564.493	564.493	356.229	346.508	223.116	219.487
30°	464.275	464.275	361.757	350.27	209.404	205.78

Figure 2: Base shear of structure.

Among all slope angles, the 10° slope showed the highest base shear and storey drift. It was also observed that displacement is consistently higher at the top storey across all models in both X and Y directions. Mode shapes for 15-storey buildings show the longest time period at the top and bottom storeys, while the overall mode period tends to decrease as the slope angle increases. Additionally, base shear is more significant in the X-direction than in the Y-direction for sloped configurations. These findings highlight the increased seismic vulnerability of buildings on sloping terrain, especially around the 10° incline.

VI. Ghosh, Rahul, and Rama Debbarma. "Effect of slope angle variation on the structures resting on hilly region considering soil-structure interaction." International Journal of Advanced Structural Engineering 11 (2019): 67-77.

This study investigates the impact of varying slope angles (0°, 15°, 30°, and 45°) on the seismic performance of structures resting on sloping ground, considering both fixed-base and flexible-base conditions to account for soil-structure interaction (SSI). The analysis is carried out using multiple methods, including the Equivalent Static Force Method (ESFM), Response Spectrum Method (RSM), Time History Method (THM), Nonlinear Static Method (NLSM), and Nonlinear Time History Method (NLTHM).

The results reveal that increasing slope angles generally intensify structural vulnerabilities, with SSI playing a significant role in modifying the seismic response. While higher slopes tend to reduce the fundamental time period due to increased stiffness, the inclusion of SSI adds flexibility, leading to longer time periods. Base shear typically increases with slope angle but decreases when SSI is considered, particularly for steeper slopes. Displacement decreases with increasing slope angle on the whole but remains higher on the taller side of the structure; SSI further amplifies overall displacement. Additionally, bending moments are more pronounced in shorter columns situated on the upper side of slopes, and torsional effects become more severe with both increased slope and SSI. The findings emphasize the critical need to account for both slope geometry and SSI in seismic analysis, as they significantly affect the structural response and are essential for the safe and accurate design of buildings on sloped terrain.

VII. Mohammad, Zaid, Abdul Baqi, and Mohammed Arif. "Seismic response of RC framed buildings resting on hill slopes." Procedia engineering 173 (2017): 1792-1799.

This study investigates the seismic performance of reinforced concrete (RC) framed buildings constructed on

hilly terrain, focusing on step-back and step-back setback configurations. Using ETABS v9.0, the research employs Equivalent Static and Response Spectrum Methods to analyze key seismic parameters including fundamental time period, storey displacement, drift, base shear, and torsional effects.

The research concludes that step-back buildings exhibit longer time periods and greater flexibility, leading to increased displacements, storey drift, and torsional instability particularly in upper floors and shorter uphill columns. In contrast, step-back setback configurations demonstrate enhanced stiffness, with significantly lower base shear, more uniform force distribution, and reduced torsional response, improving overall seismic stability.

The study further emphasizes that seismic behavior varies across and along slopes, necessitating accurate 3D modeling for reliable assessment. Additionally, empirical formulas from IS 1893 (2002) are found insufficient in predicting these behaviors, reinforcing the importance of detailed response spectrum analysis. Overall, the research underscores the advantages of step-back setback designs and the need for optimized structural reinforcements and advanced analytical approaches to ensure the seismic resilience of RC buildings on sloped ground.

VIII. Manjunath, P., and Yogeendra R. Holebsgilu. "Seismic analysis of multi storey building with flat slab resting on plain and sloping ground." Bonfring International Journal of Machine Interface, ISSN (2016): 2277-5064.

This study explores the seismic performance of 10-story flat slab buildings situated on both flat and sloping terrain, using Response Spectrum Analysis in ETABS to assess the influence of varying slope angles (0°, 10°, 20°, and 30°) and soil types under Zone V seismic conditions. Buildings on sloping ground, due to their irregular and asymmetric geometry, demonstrate increased vulnerability to seismic forces.

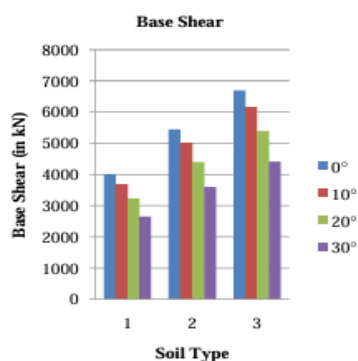


Figure 3: Base shear in different soil

The research concludes that as slope angle increases, base shear decreases attributed to reduced seismic mass while displacement and torsional effects increase, particularly in buildings on 30° slopes.

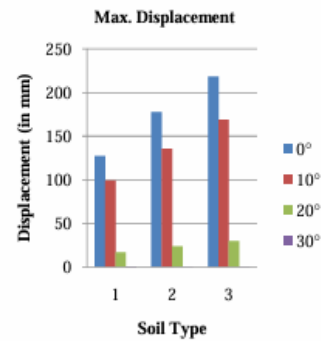


Figure 4: Max. Displacement in Different Soil.

Maximum displacement and acceleration are observed in buildings on flat ground, especially in soft soil, whereas sloped structures exhibit reduced acceleration but greater lateral instability. Storey drift is highest at lower floors and diminishes with increasing slope due to enhanced base fixity.

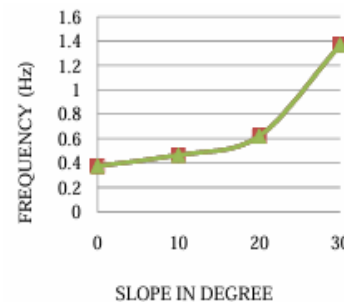


Figure 5: Frequency for 1st mode.

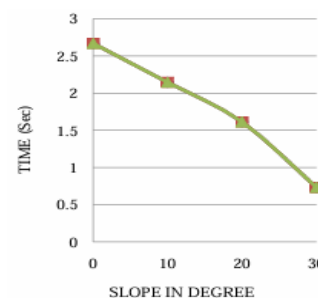


Figure 6: Time for 1st mode.

Additionally, as slope angle increases, the natural frequency of the structures rises and the time period shortens, indicating increased stiffness but a higher susceptibility to torsional behavior. The study concludes that while flat ground buildings are more stable due to higher base shear, sloped structures require careful design considerations, including additional reinforcement and

attention to soil stiffness, to mitigate increased displacements, drift, and torsional responses during seismic events.

IX. Zaidi, Sahil Abbas, Tabassum Naqvi, and Syed Muhammad Ibrahim. "Study on the effects of seismic soil-structure interaction of concrete buildings resting on hill slopes." Materials Today: Proceedings 43 (2021): 2250-2254.

This study investigates the seismic impact of Soil-Structure Interaction (SSI) on reinforced concrete (RC) buildings located on varying hill slopes (0°, 15°, and 27°) using nonlinear static pushover analysis in SAP2000. The analysis evaluates base shear, displacement, and structural performance, revealing that SSI plays a crucial role in reducing seismic forces through energy dissipation in the soil.

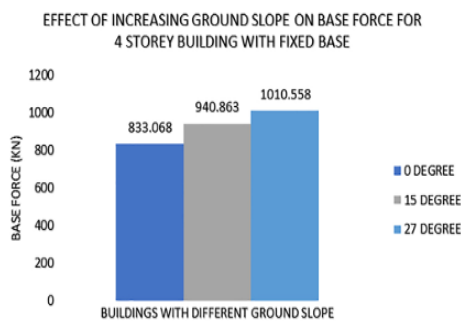


Figure 7: Variation of base force with increment in ground slope for building with fixed base.

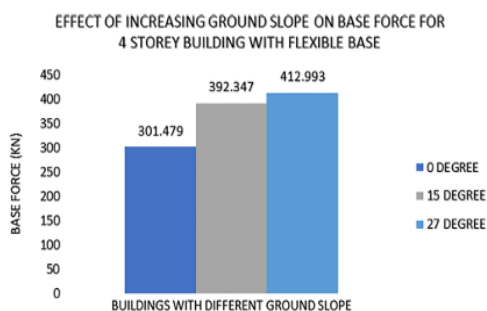


Figure 8: Variation of base force for increment in ground slope for building with flexible base.

The research concludes that base shear increases with slope angle by 21% in fixed-base and 37% in flexible-base buildings while displacement decreases significantly in fixed-base models but only marginally in flexible-base ones, highlighting the added flexibility and deformation in SSI-sensitive structures. Soil type also significantly influences structural response, with hard soil offering greater stability and soft soil amplifying displacement and vulnerability. Pushover analysis reveals that while fixed-base buildings reach failure thresholds earlier, flexible-

base models exhibit greater deformation yet benefit from reduced base shear due to improved energy dissipation. Overall, the research emphasizes the importance of considering SSI in seismic design, as it not only reduces seismic demand but also supports performance-based and cost-effective design strategies, especially for buildings in sloped and seismically active regions.

X. Shabani, Mohammad Javad, and Ali Ghanbari. "Comparison of seismic behavior of steel building adjacent to slope topography by considering fixed-base, SSI and TSSI." Asian Journal of Civil Engineering 21.7 (2020): 1151-1169

This research analyzes the seismic behavior of a 10-storey steel moment-frame building situated adjacent to a slope, using fixed-base (FB), soil-structure interaction (SSI), and topographic soil-structure interaction (TSSI) methods through 3D finite element modeling and laboratory shaking table tests.

The study reveals that buildings near the slope crest experience significantly amplified acceleration up to 4.5 times the input motion due to seismic wave reflections, while those at the slope toe face lower amplification. TSSI models show more realistic results, incorporating both soil flexibility and topographic effects, with lateral displacements up to seven times greater than FB models and base shear nearly doubling compared to SSI. Steeper slopes (45°) and soft soils further increase displacement, torsion, and base shear, while hard soils offer better seismic stability. Storey drift is highest at lower levels, especially near the slope crest, making short columns more vulnerable to failure. The study concludes that traditional FB analyses underestimate seismic demands in sloped terrains, and emphasizes the need to integrate TSSI in design to accurately capture the impact of slope angle, soil type, and location on seismic response. Buildings in such regions require advanced reinforcement and damping strategies for enhanced structural resilience.

3. CONCLUSIONS

The findings from the reviewed studies demonstrate that buildings on sloping terrain exhibit increased seismic vulnerabilities due to irregular mass, stiffness, and foundation conditions. The key conclusions from the analyses are as follows:

1. Structures built on inclined terrains exhibit greater vulnerability due to irregular column heights, asymmetrical mass distribution, and the amplification of seismic forces. Step-back and Step-back Setback configurations, particularly on steep slopes, tend to experience increased torsional effects, base shear, and top-story displacements. Among these, Step-back Setback

buildings demonstrate better structural balance and reduced torsional vulnerability, making them more suitable for hilly regions.

2. Pushover and response spectrum analyses consistently show that seismic demand including base shear, displacement, and plastic hinge formation intensifies with seismic zone severity (from Zone II to V). Buildings in higher zones require retrofitting, especially of lower-story columns, which bear the brunt of lateral forces. Bracing systems, such as X and Inverted V configurations, and strategically placed shear walls, especially at exterior corners, significantly enhance structural stiffness and minimize displacement and drift.
3. Additionally, building height and slope inclination are crucial factors; low-rise buildings tend to exhibit higher base shear due to stiffness, while mid- and high-rise structures show increased flexibility and displacement, particularly on steeper slopes. Base shear peaks around 10° slopes, but torsional effects are more severe at 30°, necessitating tailored reinforcement strategies. Time History Analysis proves especially effective in capturing the complex dynamic behavior of tall buildings.
4. As the slope angle increases, buildings experience a decrease in base shear because of the reduced seismic weight. However, they also face increased lateral displacement, torsional effects, and structural instability. Structures situated on steeper slopes (such as 30° to 45°) are especially susceptible to inelastic deformations and may fail at an early performance point under seismic loads.
5. Incorporating SSI into analysis significantly alters seismic response predictions. While fixed-base models overestimate base shear and stiffness, flexible-base models allow greater deformation, revealing increased displacement and torsion. SSI dissipates seismic energy through soil damping, thereby reducing base shear but increasing structural flexibility.
6. Buildings situated near slope crests are especially vulnerable due to seismic wave amplification. TSSI analysis demonstrates that both soil flexibility and topography significantly amplify seismic responses, far beyond what is captured by SSI alone.
7. Step-back building configurations suffer from higher storey drift, torsion, and localized failure, especially in shorter uphill columns. In contrast,

step-back setback configurations show improved force distribution, lower torsional effects, and better seismic performance.

8. Soft soils increase displacement, drift, and acceleration, reducing structural stability. Conversely, hard soils improve seismic resistance, highlighting the critical need for geotechnical evaluation in seismic design.
9. Buildings on sloped terrain typically exhibit shorter time periods and higher natural frequencies due to increased stiffness from shorter columns. However, asymmetrical configurations also result in greater torsional irregularities.

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