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Seismic Response of RCC Buildings on Hill Slopes with Step Back and Step Back - Set Back Configuration

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Framed structures constructed on hill slopes have different structural behavior than those on flat ground due to the scarcity of flat land. As these buildings are unsymmetrical, they attract large amounts of shear forces and torsional moments, leading to unequal distribution due to varying column lengths. In this study, the dynamic response of hill buildings has been compared with step back and step back set back building without and with bracing at corner of the building in terms of maximum storey stiffness and storey displacement. Two different types of buildings have been modeled and analyzed using ETABS v 18.0 finite element code. A parametric study has been conducted, in which hill buildings are geometrically varied in height of the structure due to hill slope. All sixteen analytical models have been subjected to seismic forces along and across the hill slope direction and analyzed by using the Response Spectrum Method.
All 16 models were analysed using ETABS v18. Three dimensional space frame analysis is carried out for four different configurations such as step back buildings with bracings at corner of the building, step back buildings without bracings, step back and set back building with bracings at

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corner of the building, step back and set back building without bracings. The maximum storey stiffness and storey displacement for the step back and step back-setback buildings with and without bracing are at 15° and 30°, respectively, compare with bracing buildings, the value in step back & step back set back building drastically decreases, resulting in the stability of the building.

Keywords: Seismic response; earthquake; slope; bracing; ETABS v18; step back; step back & set back.

1. INTRODUCTION

The northern regions of India, have a significant number of sloping landscapes. Due to the mountainous terrain in the north and northeast regions of India also in the southern regions of Rajasthan (Udaipur). There is a high demand for the construction of multi-storey RCC buildings on hill slopes, driven by economic growth and fast urbanization in these hilly areas. Structures on slopes differ from those on plains in that they are asymmetrical both horizontally and vertically [1]. The shortage of flat land in mountainous places, construction activity on sloping ground is required, resulting in a variety of important buildings such as reinforced concrete framed hospitals, colleges, hotels, and offices resting on hilly slopes. Since the behavior of buildings during earthquakes is determined by the distribution of mass and stiffness in both the horizontal and vertical planes of the building, both of which vary in the case of hilly buildings with irregularity and asymmetry caused by step back and step back-set back configuration [2]. Previous studies of earthquakes in hill regions, such as Uttarkashi (1991), Chamoli (1999), Sikkim (2011), Doda (2013), and others, demonstrate that buildings with varied heights of columns within the same level were the most sensitive to earthquake damage [3].

These designs try to reduce the effects of wind loads and seismic forces on the building by including setbacks or terraces at various heights. Different step-back and set-back building configurations with various seismic analysis techniques to evaluate their performance. This technique is frequently used to predict how earthquake-prone structures will react. It involves a range of vibrational periods. The spectrum, which is produced using ground motion information, contains details regarding the displacement of the building, storey drift, overturning moments etc.

In earthquake-prone regions, there are two types of structures commonly found in these regions: step-back structures and set-back structures. Step back structure have progressively reduced storey towards the base of each bay while maintaining the same roof level. On the other hand, set-back structures do not have a uniform roof level. Step-back and set-back buildings are architectural design strategies commonly used in seismic regions to enhance the structural integrity and seismic performance of tall buildings.

Compared to standard structures, both of these types of developments in seismically inclined terrain are exposed to greater shear and torsion forces, this can have an effect on their performance during an earthquake. One of the challenges with step-back buildings is that the shorter columns on the uphill side attract higher lateral forces, which can lead to the failure of these columns. The stiffness and strength characteristics of the walls play a crucial role in determining how much lateral load is shared by the structure [4]. Studied various configurations of step-back and set-back buildings using different seismic analysis approaches such as the Response Spectrum Method (RSM).

Research projects have been conducted around the world in recent decades to examine the causes of the failure of various types of buildings during strong seismic excitations [5]. Geological features are very significant in some areas due to the increased demand for space, certain buildings must now be built without altering the existing geological profile.The seismic waves that arrive at an area on the earth's surface are the consequence of complicated superposition, which causes unstable motion and ground shaking [1].

These designs try to reduce the effects of wind loads and seismic forces on the building by including setbacks or terraces at various heights. Different step-back and set-back building configurations with various seismic analysis techniques to evaluate their performance. This technique is frequently used to predict how earthquake-prone structures will react. It involves a range of vibrational periods. The spectrum, which is produced using ground motion information, contains details regarding the displacement of the building and storey stiffness etc.

These designs that aim to reduce the impact of wind loads and seismic forces by incorporating setbacks or terraces at different heights. Different building configurations are used, and various seismic analysis techniques are employed to evaluate their performance. This technique involves predicting how earthquake-prone structures will react by analysing a range of vibrational periods using ground motion information. The resulting spectrum provides details on the displacement of the building and storey stiffness.

2. LITERATURE REVIEW

Dangi and akhtar [1] studied the behaviour of 6-storey structure on sloping ground, exploring impacts of shear walls at 15°, 30°, and 45° angles. Results showed significant seismic improvement with shear walls, reducing lateral displacement and member forces. Maximum displacement occurred at 45° without shear walls, indicating increased risk with steeper slopes. Shear walls notably increased base shear, with the highest at 45°, similarly affecting axial forces.

Reshi and Singh [3] studied G+3 and G+4 buildings with slope angles ranging from 0° to 30° in seismic zone IV. Step-back and set-back configurations were analysed using a 3D model in Staad. Findings revealed that shorter columns on elevated terrain endured higher shear force compared to longer columns on lower terrain. Step-back-set-back structures exhibited superior seismic resistance over step-back designs, attributing lower base shear and top floor displacement to their flexibility in accommodating sloping ground.

Patel et al. [5] studied the structural analysis initiatives E-tabs examined the impacts of various column heights on ground floors due to sloping ground and the effects of shear walls at different positions during earthquakes. Seismic analysis was performed using linear static and linear dynamic methods, and the results were evaluated using pushover analysis. Analysed buildings on sloping terrain using six different models, and the performance of buildings on sloping terrain was found to show increased vulnerability of the structure with the creation of column hinges at the base level and beam hinges at each storey level at the performance point.

Madhav et al. [6] studied the seismic reaction and dynamic response of structures lying on hill slopes were investigated for step-back and step-back-set-back buildings. Most studies agreed that buildings on sloping terrain had higher displacement and base shear than buildings on flat ground, and the shorter column attracted more pressure and sustained more damage during an earthquake. Step-back buildings may be more vulnerable to seismic excitation than set-back and step-back set-back buildings.

Singh & Gade [7] investigated that, dynamic analysis of a building with a 45-degree slope and vertical cuts of varying heights, considering five different ground movements from the Pacific earthquake engineering research center database, the most vulnerable part of the building was found to be the floor at road level if downhill structures occurred. Buildings with a step-back structure were vulnerable to severe torsional impacts and inter-storey drifts that varied from building to building. The damage pattern observed during the Sikkim earthquake supported these findings and pointed towards the brittleness of the ground floor and torsional impacts in step-back buildings.

Kumar et al. [8] studied vertical irregularities, such as geometric irregularities and buildings resting on sloping ground, for which two types of configurations were considered: buildings resting on sloped ground in the x-direction and buildings resting on sloped ground in the y-direction. They observed that sloping ground buildings were extremely fragile, attracting huge forces that deformed them significantly. The base shear of a building on a steep slope was estimated to be 6019.2 kn, which was around 25–55% larger than that of other buildings, and displacement was determined to be 83.4 mm. Which was moderately greater than other structures. They observed that the performance target of sloping ground constructions in the x-direction was not met, but it succeeded after the collapse pointed in the y-direction. As a result, they conclude that structures on sloping terrain are more vulnerable to earthquakes than buildings on flat ground.

Halkude et al. [9] studied on buildings resting on sloping terrain with various numbers of bays and hill slopes were subjected to seismic evaluation. They investigated the variation of time period, base shear, and top storey displacement in relation to variation in the number of bays along slope direction and hill slope angle in various configurations, such as step-back and step-back-set-back buildings, which had 4–11 storeys and 3-6 bays in the x-direction. They investigated one bay along the y-axis with slopes of 16.32°, 21.58°, 26.56°, and 31.56°, with the horizontal in seismic zone iii. Base shear increases with the number of storeys in all configurations, and step-back buildings had larger values of time period and displacement than step-back-set-back buildings. Step-back building frames were considered unfavorable to use on sloping terrains. However, if an instrument could regulate significant displacement, they might have been used. Upon comparison of different arrangements, it was found that step-back buildings have a higher base shear than stepback-set-back buildings.

Suresh and Arunakanthi [10] Investigating In hilly areas, building construction can be challenging due to the local topography. As a result, the height of columns may vary, leading to inconsistent structures. This inconsistency can cause higher torsion and shear during seismic activity. Studies have shown that buildings with step-back and set-back frames perform better than those with step-back frames alone. However, when bracings are added to step-back frames, their performance surpasses both step-back and set-back frames. According to seismic analysis, buildings with dual-system structures, which include shear walls or bracing frames, are more effective at handling lateral forces based on their stiffness. Buildings with step-back frames but no bracings experience higher base shear compared to other frames. However, they are more vulnerable to seismic impact and induce more torsion compared to other building layouts. If step-back frames are recommended, construction should take into account the increased moments in columns caused by earthquakes.

Vaidya et al. [11] studies behaviour of the building on sloping ground for various shear wall positions as well as the effectiveness of shear walls on sloping ground. Model 1 was a frame-type structural system, while the remaining three were dual-type (shear wall-frame interaction) structural systems with three different shear wall placements. Sap 2000 finite element software was used for response spectrum analysis. Evaluated the building's performance in terms of displacement, storey drift, and maximum forces in columns. The roof displacement for model iii was reduced by up to 43.62% when compared to model 1 and essentially 43.38% when compared to model. Storey drift was stronger for shear wall frame interaction systems than for frame-type structural systems on other sides of the structure; this could be because of stiffness inconsistencies.

Joshua and Kamasundari [12] carried out an experimental study compared the dynamic behaviour of hill and regular buildings during earthquakes. Hill buildings were found less flexible due to stiffness differences, with regular buildings on flat ground being 1.33 to 2.07 times more flexible. Further, certain configurations showed higher flexibility in hill buildings. A 6-storey RC frame analysis highlighted differences in torsional forces during earthquakes between hill and regular buildings in seismic zone IV. Linear static and dynamic methods were employed for seismic research.

Misal and Bagade [13] studied the performance of two different types of buildings, such as step-back buildings without bracings, with different configurations of buildings ranging from G+8, G+10, and G+12 resting on sloping ground. Storey shear for first stories step back without bracings and step-set building frames is less than step back with bracing frames. The maximum torsion is generated at the G+12-storey building. Time period and displacement are both established maximums in regular buildings. Hence, step-back building frames without bracings on sloping ground are not desirable. However, it may be adopted by providing a bracing system to control displacements. The maximum torsional moment for step-set and regular buildings on plain ground frames is less than that for step-back with bracings and step-back without bracing frames. As the number of storeys increases, the time period and top-storey displacement also increase. Step back frames with bracings give less displacement compared with step back frames without bracings and also step and set back frames.

Imran and Rajesh [14] studied compared the performance of various building configurations on sloping and flat ground. Step-back buildings without bracings exhibited higher storey shear compared to those with bracings, with the maximum torsion observed in G+12 buildings. Regular buildings showed maximum time period and displacement. Step-back structures without bracings on sloping ground proved undesirable, but could be made viable with a bracing system. Step-set and regular buildings on plain ground experienced lower torsion compared to step-back designs. As storeys increased, time period and displacement also rose. Step-back buildings with bracings displayed lesser displacement than those without, and compared to step-set structures.

Joseph et al. [15] investigated A G+14 storey building with varying slopes of ground was designed and analyzed using ETABS 2015 software. The seismic response of the building changes with the addition of braces in the structure. The inclusion of braces increases the base shear and the maximum base shear value in braced structures is higher than that of unbraced structures. This is because the addition of braced members increases the stiffness of the building, thereby reducing vibrations caused by earthquakes and minimizing joint displacement. Buildings with bracing have less displacement compared to those without, and single-diamond bracing has less displacement than cross-bracing. Cross-bracing provides the least displacement. As the slope of the structure increases, the displacement and storey drift also increase.

Mohammad et al. [16] carried out an experimental study in assessed seismic performance by altering hill building heights and lengths geometrically across 18 analytical models. Seismic forces were applied along and across hill slopes, using the response spectrum method. Step-back buildings notably increased Fundamental Time Period (FTP) in the across-slope direction (0.575 sec to 1.089 sec). Dynamic analysis revealed time period variations (0.575 sec to 0.695 sec) differing from empirical calculations (0.543 sec to 1.026 sec). Top-storey displacement ranged from 28.37 mm to 15.57 mm, showing deviation in lateral stresses. Ground column shear forces (18.89 kN to 105.24 kN) mirrored step-back layouts. Step-back structures experienced a 45% lower base shear, more drift, and heightened vulnerability to seismic stress compared to set-back buildings. The slope direction impacted shear and drift differences, ranging from 10.19% to 51.54%. Shear concentrated in mid-heights and increased with model length, showing up to a 299.92 kN difference between set-back and step-back buildings.

Sindhurashmi and Shankar [17] investigated the buildings on flat ground and hill slopes, noting unsymmetrical hill structures faced increased shear forces and torsional moments with uneven column length distribution. Step-back designs displayed longer mode durations except the initial mode. Step-back setbacks showed lower maximum storey displacement in the y direction but greater values in the x direction for top stories. They also exhibited reduced storey shear and drift compared to traditional step-backs, suggesting improved stability in various directions.

Phatale and Parekar [18] studied the dynamic characteristics of hill buildings, which were irregular and unsymmetrical in both horizontal and vertical directions. These irregular variations result in a significant torsional response when subjected to lateral loads. Bracing systems, such as X, V, inverted V, diagonal, and bare frames, can reduce these torsional moments. The analysis of dynamic parameters, such as fundamental time periods, maximum top storey displacements, storey drifts, and base shear, reveals that cross bracing increases frame stiffness and frequency, while inverted V and X bracing provide better results for step-back buildings on sloping ground.

Vasudav and Shreyas [19] investigated the buildings between hilly and level terrains. Hillside structures exhibited varying column heights due to site conditions. Using the response spectrum method, two structure types on slopes were analysed using ETABS v17. Results compared storey displacement, shear, time period, and drift across 18 models on slopes of 15°, 20°, and 25°, and heights of 24m, 27m, and 30m. Step-back frames showed higher storey displacement compared to step-back and set-back frames. Implementing step-back structures reduced storey shear by 30–35%, and 7–10% in storey drift. Height of building and hill slope increased storey displacement increased.

Verma and Dubey [20] evaluated seismic behaviours in buildings using L-shear walls at corners, C-shear walls at the core, and reinforced concrete-filled steel tube columns in step-back and step-back-setback configurations. Key parameters included base shear, column forces, drift, displacement, and time period. Diagonal strut angles were set at 26.5650 and 44.740 degrees for different wall configurations. The buildings were 30m × 25m, 3.2m per floor, with slanted storeys at 280. Results showed seismic response improvements of 70-80%, base shear increments of 2-3 times, and reduced displacement by 5-7 times with shear walls. However, on inclined ground, taller columns experienced increased bending moments due to reduced height.

3. MODELLING AND ANALYSIS

The buildings in question share the same material properties and are built on sloping grounds with varying degrees of incline - 7.5°, 15°, 22.5°, and 30°. They have a bay width of 5 meters in the horizontal X-direction and 4 meters in the horizontal Z-direction. The storey height from the ground to the terrace is 3.0 meters, and all buildings have column and beam sizes according to Table 1. The buildings are designed in compliance with the Indian code IS 1893 (Part I): 2016 and are intended for use in zone V. They have one-way sloping stories that have different degrees of inclination. The plan dimensions are 30m x 20m, as depicted in Fig. 1 and Fig. 2. It's worth noting that the buildings rest on sloping ground and the height of columns in the ground stories varies. The columns on the lower side are long columns, while the columns on the higher side are short columns with bracing used at the building's corner.

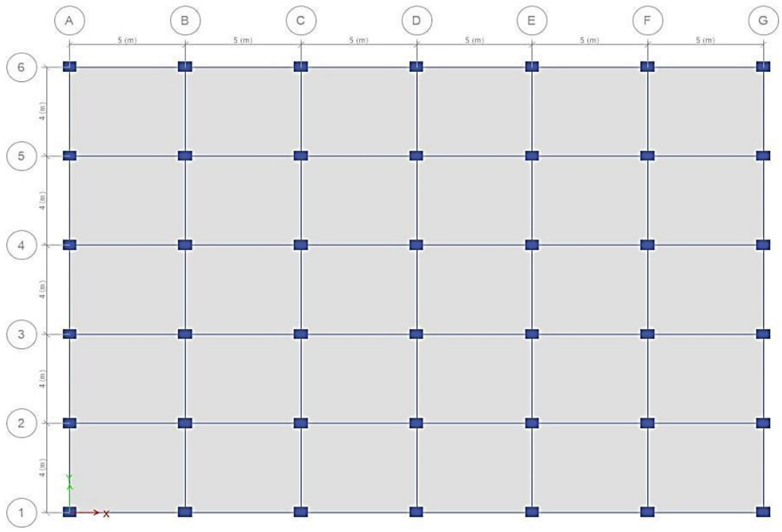


Fig. 1. Building configuration

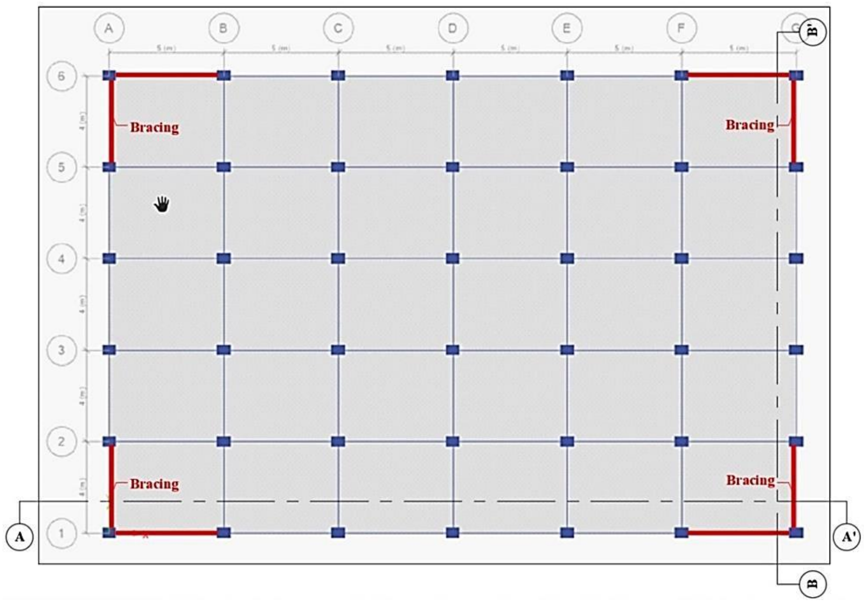


Fig. 2. Building configuration with bracing at the corner

3.1 Detailed Data of Building

Table 1. The properties adopted for the buildings are as shown

Properties	
Total stories	10 (G+9)
Plan Size	30mX20m
Storey height	3m
Spacing in X direction	5m
Spacing in Y direction	4m
Building used	Office building (SMRT)
Foundation	Isolated Footing
Seismic zone	Zone V
Soil type	Medium Soil
Concrete grade	M25
Steel grade	Fe415
Young's modulus of M25 concrete, E	2.5x104 MPa
Poisson's ratio of concrete	0.2
Density of concrete	25 kN/m3
Structural Members	
Thickness of slab	125mm
RCC Beam size	300 x 350 mm
Bracing	300 x 300 mm
RCC Column size	450 x 450 mm and 450 x 600mm
Super imposed Dead Load	
Floor finishes	1.5 kN/m3
Wall Load	5.5 kN/m3
Live Load	
Terrace	1.5 kN/m3
Floor	3 kN/m3
Response reduction factor	5
Damping ratio	5%(IS 1893:2016)
Impact factor	1.5
Poisson ratio	0.2

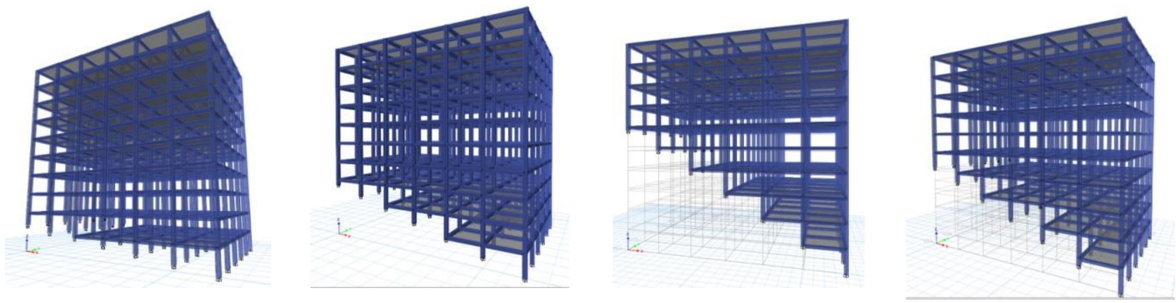
3.2 Model Specifications of Step Back Step Back – Set Back Buildings with and without Bracing

Table 2. Details of the model with different irregularities for step back building

S. No.	Type of Buildings	Irregularity Involved		Model No.	Zone
1	Step back building	M1	Building with 7.5˚ hill slope	7.5S	
2		M2	Building with 15˚ hill slope	15S	
3		M3	Building with 22.5˚ hill slope	22.5S	V
4		M4	Building with 30˚ hill slope	30S	
5	Step back with bracing	M5	Building with 7.5˚ hill slope	7.5SB	
6		M6	Building with 15˚ hill slope	15SB	
7		M7	Building with 22.5˚ hill slope	22.5SB	V
8		M8	Building with 30˚ hill slope	30SB	

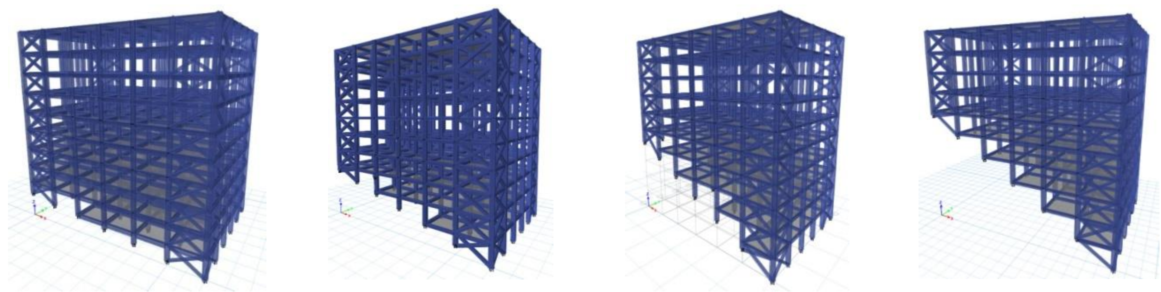
Table 3. Details of the model with different irregularities for step back-set back building

S. No.	Type of Buildings	Irregularity Involved		Model No.	Zone
1	Step back-set back Building	M9	Building with 7.5˚ hill slope	7.5SS	V
2		M10	Building with 15˚ hill slope	15SS	
3		M11	Building with 22.5˚ hill slope	22.5SS	
4		M12	Building with 30˚ hill slope	30SS	
5	Step back-set back Building with bracing	M13	Building with 7.5˚ hill slope	7.5SSB	V
6		M14	Building with 15˚ hill slope	15SSB	
7		M15	Building with 22.5˚ hill slope	22.5SSB	
8		M16	Building with 30˚ hill slope	30SSB	



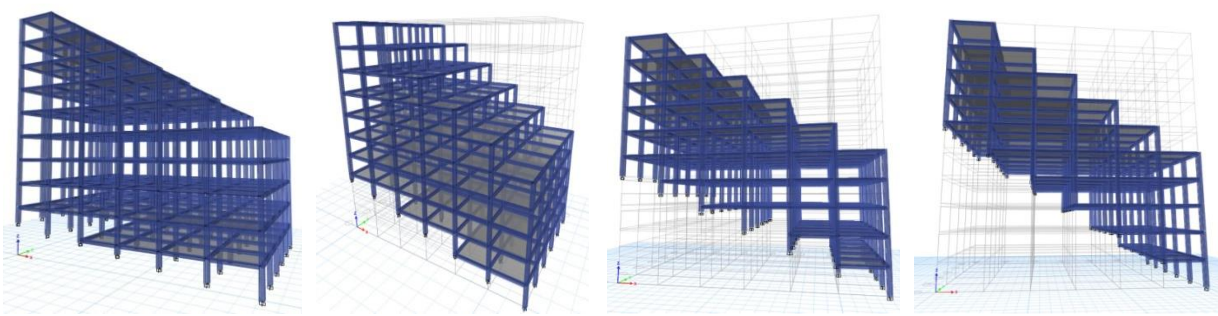
7.5S 15S 22.5S 30S

Fig. 3. Details of the model with different irregularities for step back building



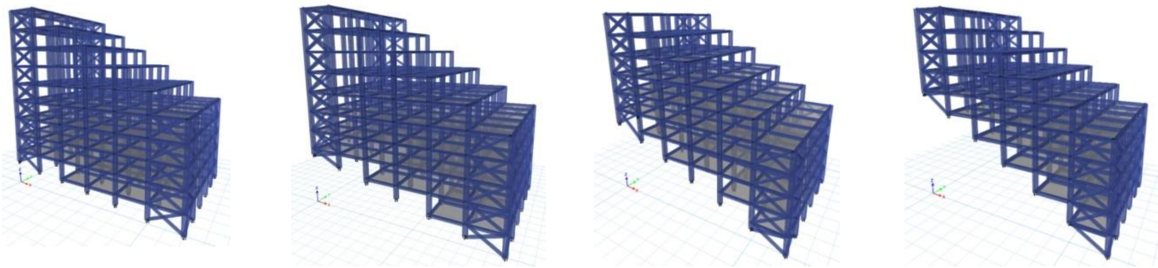
7.5SB 15SB 22.5SB 30SB

Fig. 4. Details of the model with different irregularities for step back building with bracing



7.5SS 15SS 22.5SS 30SS

Fig. 5. Details of the model with different irregularities for step back-set back building



7.5SSB 15SSB 22.5SSB 30SSB

Fig. 6. Details of the model with different irregularities for step back-set back building with bracing

4. RESULTS AND DISCUSSION

4.1 Storey Stiffness

The storey stiffness of a building is determined by the combined stiffness of its walls and columns. In RSM, stiffness variations along the storey heights are comparable. However, models on the slope suggest that RSM has exceptionally low rigidity, making it more susceptible to earthquake damage. Structures' relative resistance to lateral pressures such as wind or seismic activity is determined by the stiffness of each level or storey. Essentially, it measures how well each level of a building can withstand external pressures without deforming. In high-rise buildings, it is crucial to maintain a balanced distribution of stiffness to prevent extreme movements between storeys, which could potentially lead to structural issues or discomfort for occupants.

4.1.1 Storey stiffness for step back building

The study investigated the storey stiffness of a step-back building with nine floors (G+9) at four different sloping angles, namely 7.5°, 15°, 22.5° and 30°. Results indicated that the maximum storey stiffness occurs at a certain storey height and subsequently decreases throughout the building without the use of bracing, as well as with corner bracing. In Zone V, the storey stiffness in both x and y directions is the same for all sloping angles at specific storeys of the building.

In the X direction, the analysis results indicate that the 30° angle exhibits the highest value of storey stiffness in step back buildings, as compared to three other angles (7.5°, 15° and 22.5°). Both cases (without and with bracing) showed the maximum value of 590×10^5 kN and 42.7×10^5 kN at the 3rd and 1st storeys, respectively. Similarly, in the Y direction, the 30° angle demonstrated the highest value of storey stiffness in step back buildings as compared to other angles (7.5°, 15° and 22.5°). Both cases (without and with bracing) showed the maximum value of 389×10^5 kN and 22.5×10^5 kN at the 1st and 2nd storeys, respectively.

The data presented in Fig. 7 illustrates the changes in storey stiffness for zone V in the x-direction with and without bracing. The maximum storey stiffness is observed at a 30° angle in both cases, however, the addition of bracing to the building significantly reduces the stiffness value. Furthermore, the study analysed the changes in storey drift at the 3rd and 7th storeys, without and with bracing, respectively.

The stiffness of storeys in the y-direction for zone V was analysed both with and without bracing. Fig. 8 illustrates that the maximum storey stiffness was observed at a 30° angle in both cases. However, the addition of bracing to the building led to a significant reduction in storey stiffness. Specifically, the investigation focused on changes in storey drift at the 1st and 6th storeys without bracing and with bracing, respectively.

4.1.2 Storey stiffness for step back – Set back building

The analysis results indicate that the 30° angle exhibits the highest value of storey stiffness in a step back building. In the X direction, the maximum value in both braced and un-braced cases is 453×10^5 kN and 43×10^5 kN at the 2nd and 4th storey, respectively, when compared to three other angles (7.5°, 15°and 22.5°). Similarly, in the Y direction, the maximum value in both braced and un-braced cases is 389×10^5 kN and

$61.2x10^5$ kN at the 1st storey, respectively, when compared to three other angles (7.5°, 15° and 22.5°).

Fig. 9 shows the variation in storey stiffness for zone V in x - direction with and without bracing. Storey stiffness is maximum at 30°in both the cases. But it reduces by high value as we added X bracing to the building. Investigated the storey drift changes at particular storey 2th and 4th without bracing and with bracing respectively in the building.

Fig. 10 Investigates the variation in storey stiffness for zone V in the y-direction with and without bracing. The study found that storey stiffness is maximum at 30° in both cases. However, the addition of X bracing to the building resulted in a significant reduction in storey stiffness. The study also looked at the changes in storey drift at particular storeys (first and fourth) without bracing and with bracing in the building. It was observed that as the floor area decreases, the number of members resisting the lateral forces also decreases, resulting in irregularity. This irregularity causes the centre of mass and the centre of stiffness to not coincide with each other, leading to a disturbance in storey stiffness and torsional response [16].

4.2 Storey Displacement

The storey displacement refers to the amount of lateral displacement that a building experiences at any given point with respect to its original position. This measurement is significant in evaluating the structural safety and integrity of a building, particularly during dynamic loading events like an earthquake. The maximum displacements at each storey level concerning the ground are determined using the response spectrum method in both X and Y directions. This is to account for the influence of torsion when a force acts in a given direction. The storey displacement is typically highest at the top floor and gradually decreases towards the bottom floor. By analysing this displacement data, engineers can better understand the behaviour of a building during seismic events and design structures that can withstand such forces.

4.2.1 Displacement for step back building

The study examines the displacement in various zones of a G+9 storey building at different angles of 7.5°, 15°, 22.5°and 30°. The findings suggest that the highest displacement value is at the 10th storey of the building, indicating that zone V at a 15° angle has the highest value of displacement at the top due to seismic activity. The results indicate that the zones and hill slopes rise, and the maximum storey displacement varies on top of structures in both directions, with and without bracing. Further analysis reveals that in the X direction, the largest value from all angles is at 15° (with & without bracing), which is 6.66 mm and 62.15 mm at the 10th storey, respectively, when compared with three other angles of 7.5°, 22.5° and 30° including with bracing, which is 1.85 mm, 4.12 mm, and 3.03 mm, respectively, as compared without bracing, which is 29.52 mm, 12.06 mm, and 31.03 mm. Similarly, in the Y direction, the largest value from all angles is at 15° (with & without bracing), which is 6.38 mm and 86.16 mm at the 10th storey, respectively, when compared with three other angles of 7.5°, 22.5°, and 30° including with bracing, which is 0.85 mm, 5.23 mm, and 5.84 mm, respectively, as compared without bracing, which is 35.07 mm, 8.35 mm, and 10.9. mm.

Results presented in Fig. 11 demonstrates the difference in storey displacement between zone V in x direction when comparing a building with and without bracing. The maximum storey displacement occurs at the topmost storey with a 15° tilt. The results indicate that the use of bracing significantly reduces storey displacement in the building.

The graph in Fig. 12 illustrates the change in storey displacement for Zone V in the y-direction, both with and without bracing. The maximum storey displacement occurs at the topmost level, specifically at an angle of 15 degrees. The results indicate that using bracing in the building leads to a significant reduction in storey displacement.

4.2.2 Displacement for step back – Set back building

The largest value in the X direction from all angles is at 15° and 7.5° (with and without bracing), which measures 4.53 mm, 39.26 mm, and 2.56 mm, 72.73 mm, respectively, at the 10th storey. In comparison, the two other angles tested, 22.5° and 30°, including with bracing, measured 1.71 mm and 12.22 mm, respectively, as compared to without bracing, which measured 1.07 mm and 21.21 mm. Similarly, in the Y direction, the largest value from all angles is at

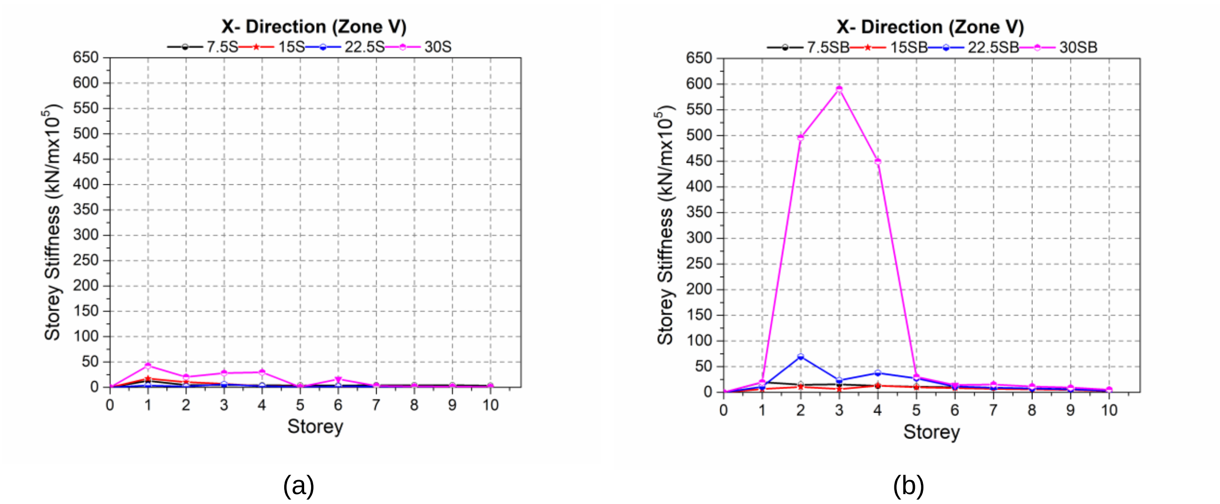


Fig. 7. Step back building storey stiffness at x – direction (a) without bracing (b) with bracing

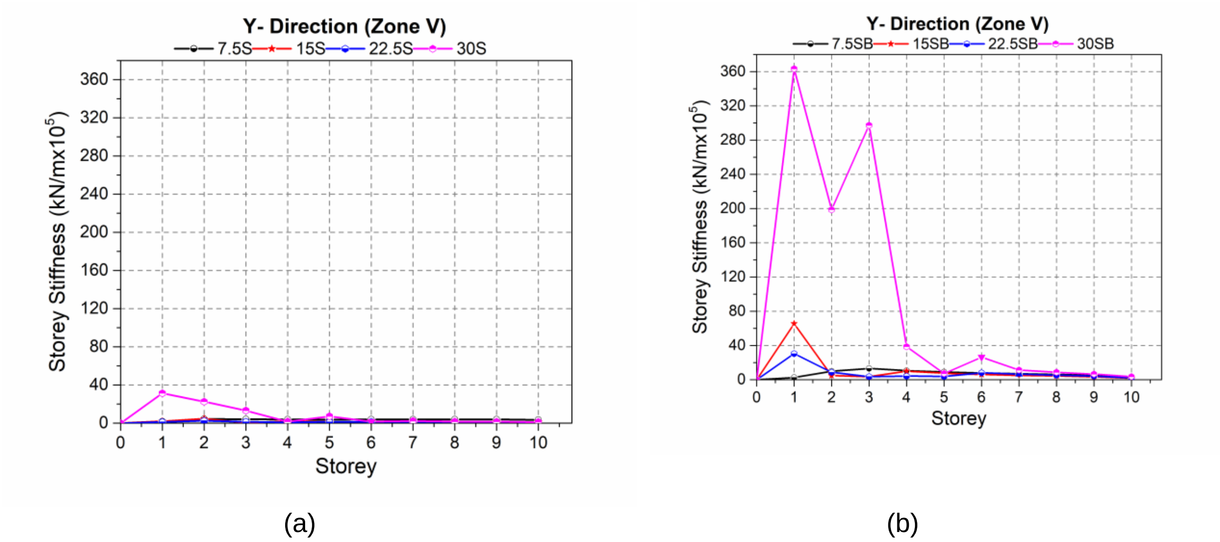


Fig. 8. Step back building storey stiffness at y – direction (a) without bracing (b) with bracing

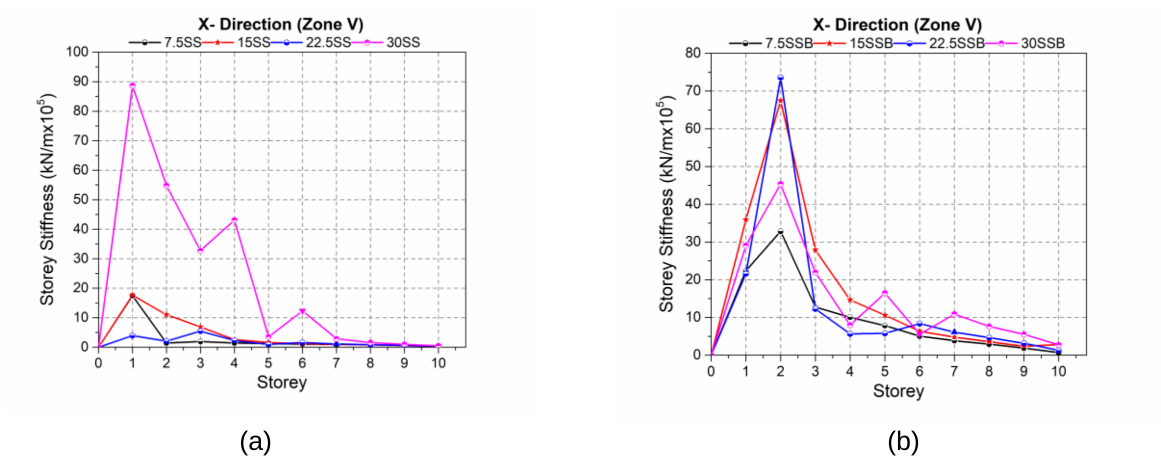
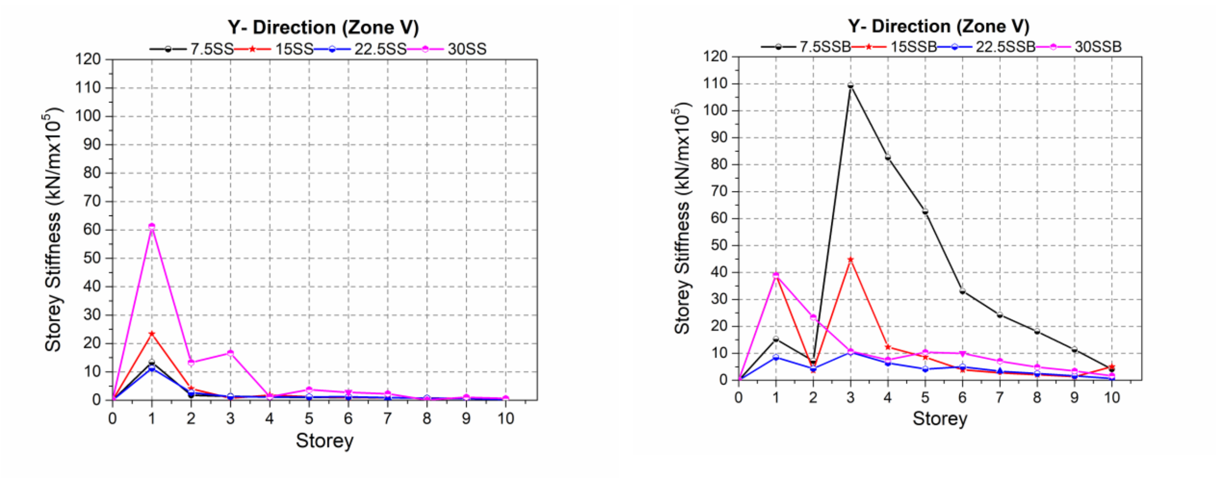


Fig. 9. Step back – set back building storey stiffness at x – direction (a) without bracing (b) with bracing



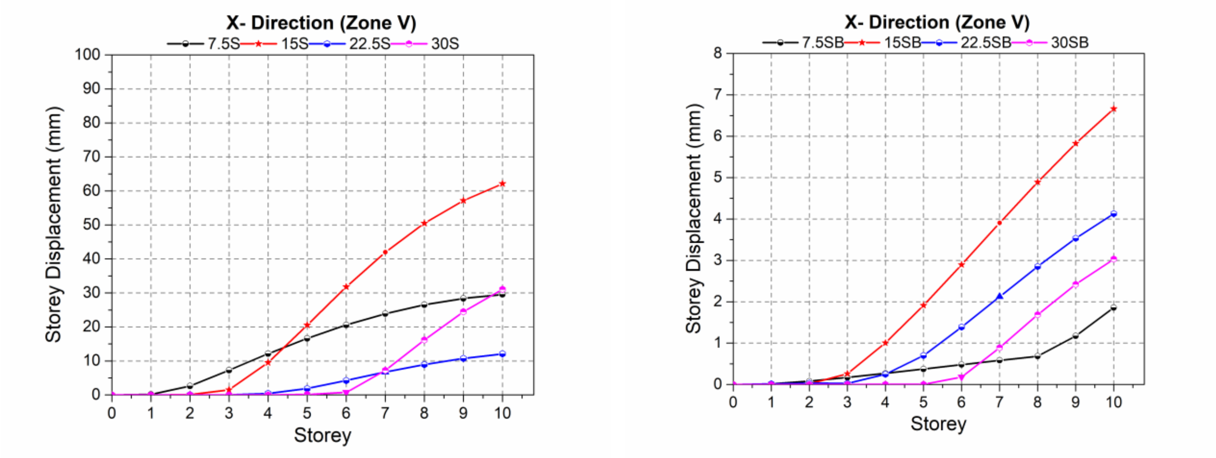
(a) (b)

Fig. 10. Step back – set back building storey stiffness at y – direction (a) without bracing (b) with bracing

15° and 7.5° (with and without bracing), which measures 2.79 mm, 6.16 mm, and 0.95 mm, 92.44 mm, respectively, at the 10th storey. In comparison, the two other angles tested, 22.5° and 30°, including with bracing, measured 0.62 mm and 4.56 mm, respectively, as compared to without bracing, which measured 0.152 mm and 7.255 mm.

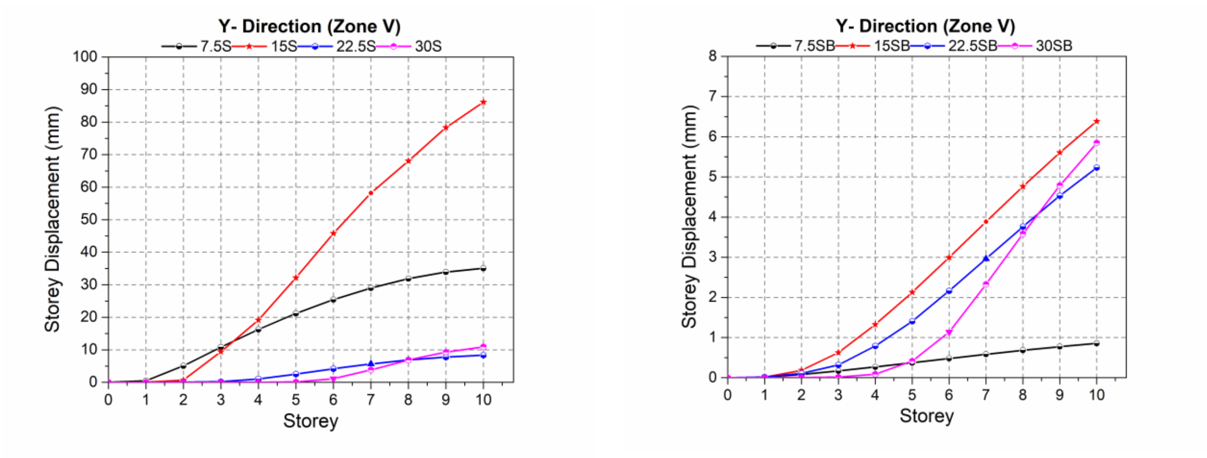
Fig. 13 illustrates the variation in storey displacement for zone V in the X direction with and without bracing. Storey displacement is maximum on the topmost storey at 7.5° without using bracing and 15° with bracing. The results indicate that using bracing reduces storey displacement by a significant margin.

The displacement of storeys in zone V, in the y direction, was examined with and without bracing in Fig. 14. The maximum storey displacement was observed to occur at the topmost storey with a 7.5° angle and no bracing, and at a 15° angle with bracing. Results indicated that using X-bracing significantly reduced storey displacement. The analysis also revealed that short columns were more susceptible to earthquake impacts. Based on the findings, it was recommended that buildings constructed on hill slopes should adopt a step-back or step-back-set-back building configuration [1].



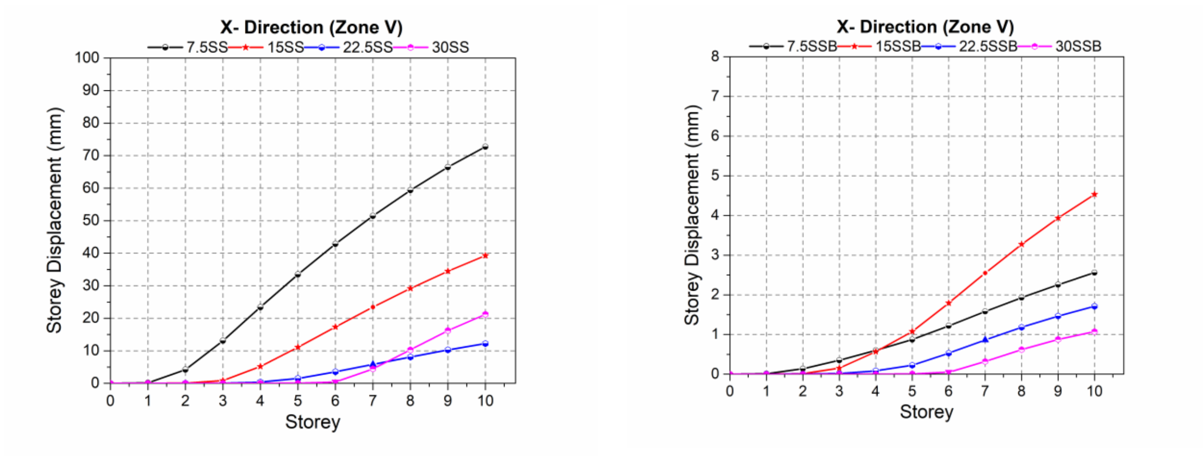
(a) (b)

Fig. 11. Step back building displacement at x-direction in zone V (a) without bracing (b) with bracing



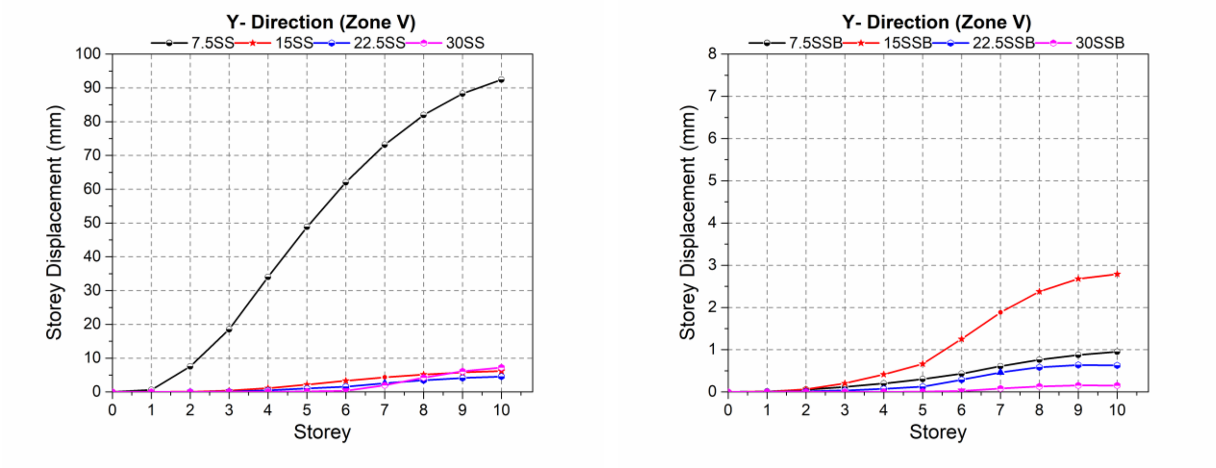
(a) (b)

Fig. 12. Step back building displacement at y-direction in zone V (a) without bracing (b) with bracing



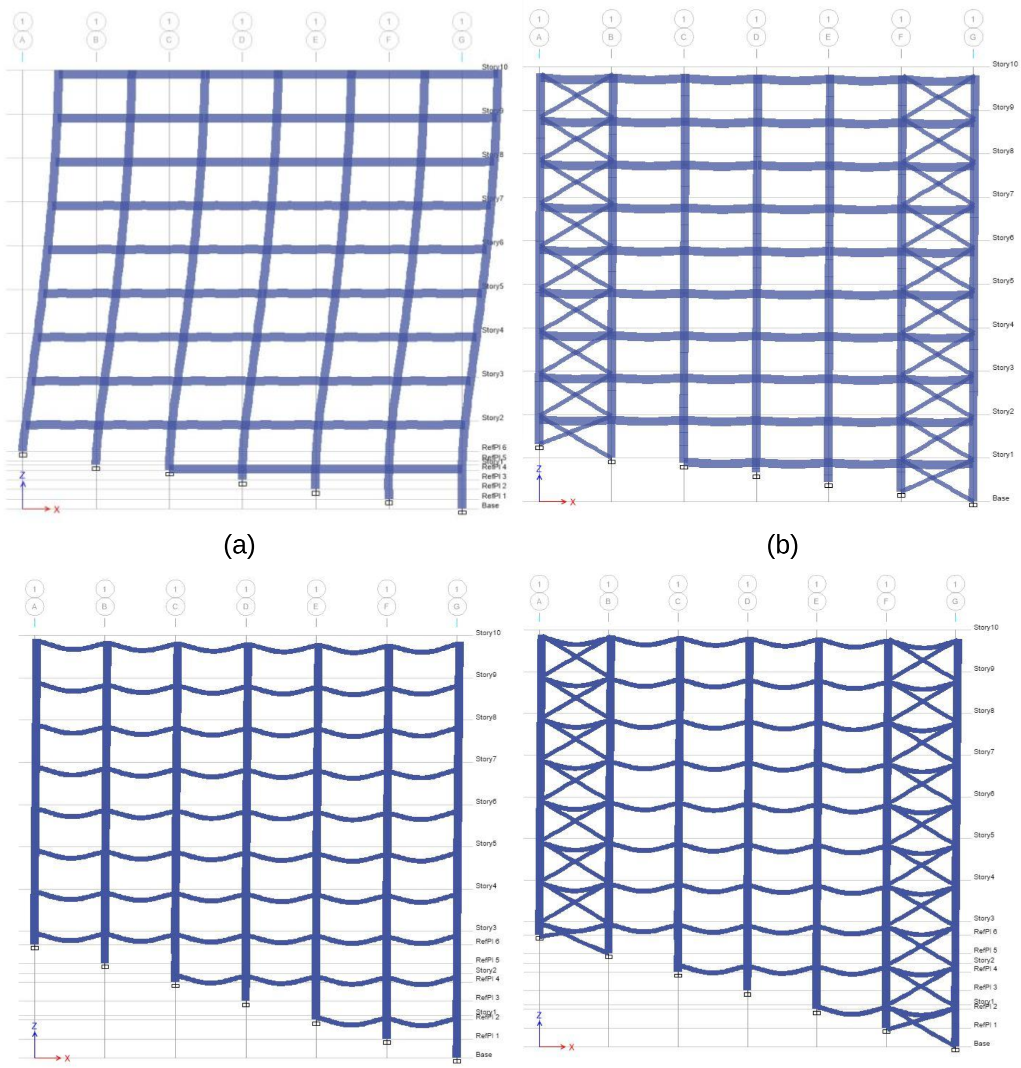
(a) (b)

Fig. 13. Step back – set back building displacement at x-direction (a) without bracing (b) with bracing



(a) (b)

Fig. 14. Step back – Set back building displacement at y-direction (a) without bracing (b) with bracing



(a) (b) (c) (d)

Fig. 15. Deflected shapes of hill sloped building at (a) 7.5S and (b) 7.5SB (c) 15S and (d) 15SB

The deflected shape of a G+9 structure with and without bracing in a step-back building in zone V for both the x and y directions is shown in Fig. 15. The maximum storey displacement occurs at the topmost storey, which is 7.5° without bracing and 15° with bracing. The results indicate that using X-bracing in the building significantly reduces storey displacement.

5. CONCLUSION

Study conducted to investigate the seismic response of buildings constructed on slopes. The study found that step back and step back-set back buildings with and without bracing show significant differences in their performance when subjected to seismic activity. The study also highlights the architectural and environmental benefits of step back and step back-set back buildings, including improved ventilation, enhanced aesthetics, and increased energy efficiency. Investigating the potential applications of these building techniques could contribute to the development of sustainable architecture and urban design.

Based on the results obtained, we can draw the following conclusions.

- The displacements in both X and Y directions are minimal. However, as the hill slope increases, the displacement increases, and it is maximum at 15°in step back and step back-setback structures. The addition of bracing in the building drastically reduces the lateral displacement, ensuring the safety of the structures.

- When structures are subjected to bracing on the corners of buildings with hill slopes, the value decreases, thus affecting the overall behaviour of the structures. As the number of stories increases, the displacement of both step back and step back-setback buildings increases.
- In step back buildings, the stiffness of the storey increases to a maximum at 30° as the hill slope increases. When bracing is used, the stiffness decreases due to the base shear of the building. In step back-setback buildings, the maximum stiffness is at 7.5° and shifts to 15° with bracing due to the reduction of the structure.
- As the storey height rises, the displacement increases, causing storey drift. In step back structures, the hill slope of 15° has the highest drift value compared to 7.5° and 15° in step back-setback buildings. However, when we add bracing, the storey drift value starts decreasing for all hill slopes.
- Buildings with bracing have a decreased value of storey stiffness and storey displacement, which helps move towards the safety of the building.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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