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Seismic Analysis of Multistorey Building on Sloping Ground Using NBC 105:2020

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Abstract

The purpose of this study is to investigate the seismic behavior of RC buildings in steep or sloping terrain. It has been investigated how the structure responds dynamically in slope ground. Nearly seven distinct structural arrangements have been investigated. Three of them are step-back and set-back, three of them are step- back and one is Building on flat land. This structural configuration comprises buildings constructed at varying slope angles 0^o (flat ground), 15^o, 25^o and 35^o. The complete building configuration under consideration is stimulated using ETABS v22.0.0, and NBC 105:2020. The response spectrum is then analyzed using comparable static analysis methodologies. The buildings under consideration were then compared in terms of fundamental time period, top storey displacement, drift, and story stiffness. The seismic behavior of structures on flat ground differs from that of structures on steep terrain (sloping ground). The fundamental time period of vibration and base shear has decreased with increase in slope. However, higher slopes result in large stiffness variations across storeys, increasing the risk of torsional effects and soft-storey formation. The study shows that steeper slopes significantly reduce seismic base shear but introduce other structural challenges like torsional effects, irregular mass distribution, and local stress concentrations that should be carefully considered in design.

***Keywords*:** Slope land, Hilly areas, Step-back configuration, Step-back & Set-back configuration, Response spectrum method

1. Introduction

Nepal, a country characterized by rugged mountainous terrain and hilly topography, has witnessed rapid urban expansion in recent decades. Due to the scarcity of flat land, a significant portion of urban and rural settlements is built on sloping ground. Cities such as Kathmandu, Pokhara, Dharan, and other hilly regions have seen a surge in multistorey buildings constructed on slopes to accommodate the growing population[1]. However, Nepal is located in highly active seismic zone so the performance of such buildings under large earthquakes is a major concern. While designing, it must be noticed that structures on inclines are not the same as those in plain land, i.e. they are exceptionally unpredictable and unsymmetrical in flat and vertical planes[2]. The building on the sloping ground suffered disproportionate damage during devastating Gorkha Earthquake of 2015 (Mw 7.8)[3].

Building performance and structural behavior during seismic occurrences are greatly impacted by the special difficulties that sloping terrain presents. Previous studies shows that the buildings situated on hill slopes in earthquake prone areas are generally irregular, torsionally coupled & hence, susceptible to serve damage when affected by earthquake ground motion [2][4] [5]. The distribution of mass and stiffness along each floor of multi-story building is non-uniform throughout the height of the buildings[6] [7]. If these factors are not adequately addressed, they can intensify seismic pressures and result in catastrophic failures. In order to better understand how various slope geometries, soil characteristics, and structural configurations affect a building's performance under seismic stresses, this study intends to examine the seismic response of multi-story buildings situated on sloping sites using NBC 105:2020.

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2. Objectives of the study

I. To study the seismic behaviour of different building configurations on sloping ground such as step back, set-back step-back and set back buildings.
II. To determine and compare the performance of building on sloping and plane ground.
III. To study the behaviour of buildings with increasing slope in terms of parameters like stiffness, mass, Time period, base reaction, Storey Displacement.

3. Methodology

The buildings constructed on hill slope generally follows two configurations[5];

- Step-Back: Buildings on slopes have their foundations at different levels, with the structure stepping back as it ascends the slope. (as shown in figure 2(a)).
- Step-Back & Set-Back: Buildings on slopes may also have setbacks to accommodate the terrain and provide stability (as shown in figure 2(b)).

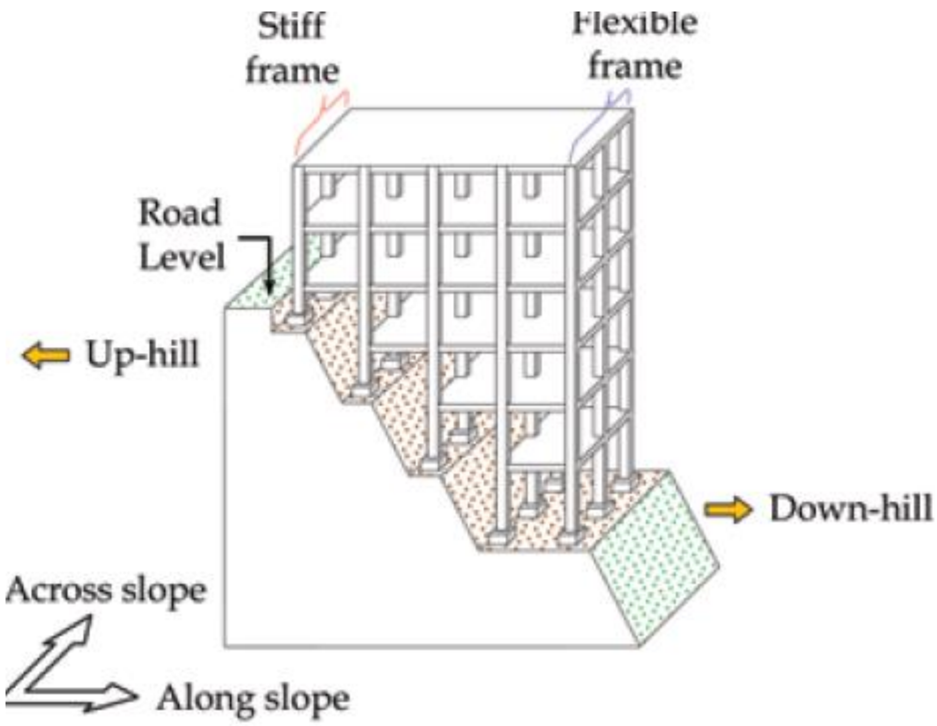
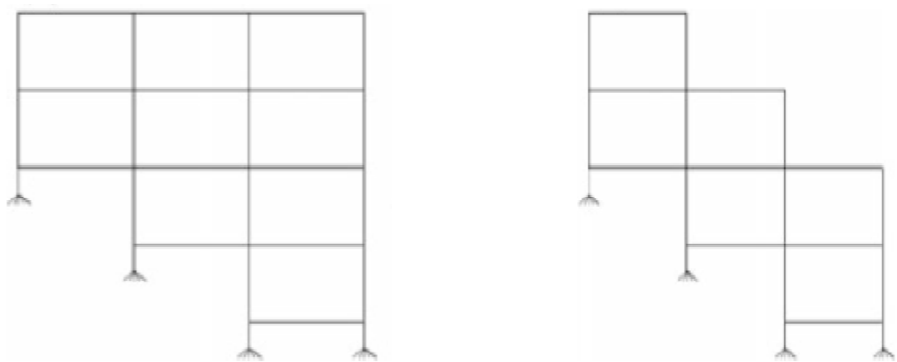


Figure 1 Step back configuration of building on sloping ground [8]



(a) (b)

Figure 2 Step back configuration b) Step-back and set-back configuration

For this study, seven-story reinforced concrete structures, including Step-Back and Step-Back & Set-Back buildings, on level and sloping terrain are taken into consideration. From NBC 105:2020[9], the RC Bare frame is designed with Soil Type D—Very Soft Soil Sites—in consideration. The buidings were analyzed using finite element software ETABS V22, and earthquake load is taken from response spectrum analysis as specified in NBC 105:2020.

3.1. Models considered for analysis

Model 1: Step-back Building on 0^{o} slope land

Model 2: Step-back Building on 15^{o} slope land

Model 3: Step-back Building on 25^{o} slope land

Model 4: Step-back Building on 35^{o} slope land

Model 5: Step-back & Set-back Building on 15^{o} slope land

Model 6: Step-back & Set-back Building on 25^{o} slope land

Model 7: Step-back & Set-back Building on 35^{o} slope land

3.2. Modelling assumptions and limitations:

- The building is modeled as a moment-resisting reinforced concrete (RC) frame structure.
- Foundation flexibility is neglected; supports are assumed as fixed.
- Concrete and steel are assumed to be homogeneous, isotropic, and linearly elastic throughout the analysis.
- All floors are considered rigid in their own planes (diaphragm action is assumed).
- The plan of the building remains the same at all floor levels, and only vertical irregularity due to slope-induced height variation is considered.
- The slope of the ground is assumed uniform along the longitudinal direction.
- The influence of infill walls is neglected in primary analysis (bare frame model) unless otherwise specified.

3.3. Structural specifications

Table 1 Structural Properties and Material Properties

No of storey	7
Size of Building	26.52mX18.29m
Spacing of frames in X direction	4.57m
Spacing of frames in Y direction	4.57m
Size of Beam	300X500mm
Size of Column	500X500mm
Storey height	3.45m
Thickness of slab	140mm
Thickness of wall	230mm
Thickness of shear wall	230mm
Grade of Concrete	M25
Grade of Steel	Fe500

Table 2 Load Intensities [10], [11]

Live load on roof	1.75KN/mm^2
Live load on floor	3KN/mm^2
Floor Finish	1.5KN/m^2

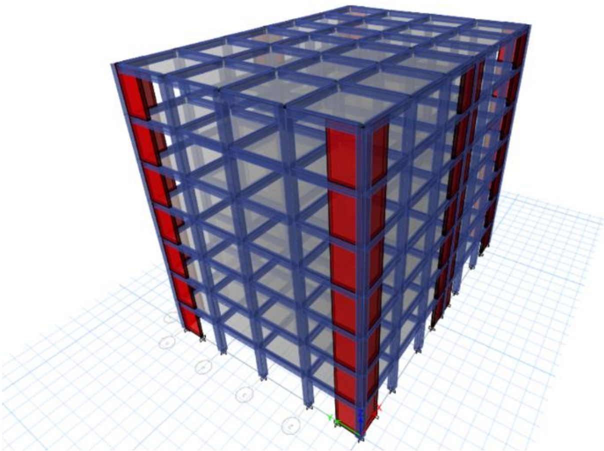


Figure 3.Building at Plain Ground

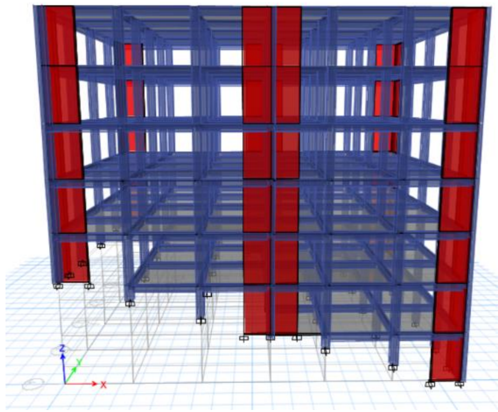


Figure 4.Step-Back Building (15˚)

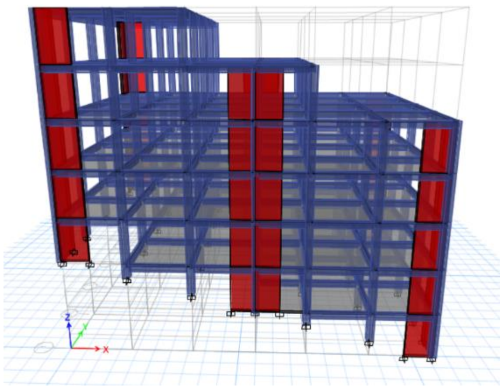


Figure 5.Step-Back & Set-Back Building (15˚)

4. Results and discussion

4.1 Time period

Table 3 Time Period of Step-Back Building

MODE	0°	15°	25°	35°
1	1.038s	0.751s	0.483s	0.303s
2	0.827s	0.576s	0.357s	0.172s
3	0.658s	0.452s	0.271s	0.144s
4	0.277s	0.192s	0.121s	0.107s
5	0.209s	0.142s	0.087s	0.095s
6	0.159s	0.112s	0.073s	0.083s
7	0.126s	0.084s	0.056s	0.071s
8	0.091s	0.065s	0.053s	0.054s
9	0.074s	0.06s	0.043s	0.047s
10	0.068s	0.049s	0.041s	0.046s
11	0.053s	0.045s	0.035s	0.035s
12	0.051s	0.042s	0.033s	0.034s

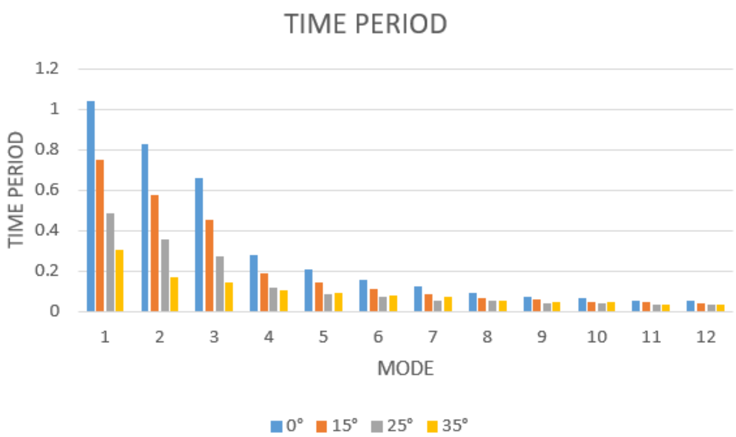


Figure 6 Time Period of Step-Back Building

Table 4 Time Period of Step-Back & Set-Back Building

Step-back & Set-back Building			
Mode	15°	25°	35°
1	0.612s	0.369s	0.208s
2	0.483s	0.285s	0.157s
3	0.379s	0.213s	0.141s
4	0.181s	0.133s	0.097s
5	0.138s	0.095s	0.091s
6	0.109s	0.08s	0.088s
7	0.094s	0.063s	0.075s
8	0.076s	0.058s	0.069s
9	0.073s	0.053s	0.058s
10	0.056s	0.05s	0.051s
11	0.05s	0.036s	0.04s
12	0.048s	0.033s	0.038s

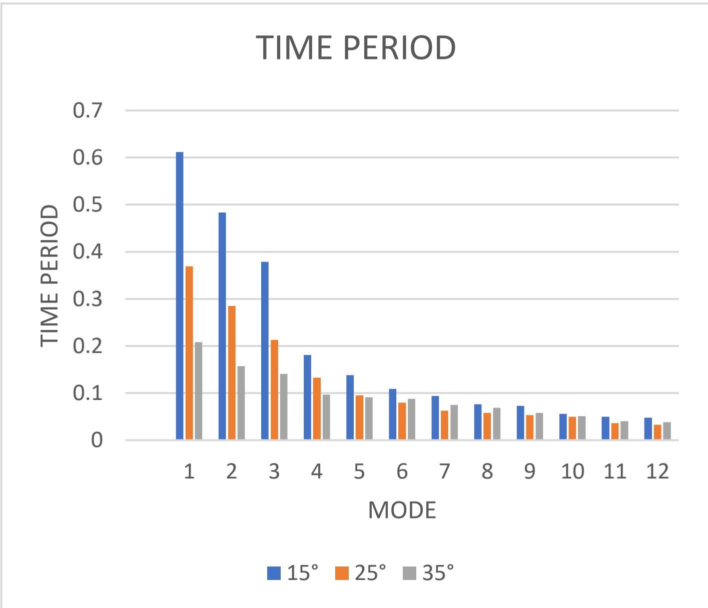


Figure 7 Time Period of Step-Back & Set-Back Building

This result indicates that the time period decreases as the angle of the sloping ground increases. For step-back building, at 0° slope, the second and third modes have significant contributions (0.827s, 0.658s), suggesting dominant lateral swaying motion. At 35° slope, the third mode is reduced to just 0.144s, meaning higher modes could contribute more significantly to the response, increasing localized accelerations and torsional effects. Since higher slopes result in lower periods, the spectral acceleration increases, leading to greater seismic force demand. This explains why steep-slope structures require stronger foundation and lateral load-resisting elements to withstand the increased force. Longer periods (at 0° slope) lead to larger lateral displacements, increasing the risk of soft-storey failures in lower storeys. Shorter periods (at 35° slope) suggest a stiffer structure, which is more prone to brittle failure and requires better energy dissipation mechanisms such as ductile detailing or dampers.

Additionally, the time period of step-back and set-back buildings is shorter compared to step-back buildings alone. This suggests that step-back buildings are more vulnerable than step-back and set-back buildings.

Recent studies on analysis of buildings on sloping ground suggests that

4.2 Maximum displacement

Table 5 displacement for load case EQ_X for step-back building

STOREY	Displacement in x-direction (mm) 0°	15°	25°	35°
F7	54.972	27.27	10.628	2.39
F6	47.121	21.8	7.443	1.565
F5	38.388	15.78	4.152	1.012
F4	28.869	9.636	1.426	0.518
F3	19.118	4.178	0.116	0.124
F2	10.076	1.025	0.079	0.012
F1	3.116	0.005	0.033	0.001
Base	0	0	0	0

Table 6 displacement for load case EQ_Y for step-back building

STOREY	Displacement in y-direction (mm) 0°	15°	25°	35°
F7	85.674	50.915	21.91	8.733
F6	74.692	42.2	16.179	6.269
F5	61.896	32.176	9.895	4.239
F4	47.355	21.286	4.187	2.383
F3	31.909	10.848	0.832	0.908
F2	17.135	3.511	0.108	0.148
F1	5.37	0.101	0.131	0.013
Base	0	0	0	0

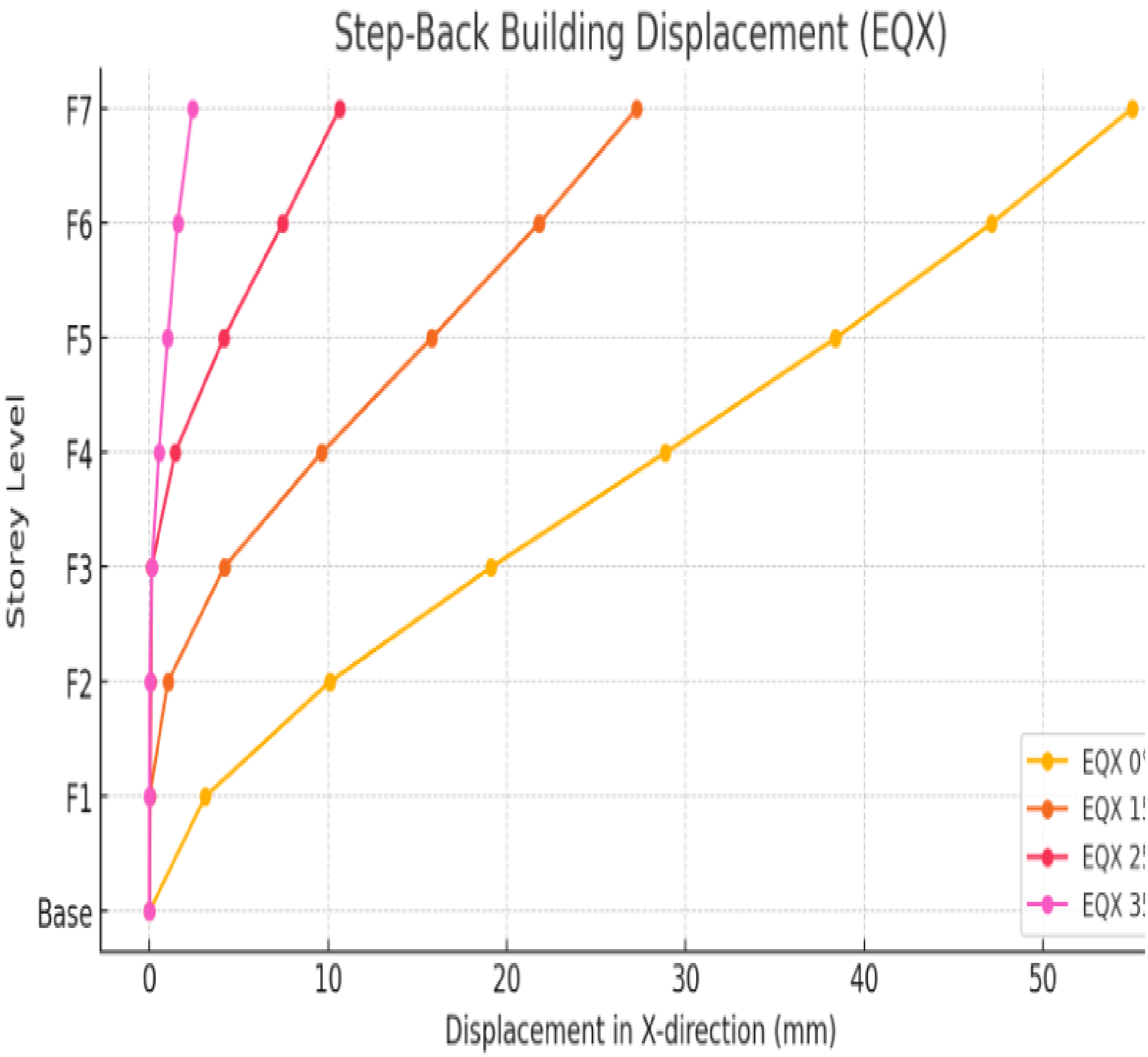


Figure 8 Displacement in various stroey of step-back building in X -direction for varying slope

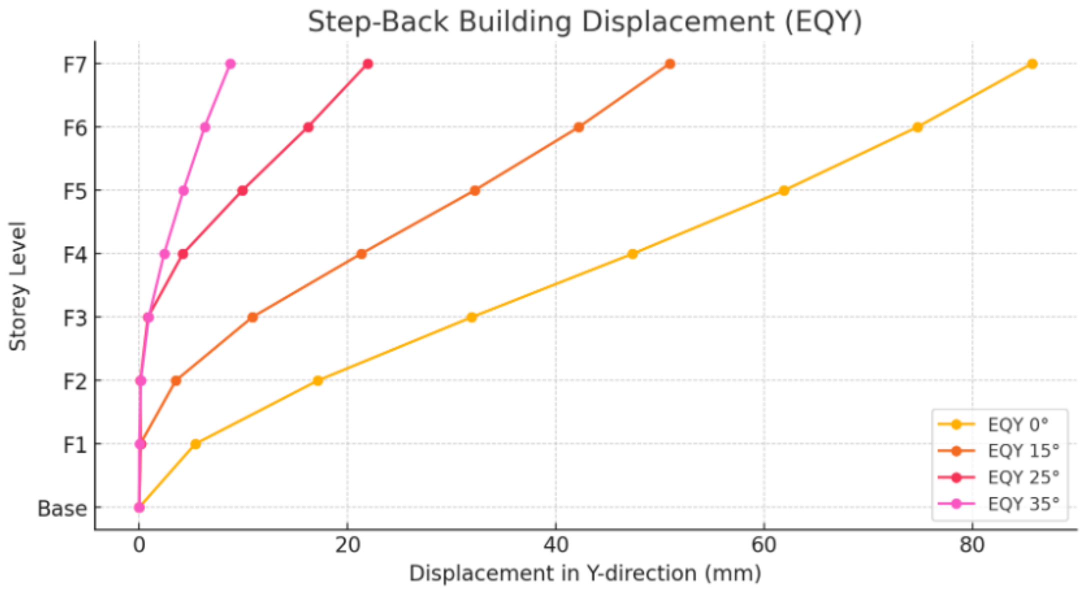


Figure 9 Displacement in various stroey of step-back building in Y -direction for varying slope

Table 7 displacement for load case EQ_X for step-back and set-back building

STOREY	Step-back & Set-back Building (X-direction,mm) 0°	15°	25°	35°
F7	54.972	22.408	8.384	1.969
F6	47.121	17.763	5.601	0.988
F5	38.388	12.797	3.096	0.878
F4	28.869	7.866	1.098	0.517
F3	19.118	3.449	0.1	0.138
F2	10.076	0.864	0.054	0.017
F1	3.116	0.007	0.022	0.001
Base	0	0	0	0

Table 8 displacement for load case EQ_X for step-back and set-back building

STOREY	Step-back & Set-back Building (Y-direction,mm) 0°	15°	25°	35°
F7	85.674	34.868	1.934	3.581
F6	74.692	29.515	1.446	2.397
F5	61.896	23.267	0.954	3.004
F4	47.355	15.413	0.721	1.85
F3	31.909	7.863	0.254	0.777
F2	17.135	2.554	0.014	0.155
F1	5.37	0.076	0.049	0.004
Base	0	0	0	0

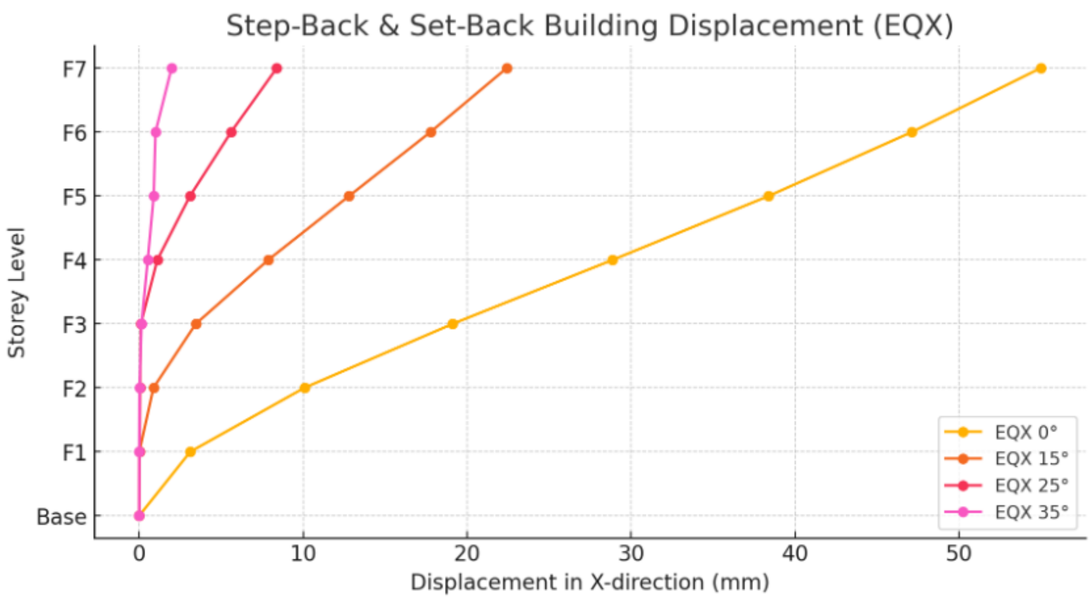


Figure 10 Displacement in various stroey of step-back & set-back building in X -direction for varying slope

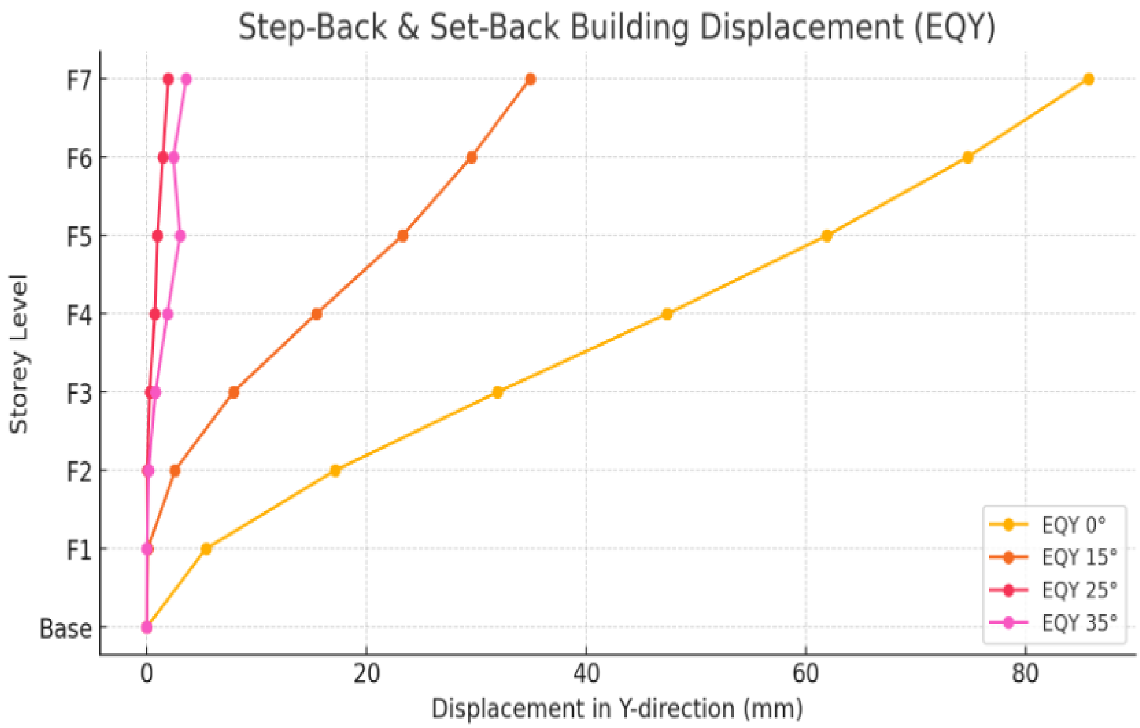


Figure 11 Displacement in various stroey of step-back & set-back building in Y -direction for varying slope

This result shows that the maximum displacement decreases as the angle of the sloping ground increases indicating higher stiffness and lower overall deformation. At 0° slope, the top storey displacement in x- direction is 54.972mm, which reduces to 2.39 mm at 35^{0} slope which is 95.6% reduction. Lower storeys experience minimal displacement at higher slopes due to stiffening effects from shorter columns and foundation influence.

Additionally, the displacement is higher in step-back buildings compared to step-back and set-back buildings. This suggests that the additional setback contributes to better lateral force distribution, reducing displacements.

4.3 Base Shear

Table 9 Seismic Weight of step back and set back building for varying slope

	Seismic Weight of building (kN)			
	0°	15°	25°	35°
Step Back	21579.37	19366.53	16142.84	12860.98
Step back and Set back	21579.37	17030.12	13806.43	10530.61
Reduction in seismic weight (Step back Building)	0.0%	10.3%	25.2%	40.4%
Reduction in seismic weight (Step back and set back Building)	0.0%	21.1%	36.0%	51.2%

The seismic weight of building on flat ground was found to be 21579.37 kN for building on flat ground and with increase in slope the seismic weight of building has been reduced by 40.4% for step back building in inclined slope at 35% whereas the seismic weight of building has been reduced by 51.2% for step back and set back building in inclined slope at 35%. This reduction is seismic weight is very obvious due to decrease in dead load of structure as shown in model presented in Figure 3, Figure 4 and Figure 5.

Table 10 Maximum Base Shear for Step Back building for varying slope

MAXIMUM BASE SHEAR in kN (Step-Back building)	0°	15°	25°	35°
EQx (ULS)	7168.43	5520.56	3308.98	2335.04
Reduction in Base Shear in EQx	0.0%	23.0%	53.8%	67.4%
EQy (ULS)	7172.58	4979.72	3824.45	2630.3
Reduction in Base Shear in EQy	0.0%	30.6%	46.7%	63.3%

Table 11 Maximum Base Shear for Step-Back & Set-back building for varying slope

MAXIMUM BASE SHEAR in kN (Step-Back & Set-back building)	0°	15°	25°
EQx (ULS)	7168.43	4435.01	2153.53
Reduction in Base Shear in EQx	0.0%	38.1%	70.0%
EQy (ULS)	7172.58	4211.34	2578.46
Reduction in Base Shear in EQy	0.0%	41.3%	64.1%

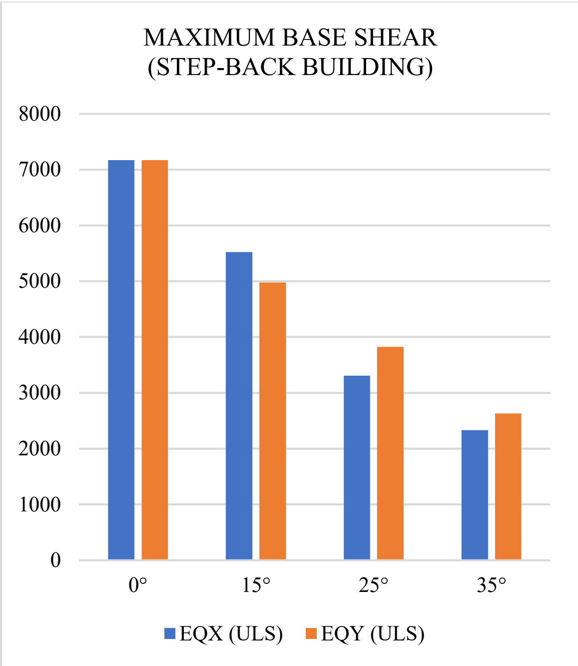


Figure 12 Maximum Base Shear (in kN) in X and Y directions for Step back building at different slopes

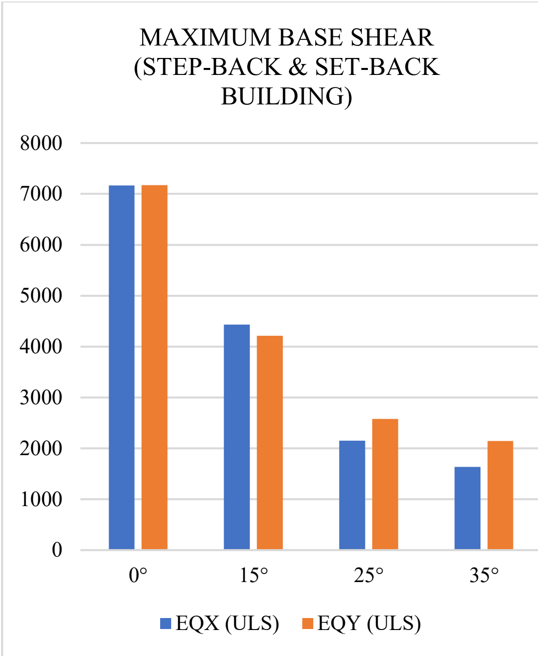


Figure 13 Maximum Base Shear (in kN) in X and Y directions for Step back & Set-back building at different slopes

The maximum base shear for Step-back and Step-back & Set-back building for varying slope is presented is Table 10 and 11 respectively. The base shear of the building in x and y direction at flat land (0° slope) in ultimate limit state (ULS) is found to be 7168.43 kN and 7172.58 kN respectively. As the slope increases from 0° to 35°, there is progressive reduction in base shear in both EQx and EQy directions. The base shear has been decreased upto 67.4% and 63.3% for step-back building at 35° slope in x and y direction respectively whereas the same reduction is found to be 77.2% and 70.1% in x and y direction respectively for Step-back and Set-back building at 35° slope. This decrease in base shear is primarily due to reduction in effective mass of the building while increasing slope but still base shear seems to be significantly reduced in comparison to reduction in seismic weight as discussed in Table 9. Buildings on steeper slopes tend to have a reduced effective mass contributing to base shear, as the structure adapts to terrain constraints. As the slope increases, the height difference between adjacent columns increases, leading to more flexible lateral load paths and reduced seismic demand.

The Step-Back & Set-Back building consistently has a greater reduction in base shear than the step-back building. This suggests that the set-back feature further reduces seismic demand, potentially due to better mass distribution and distribute seismic force more effectively by reducing torsional effects. These results are comparable with recent research findings which have concluded that for construction of the building on slopy ground the step back setback building configuration is suitable[12] [13].

4.4 Stiffness

Table 12 Maximum Stiffness in x- direction for Step-back building for varying slope

STIFFNESS IN X DIRECTION (EQX) Step-back Building				
STOREY	0°	15°	25°	35°
F7	185365.7	243126.543	383453.208	1029523.147
F6	373780.4	498276.686	821800.625	1047690.183
F5	493814.4	699630.527	1372303.187	387960.347
F4	592693.2	961213.847	392069.896	1352497.645
F3	721887.2	121831.973	12658456.11	1121684.181
F2	1000043	638197.272	1886954.647	3716287.392
F1	2338884	232105696	1054219.997	10714954.02
Base	0	0	0	0

Table 13 Maximum Stiffness in y- direction for Step-back building for varying slope

STIFFNESS (EQY) IN Y DIRECTION, Step-back Building				
STOREY	0°	15°	25°	35°
F7	134964.8	165865.472	242013.864	580761.994
F6	259455.7	323682.78	495875.066	20841.482
F5	328116.7	432882.153	813059.695	285035.129
F4	379806	569621.35	227408.168	301481.026
F3	447796	264356.703	1411665.282	21536.73
F2	599383.8	144029.629	25704416.07	1970559.279
F1	1361760	37875650.5	2480829.131	9293830.334
Base	0	0	0	0

Table 14 Maximum Stiffness in x- direction for Step-back & Set-back building for varying slope

MAX STIFFNESS (EQX) IN X DIRECTION Step-back and Setback Building			
STOREY	15°	25°	35°
F7	118771.529	186037.27	430613.426
F6	355494.93	627968.602	4232508.946
F5	646854.088	1382071.162	916688.364
F4	965590.016	211568.135	1854386.552
F3	151452.535	11978408.19	897062.574
F2	458233.204	2019507.456	2563639.702
F1	125477109	850921.762	15089467.32
Base	0	0	0

Table 15 Maximum Stiffness in y- direction for Step-back & Set-back building for varying slope

MAX STIFFNESS (EQY) IN Y DIRECTION Step-back and Setback Building			
STOREY	15°	25°	35°
F7	81852.639	121113.97	308710.02
F6	229219.86	352337.698	3767322.34
F5	402511.276	858153.592	278309.84
F4	583405.776	239730.724	372225.23
F3	256375.372	1320006.084	105825.54
F2	165461.902	8542056.333	1374307.53
F1	36037061.31	2867868.336	35476538.5
Base	0	0	0

Table 12 and 13 shows stiffness distribution of the step-back building in x and y direction respectively and Table 14 and 15 shows stiffness distribution of Step-back and Set-back building in x and y direction respectively. The stiffness of a structure is likely influenced by column height variations, load distribution and dynamic response variations. The analysis results shows that the stiffness generally increases with slope but the values fluctuate inconsistently across storeys. The sharp increase in stiffness suggests that the typical floor acts as major load-resisting element.

While a reduction in base shear is generally considered beneficial, it does not necessarily translate to improved seismic performance. Asymmetry in mass and stiffness along sloping ground leads to torsional response, which can cause excessive deformation in certain part of the building. Moreover, step-back buildings, especially on very steep slopes tend to have taller columns on downhill side, which can behave as a soft-story mechanism during an earthquake.

5. Conclusion and Recommendation:

In this study the seismic parameters like time period, displacement, base shear and stiffness are compared for *Step-back* and *Step-back & Set-back* building in varying sloping ground. Based on the results presented in this study, the following conclusions can be drawn.

- The fundamental period of vibration for first mode decreases from 1.038 sec at 0° slope to 0.308 sec at 35° slope for step-back building and 0.208sec at 35° for Step-back and Set-back building. The progressive reduction in time period with slope suggests that taller, more flexible columns on flatter ground contribute more to lateral flexibility, while on steeper slopes, the shorter, stiffer upper-storey columns dominate the response.

- Displacement decreases significantly with increasing slope, indicating higher stiffness and lower flexibility at steeper slopes.
- Step-Back & Set-Back buildings perform better in controlling displacements than pure Step-Back buildings, but torsional effects remain a concern.
- As the slope increases, the base shear reduces significantly in both the X-direction (EQX**)** and Y-direction (EQY). Buildings on steeper slopes experience lower seismic forces at the base, likely due to reduced mass participation and the concentration of forces at higher levels.
- The Step-Back & Set-Back Buildings experience a higher percentage reduction in base shear than Step-Back Buildings alone. The set-back configuration further redistributes seismic forces, making the structure more stable and reducing seismic demand.
- Higher slopes result in large stiffness variations across storeys, increasing the risk of torsional effects and soft-storey formation.
- The study shows that steeper slopes significantly reduce seismic base shear but introduce other structural challenges like torsional effects, irregular mass distribution, and local stress concentrations that should be carefully managed in design. Irregular mass and stiffness distribution across the height can lead to significant torsional motion, requiring torsional restraint mechanisms. Designers shall consider on addition of shear walls at lower storey to enhance lateral stiffness and minimize stiffness transitions and bracing systems to evenly distribute stiffness and reduce extreme variation between floors.

Recommendation for further study:

- Future research should consider the effects of flexible soil conditions and soil-structure interaction, especially for buildings located on steep or loose sloping terrain, which significantly influence base shear, settlement, and dynamic response characteristics.
- While this study adopts linear analysis methods, future investigations should utilize nonlinear time history analysis using real or synthetic ground motion records to better understand the actual seismic demand and performance of structures on slopes. Future research should incorporate performance-based design methods to evaluate the building's behavior under various performance levels such as Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP).
- Future works could model masonry infill walls using equivalent diagonal struts or nonlinear elements to account for their stiffness contribution and failure behavior during earthquakes.
- A broader parametric study incorporating various plan irregularities (e.g., L-, T-, U-shaped plans), vertical setbacks, and mass/stiffness irregularities may help develop design recommendations specific to buildings on slopes.
- In buildings located on steep hillsides, retaining walls and the lateral earth pressure exerted on basement walls can significantly affect seismic behavior and should be included in future models.

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