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НАУЧНАЯ СТАТЬЯ / RESEARCH ARTICLE

Seismic performance of step back, step back set back and set back buildings in sloping ground base

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Abstract. This paper presents the structural behavior of buildings located in the sloping ground level subjected to seismic load. Three different categories of building from three to five storey are considered for the numerical modelling namely set back building (SB), step back building (SBB) and step back set back building (SBSB). The dynamic response of different buildings are analyzed and compared to assess the seismic vulnerability associated with each buildings. The seismic vulnerability is accessed by comparing the base shear, drift, displacement and torsion factor values. Linear static method is used for the calculation of earthquake load using ETABS. It is observed that SBB and SBSB are highly affected by torsion compared to the SB building. It is desirable to use shear wall in periphery of the bottom storey to improve seismic performance of building. The results in this paper can be employed for construction of buildings with seismically active sloping ground.

Keywords: step back building, step back set back building, set back building, seismic load, sloping ground

Сейсмические характеристики зданий на наклонном основании с колоннами различной высоты

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Аннотация. Рассматривается поведение конструкции зданий, расположенных на наклонном основании, подверженных сейсмической нагрузке. Для компьютерного моделирования выбраны три категории конструкций малоэтажных зданий, а именно: здание с колоннами разной высоты по всему наклонному

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основанию (SBSB), здание с обычными по высоте и укороченными колоннами на наклонном основании (SBB) и аналогичное здание на плоском основании с колоннами одинаковой высоты (SB). Динамические отклики этих типов конструкций рассчитывались и сравнивались для оценки сейсмической устойчивости каждого здания. Сейсмическая устойчивость определялась сравнением значений сдвига, дрейфа, смещения и коэффициента кручения у основания. Линейный статический метод использовался для расчета сейсмической нагрузки в программе ETABS. Замечено, что конструкции SBB и SBSB сильно подвержены кручению по сравнению с конструкцией SB. Желательно использовать диафрагму жесткости по периметру нижнего этажа для улучшения сейсмических характеристик здания. Полученные результаты могут быть применены при проектировании зданий на сейсмически активном наклонном основании.

Ключевые слова: здание с уступом, SBB, SBSB, SB, сейсмическая нагрузка, наклонное основание

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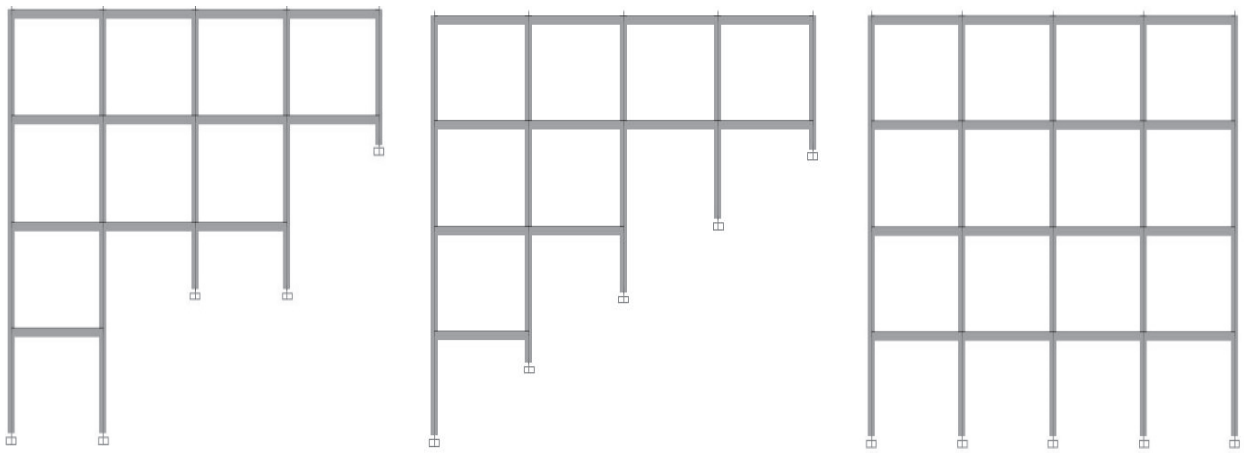
Introduction

During earthquake the seismic waves are more catastrophic to the building constructed with sloping ground foundation. Due to the terrain and geography, it is most likely that the buildings are constructed on the sloping ground with foundations at different levels. The buildings constructed in hilly regions are broadly classified as: (a) step back building (SBB), where the buildings of more than one storey height are constructed in the terraced land; (b) step back set back building (SBSB), where buildings are constructed in the pure sloping ground; (c) set back building (SB), where the buildings are constructed on the plane surface prepared by cutting the hill slope. Figure 1 shows SBB, SBSB and SB type of building constructed in sloping ground. When subjected to ground motion, such buildings constructed in masonry with mud mortar/cement mortar without conforming to code provisions have proved unsafe and resulted in loss of life and property [1]. Field reconnaissance of 3500 buildings of various types, after 2015 Gorkha earthquake, it was found that RC buildings failures were more attributed to soft story, pounding, shear failure and lack of symmetry in buildings [2]. Such buildings are more at risk, because the column of the building rest at different levels of the slope, causing irregularities in the structure. Dynamic characteristics of the buildings on flat ground differ to that of buildings on slope ground as the geometrical configurations of the building differ horizontally as well as vertically. The natural period of building decreases as the slope of the ground increases and short column resists almost all the storey shear as long columns are flexible and cannot resists the loads [3]. Also, the irregular building has the higher time period in linear static analysis [4]. The buildings in the sloping foundation produce the torsional effect as the center of mass and center of stiffness does not coincide with each other [5]. In addition to the torsion, building in the sloping ground generally experiences the short column effect which increases the vulnerability of the structures. Similarly with the increase in the column stiffness the axial force and base shear also increases in the building [6]. The increase in the storey height and number of bays will also have impact in the shear and longitudinal reinforcement of the structure [7].

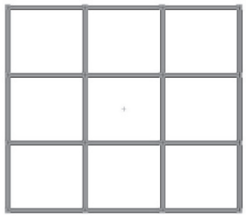
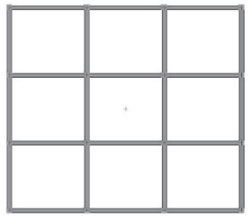
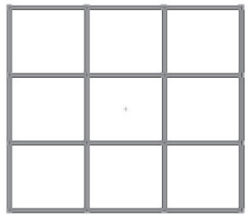
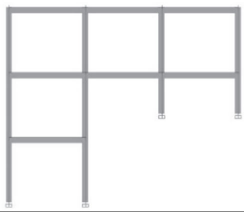
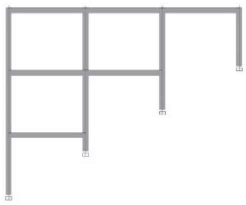
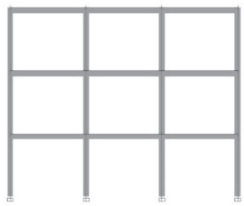
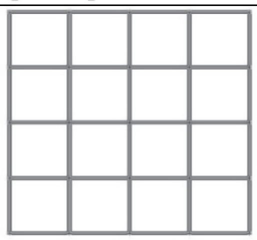
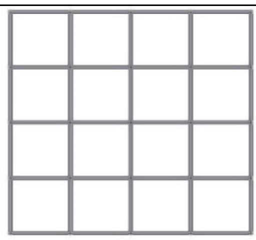
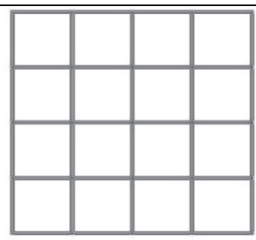
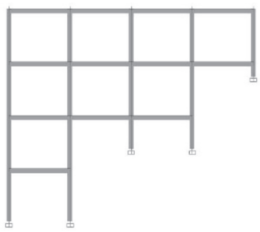
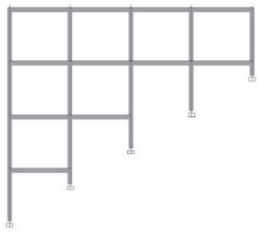
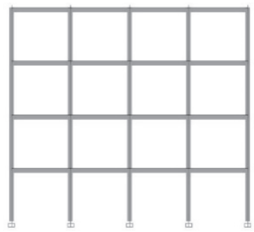
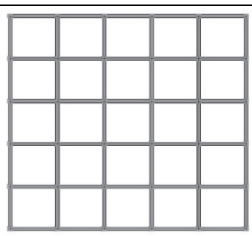
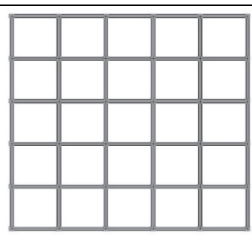
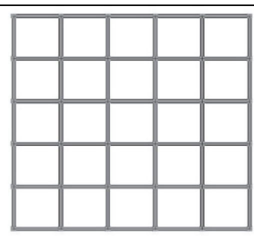
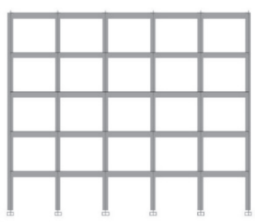
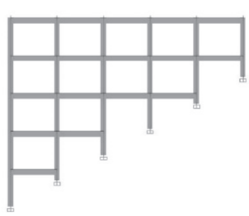
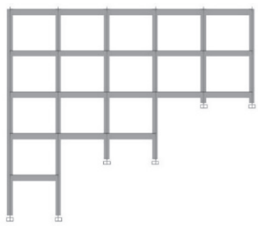


a *b* *c*

Figure 1. Different types of building in slope ground:
a – SBB; *b* – SBSB; *c* – SB

Table 1

SBB, SBSB and SB for different storey building

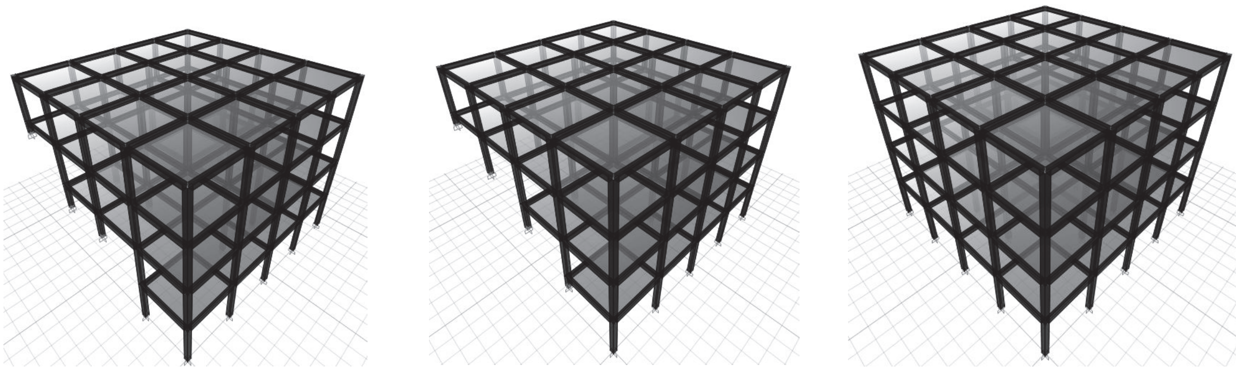
Building type	**SBB**	**SBSB**	**SB**
Plan for three storey			
Elevation for three storey			
Plan for four storey			
Elevation for four storey			
Plan for five storey			
Elevation for five storey			

Earthquake impact have amplified the problem of landslide and erosion in the hilly regions thus all residential, educational, hospital and commercial buildings in the hilly regions must be analyzed for the seismic loads. The buildings must be designed to resist the seismic waves to prevent the loss of life and property. The upcoming section of the paper discuss the seismic behavior of the differently configured buildings on hill slopes followed by the comparison of seismic behavior of hill buildings with regular buildings on the plane slope.

In this study a RC framed residential building having regular rectangular shape in plan is considered for analysis. SBB, SBSB and SB building type with three, four and five storey is consider in the modelling. For the regularity of the structure, the three-storey building consists of three bays in *x* and *y* direction, similarly four storey building consists of four bays in *x* and *y* direction and five storey building consists of five bays in *x* and *y* direction. Center to center distance between the columns in each bay is 3.9 m in both *x* and *y* direction, for all the models consider in the analysis. The plan and elevation of the building considered for the analysis is shown in Table 1. The RC beams and columns are model as three-dimensions frame elements with centerline dimensions. The rigid zone factor for beam and column joint are assign as one. The area loads is applied on slabs (model as rigid diaphragm in each storey), and non-uniform soil pressure is applied to shear walls, which are assign with pier label in model. Bracing width and thickness is taken same to wall thickness of 230 mm. Foundation is model as isolated footing in fixed condition at the base, as soil foundation interaction is not considered in present study. Regular building model was design as per[1], with torsion consideration, using different load combinations. Normal static and dynamic load combinations consist of 13 load combinations, to study the torsional effect additional 12 load combinations are adopted by considering the eccentric load combinations, making up of total 25 load combinations.

Numerical modelling

Numerical simulation of the buildings is performed by using ETABS software. Figure 2 shows the 3D diagram of the building considered for the design. Elevation geometry for SBB and SBSB are considered assuming the 30° slope to the natural level of ground. The buildings are modelled as RC frame structure. M20 grade of concrete and Fe 500 reinforcement bar is considered in the modelling. The properties of concrete and reinforcement bars used in modelling are as shown in Tables 2 and 3 respectively. Basic parameters of building models for different storey is shown in Table 4.



a *b* *c*

Figure 2. 3D model of the buildings considered in the modelling:
a – SBB; *b* – SBSB; *c* – SB

Table 2

Material properties of M20 grade of concrete

Weight per unit volume ρ	25 kN/m^3
Modulus of elasticity *E*	22360.68 N/mm^2
Shear modulus *G*	9316.95 N/mm^2
Poisson ratio ν	0.2
Coefficient of thermal expansion α	5.5×10^{-6}

Table 3

Material properties of Fe 500 grade of rebar

Weight per unit volume ρ	76.9729 kN/m^3
Modulus of elasticity *E*	2×10^5 N/mm^2
Shear modulus *G*	76923.08 N/mm^2
Poisson ratio ν	0.3
Coefficient of thermal expansion α	1.17×10^{-5}
Minimum yield stress f_y	500 N/mm^2
Minimum tensile stress f_u	545 N/mm^2

In the present study, building sole purpose is residential. Table 5 shows the loading and its pattern used in the analysis as per IS 875 (Part 2): 1987 and IS 1893 (Part1): 2016. In the analysis the soil pressure is applied as non-uniform loads in the shear wall. The soil pressure on the building demands the shear wall which is considered in the modelling of the building. Additional analysis is performed in five storey building for the cases with and without shear wall. The results for the same are discussed in the next section. The load in the shear wall is applied as per considerations made in Figure 3.

[1] IS 1893 (Part 1). *Criteria for earthquake resistant design of structures.* New Delhi: Bureau of Indian Standards; 2016.

Table 4

Basic parameters of building models for different storey

Parameters	Values	Unit	Remarks
Number of storey	3, 4,5	–	
Storey height	3.3	m	For all models consider
Column size for three-storey and four storey building	300×300	mm×mm	
Column size for five- storey building	450×450	mm×mm	
Beam size for three-storey and four storey building	300×225 (*D*×*b*)	mm×mm	
Beam size for five-storey building	500×300 (*D*×*b*)	mm×mm	
Slab depth	125	mm	For all models
Shear wall thickness	200	mm	For all models consider
Seismic zone *Z*	*V*	–	Zone factor = 0.36 (IS 1893 (Part 1): 2016)
Importance factor *I*	1	–	AS per IS 1893 (Part 1): 2016
Frame system	SMRF	–	Response reduction factor = 5, as per IS 1893 (Part 1): 2016
Soil type	Medium	–	Angle of friction 30° and unit weight 20 kN/m^3 [8]

Table 5

Loads considered in the analysis of buildings

Parameters	Value	Unit	Mass source for analysis, %	Remarks
Imposed load on floor	2	kN/m^2	25	For all cases of buildings
Imposed load on roof	1.5	kN/m^2	0	For all cases of buildings
Floor finish	1.0	kN/m^2	100	For all cases of buildings
URM infill wall load	10	kN/m	100	External wall load
URM infill wall load	6	kN/m	100	Internal wall load
Soil pressure	Applied as non-uniform loads in shear wall			

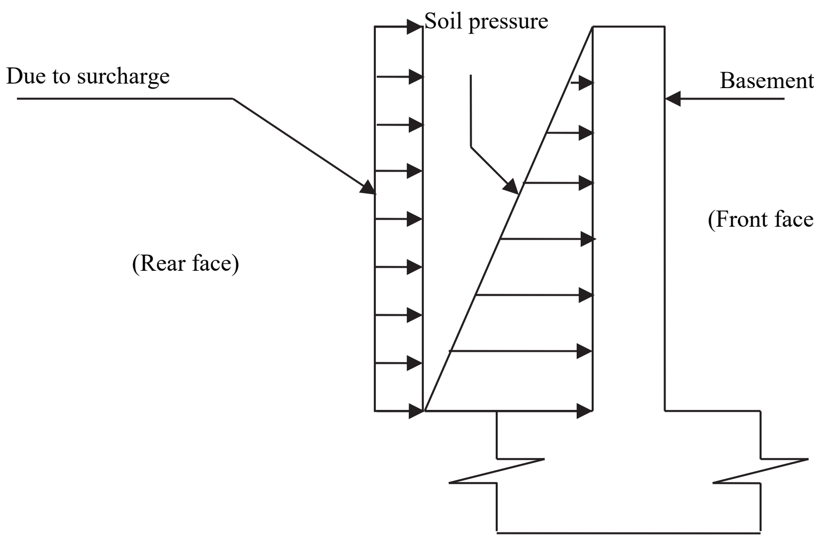


Figure 3. Soil pressure in shear wall

The seismic coefficient method (Lateral static method) is one of the static procedures for earthquake resistant design of structures. Horizontal forces are calculated as products of the seismic coefficients and weight of the structures. Design parameters depends upon the shear computation, which again depends upon the seismic weight and fundamental time period of the structure. Response reduction factor R accounts for both damping and ductility of structure. The fundamental time period is calculated based on code-based formula. This method is recommend and specified in various seismic design code, including IS 1893 (Part1): 2016, which is detail below.

The design base shear V_b along any principal direction of a building shall be determined by

$$V_b = A_h \times W,$$

where A_h – design horizontal acceleration coefficient value using approximate fundamental natural period; W – seismic weight of building.

Also,

$$A_h = \frac{Z}{2} \times \frac{I}{R} \times \frac{S_a}{g},$$

where $\frac{S_a}{g}$ is the design acceleration coefficient, $\frac{S_a}{g}$ depends on fundamental time period T, where $T = 0.075h^{0.75}$; h – the height of building as defined in IS 1893 (Part1): 2016; R – response reduction factor; I – importance factor; Z – zone factor.

Similarly design lateral force at i^{th} floor is given by

$$Q_i = \left(\frac{W_i h_i^2}{\sum_{j=1}^{n} W_j h_j^2}\right) V_B,$$

where Q_i – design lateral force at floor i; W_i – seismic weight of floor i; h_i – height of floor i measure from base.

Results and discussions

Analysis of the three dimensions structural models as explained in previous section is completed using ETABS. The results are analyzed for the dynamic response property and seismic vulnerability associated with each of the building models are them are studied. The results are presented in the form of table to thoroughly understand the behavior and draw conclusion for their suitability.

Comparison of base shear. Base shear is the estimate of the maximum expected lateral force that will occur due to seismic ground motion at the base of the structure and is the sum of all the storey lateral force above. Base shear depends upon building weight, building stiffness and the distance from the fault. Base shear is directly proportional to building weight. Building stiffness has the ultimate effect on base shear. Building stiffness generally represents how flexible or stiff the building is. Greater the flexibility of building higher is the natural period and lower is the base shear and vice versa. Greater is the base shear if the fault is near the building. Thus, as shown Table 6, base shear associated with SB building is greater than SBB and SBSB for each storey. Similarly SBB buildings base shear is greater than SBSB buildings. Higher the number of storey greater is the total design lateral force.

Table 6

Base shear at each floor of buildings

Base shear of each floor, kN		**SBB**		**SBSB**		**SB**	
	Storey No.	***x***	***y***	***x***	***y***	***x***	***y***
Three storey building	3	154.95	154.95	83.10	83.10	181.65	181.65
	2	287.20	287.20	58.52	46.51	335.60	335.60
	1	54.79	27.09	24.04	12.47	374.09	374.09
Four storey building	4	120.57	120.57	120.57	120.57	308.41	308.41
	3	120.57	120.57	120.57	120.57	663.20	663.20
	2	11.09	1.14	9.52	1.78	820.89	820.89
	1	2.08	0.31	3.86	0.69	860.31	860.31
Five storey building	5	472.36	472.36	472.59	472.59	549.40	549.40
	4	702.88	702.88	703.57	703.57	1194.33	1194.33
	3	702.88	31.36	416.21	296.45	1557.10	1557.10
	2	6.24	4.47	37.32	5.96	1718.33	1718.33
	1	1.01	4.47	13.42	3.37	1758.64	1758.64

Comparison of displacement. Table 7 shows the maximum displacement of each floor of different building models. SB shows higher displacement at all the storey, due to seismic force in both x and y direction. It is due to higher mass associated with SB building, which results in greater lateral force. Similarly, SBB building has greater displacement at different storey than SBSB. In addition building height for analysis are taken from the top most ground level for SBB and SBSB models, which significantly reduces the building height as per IS 1893: 2016.

Table 7

Displacement at each floor of buildings

Displacement of each floor, mm		**SBB**		**SBSB**		**SB**	
	Storey No.	***x***	***y***	***x***	***y***	***x***	***y***
Three storey building	3	11.32	7.89	4.33	2.68	25.34	25.34
	2	6.33	3.33	1.93	1.03	18.90	18.90
	1	2.65	1.34	0.21	0.10	8.40	8.40
Four storey building	4	2.83	2.06	2.80	2.05	46.46	46.46
	3	1.02	0.32	0.99	0.32	39.91	39.91
	2	0.31	0.02	0.29	0.01	27.28	27.28
	1	0.10	0.01	0.03	0.00	11.71	11.71
Five storey building	5	3.555	3.126	3.658	2.304	18.068	18.068
	4	2.245	1.843	2.312	1.104	16.316	16.316
	3	0.525	0.203	0.734	0.169	12.892	12.892
	2	0.093	0.03	0.192	0.005	8.382	8.382
	1	0.019	0.019	0.017	0.001	3.507	3.507

Comparison of storey drift. Storey drift is the displacement of one level relative to the other level above or below and when divided by floor height it is called drift ratio, as per codal provision of IS 1893 (Part 1): 2016 clause 7.11, drift ratio should be limited to 0.4%, for building model as bare frame, in analysis. All the buildings pass the drift category and SB has greater drift ratio compared to others and SBB has greater drift than SBSB as shown in Table 8.

Table 8

Storey drift at each floor of buildings

Drift of each floor, %		**SBB**		**SBSB**		**SB**	
	Storey No.	***x***	***y***	***x***	***y***	***x***	***y***
Three storey building	3	0.151	0.138	0.073	0.050	0.195	0.195
	2	0.112	0.060	0.052	0.028	0.318	0.318
	1	0.080	0.041	0.007	0.003	0.255	0.255
Four storey building	4	0.0550	0.0525	0.0550	0.0526	0.1985	0.1985
	3	0.0215	0.0093	0.0211	0.0095	0.3829	0.3829
	2	0.0064	0.0006	0.0079	0.0002	0.4716	0.4716
	1	0.0029	0.0002	0.0008	0.0001	0.3550	0.3550
Five storey building	5	0.0397	0.0389	0.0408	0.0364	0.0532	0.0532
	4	0.0521	0.0497	0.0481	0.0283	0.1037	0.1037
	3	0.0131	0.0069	0.0164	0.005	0.1367	0.1367
	2	0.0022	0.0003	0.0053	0.0002	0.1479	0.1479
	1	0.0006	0.0006	0.0005	2.61×10^{-05}	0.1063	0.1063

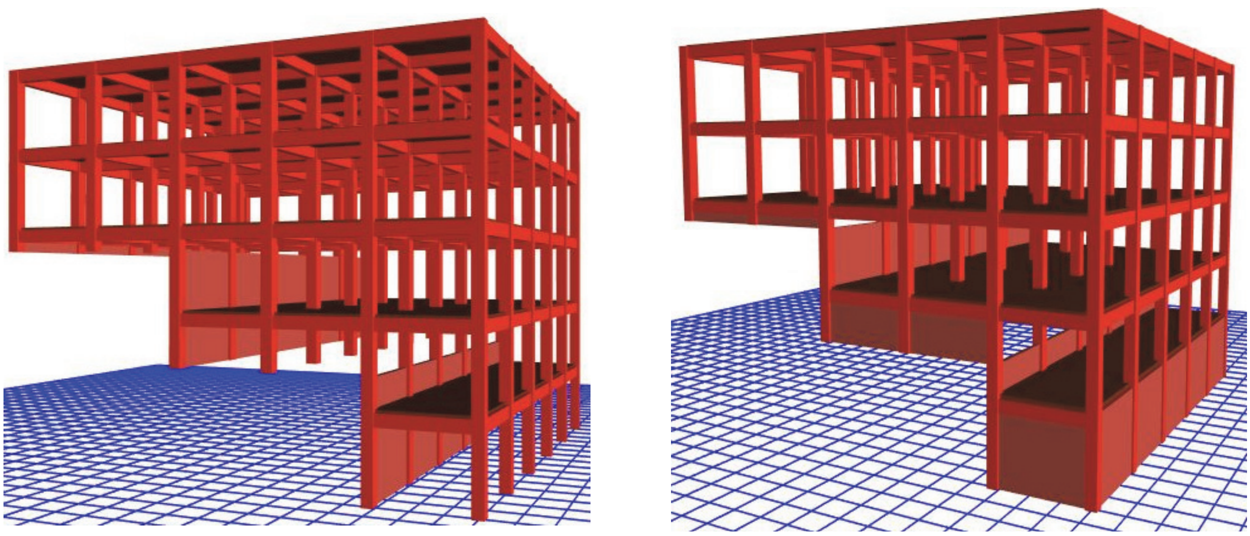
Comparison of permissible torsion factor. Buildings in sloping ground are subjected to torsion during earthquakes due to their irregular mass and stiffness distribution in horizontal or vertical plane. This torsion cause excessive shears in members that cause damage to the member, therefore study of torsion for buildings in sloping ground is very important. According to IS 1893:2016, for torsion factor within the range of 1.5 to 2, configuration should be adjusted to ensure natural period of the fundamental torsional made of oscillation shall be smaller than those of the first two translation modes and 3D dynamic analysis should be performed. If torsion factor exceeds 2, the configuration has to be revised, so a torsion factor below 1.2 for hill areas can be permissible. From Table 9 it is observed that SB buildings are safe against torsion action as every floor of each storey has torsion factor below 1.2 for both x and y direction. Whereas in both SBB and SBSB buildings values exceeds 1.2 and even 1.5 especially in middle floor level. For both of these buildings, higher the number of storey higher is the torsion, also it is observe that torsion is higher in cross-slope direction than in across slope direction. SBB buildings shows higher torsion factor compare to SBSB, making it more vulnerable against torsion as detailed in Table 9.

Table 9

Torsion factor at each floor of buildings

Torsion of each floor		**SBB**		**SBSB**		**SB**	
	Storey No.	***x***	***y***	***x***	***y***	***x***	***y***
Three storey building	3	1.36	1.11	1.5	1.09	1.02	1.02
	2	1.54	1.11	1.4	1.01	1.03	1.03
	1	1.14	1.11	0.74	1.14	1.03	1.03
Four storey building	4	1.21	1.03	1.20	1.032	1.05	1.05
	3	1.61	1.05	1.6	1.04	1.05	1.05
	2	1.72	1.25	1.41	1.42	1.05	1.05
	1	1.19	1.2	1.23	1.33	1.05	1.05
Five storey building	5	1.00	1.05	1.38	1.05	1.05	1.05
	4	1.04	1.06	1.56	1.06	1.06	1.06
	3	1.51	1.08	1.67	1.14	1.06	1.06
	2	1.93	0.98	1.67	1.11	1.06	1.06
	1	1.36	0.973	1.21	1	1.06	1.06

From the above comparison of results, it is found that SBB can be fatal than the other buildings in case of active lateral forces in building due to seismic waves. Short column is the adversely affected member in this building with higher axial and shear force, demanding more reinforcement. Some of the methods to improve the seismic behavior of SBB could be to increase the grade of concrete or increase the size of members. The present study, however, focus in the action of shear wall along the across slope of building, at periphery of the building and bracing using concrete. Figure 4 shows the 3D model using shear wall and Figure 5 shows the 3D model using bracing considered for analysis and comparison. The results of the modelling are shown in Table 10.



a *b*

Figure 4. Shear wall in SBB:
a – shear wall along earth pressure side only; *b* – shear wall along whole building

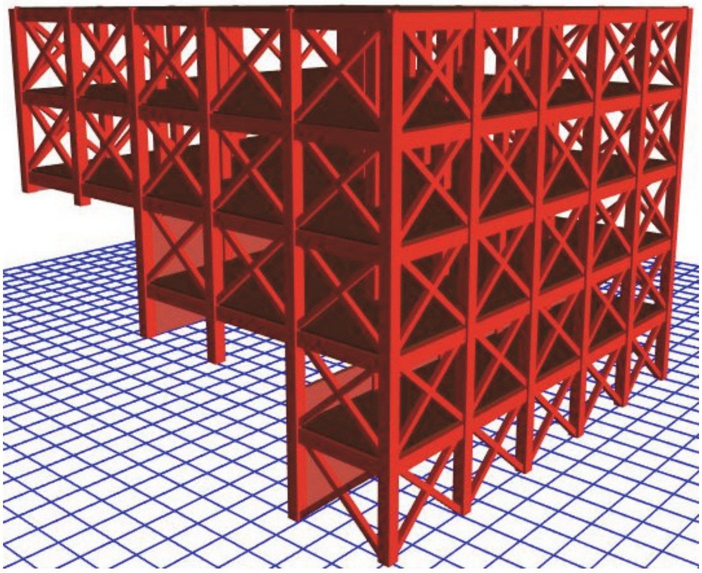


Figure 5. Bracing in SBB

Table 10

Results of SBB with shear wall and bracings

		Step back buildings		Shear wall across slope only		Shear wall along whole building		Bracing	
	Storey	***x***	***y***	***x***	***y***	***x***	***y***	***x***	***y***
Base shear, kn	1	472.36	472.36	472.36	472.36	472.36	472.36	496.68	496.68
	2	702.88	702.88	702.88	702.88	702.88	702.88	739.37	739.37
	3	702.88	31.36	702.88	702.88	702.88	702.88	739.37	739.37
	4	6.24	4.47	92.64	–40.14	83.62	83.45	236.49	42.03
	5	1.01	4.47	2.30	–4.24	1.82	0.42	112.51	3.58
Displacement, mm	1	3.555	3.126	3.428	3.058	3.01	2.835	0.72	0.564
	2	2.245	1.843	2.113	1.777	1.712	1.566	0.52	0.372
	3	0.525	0.203	0.395	0.16	0.1	0.044	0.239	0.103
	4	0.093	0.03	0.048	0.029	0.013	0.009	0.123	0.048
	5	0.019	0.019	0.005	0.016	0.001	0.003	0.037	0.017
Drift ratio, %	1	0.053	0.053	0.040	0.039	0.039	0.038	0.006	0.006
	2	0.104	0.104	0.052	0.049	0.049	0.046	0.009	0.008
	3	0.137	0.137	0.011	0.006	0.003	0.002	0.004	0.002
	4	0.148	0.148	0.001	0.000	0.000	0.000	0.003	0.001
	5	0.106	0.106	0.000	0.001	0.000	0.000	0.001	0.001
Torsion factor	1	1.002	1.054	1.17	1.051	1.105	1.051	1.25	1.03
	2	1.04	1.0574	1.24	1.053	1.129	1.053	1.349	1.035
	3	1.512	1.083	1.9	1.063	1.54	1.048	1.89	1.056
	4	1.93	0.98	1.77	1	1.091	1.059	1.89	1.091
	5	1.36	0.973	1.43	1.032	1	1	1.61	1.214

Shear wall considerably enhance the rigidity and strength of the frame structure, symmetry in position of shear wall in plan is a key factor to obtain desirable performance of shear wall structure [9]. Arrangement of bracing and it type affects the seismic performance of building, generally it increases the strength if placed accordingly [8; 10]. Form base and storey shear comparison in the present study as shown in Table 10 for SBB 5-story, bracing increases the stiffness of building and thus the base and storey shear of building. Displacement is significantly reduced by bracing, whereas shear wall across slope resisting earth pressure slightly reduce the displacement and story drift of the structure in both the directions. The shear wall along the periphery at the bottom of the structure, not only reduces the storey drift but also is very effective to reduce the torsion factor than bracing as seen in Table 10. The maximum torsion factor is 1.54 compare to 1.89 by bracing. Shear wall across slope only in SBB is not sufficient to reduce torsion effectively.

Conclusion and recommendations

This paper has presented the comparative study of the different types of buildings generally constructed in sloping ground of hilly regions. From the results it is found that SBB buildings is more seismically vulnerable as compared to SBSB and SB buildings. The short columns is the worst effected structural member during the seismic load. Top storey displacement in SB buildings are higher than other two set of buildings due to more mass associated with it then others, which increase lateral force. SB building are less affected by torsion, as they satisfy the codal criteria of torsion, whereas SBB and SBSB building shows excessive torsion, with SBB building having excessive torsion. This study also concludes that the braced SBB and shear wall across slope reduce the overall displacement is found to reduce the effect of short column effectively and improve the overall seismic performance of building. Shear wall across the periphery of the SBB is found effective to reduce both drift and torsion factor in 5-story SBB. Shear wall introduction in periphery of building in SBB has shown grater improvement in seismic behavior of building. Thus, for hillside buildings shear wall must be mandatory provided in the foundation. Shear wall shares the column loads in effective way to reduce the seismic vulnerability associated with hillside buildings.

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