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Seismic Vulnerability of Building on Hill Slope

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Abstract: Due to the scarcity of flat ground, buildings are constructed in the hill area with an irregular structural configuration having foundations at different levels. In this study, the seismic weight of regular building on flat ground is equated to that of the hill building. An analytical study was performed to compare the behaviour of these buildings. The dynamic response of hill building is compared with that of the respective regular building on flat ground in term of fundamental periods of vibration, mode shape, cumulative modal mass participation ratio, forces on member, plastic hinge formation, performance point, plastic hinge formation with base shear action induced in columns and beam of the respective building. From the analysis, based on the time period, modal mass participation ratio, force distribution and formation of plastic hinges in the column it is evident that the regular building on flat ground is flexible than the respective hill slope building.

Keywords: *Step Back Building, Spectrum Compatible Time History, Modal Analysis, Linear Dynamic Analysis, Non Linear Static Analysis*

1. Introduction

Due to the scarcity of flat land in hill area, precede the construction of building on hill slopes. Buildings constructed in hilly slope have peculiar structural configurations having foundations at different levels. Hill buildings constructed in masonry with mud mortar/cement mortar without conforming to code provisions have proved unsafe and, resulted in the loss of life and property when subjected to ground motions (Kumar 1996).

Dynamic characteristic of the building on hill slope notably differs from the building resting on the flat topography as they are irregular and unsymmetrical in horizontal and vertical direction. Further, due to site conditions, buildings on hill slope are characterized by unequal column height within the same story, which causes drastic variation of stiffness at a particular storey. Past earthquakes [e.g. Kangra (1905), Bihar- Nepal (1934 & 1980), Assam (1950), Tokachi-Oki-Japan (1968), Uttarkashi-India (1991)] (Paul et al., 1997), had substantiated the vulnerability of building on the hill slope.

Himalaya came into existence due to the collision of Indian shield with Eurasian/Tibetan Plate, compression and sequential thrusting along major faults such as Main Central Thrust (MCT), Main Boundary Thrust(MBT) and Main Frontal Thrust(MFT) (Mukhopadhyay 2011). Among these thrust MCT in Himalaya is seismically active.

In the Himalayan region, for instance, Gangtok has about 14,000 RC buildings and nearly 65% of these were built in past 15 years (Figure 1(a)). RC construction across the state in general use hand-mixed concrete based on volume batching, no mechanical vibrator, no control on the water-cement ratio, and inadequate curing.

(a) **(b)** **(c)**

Figure 1: *RC frame building in hill slopes built in last 10-15 years (a) Skyline of Gangtok city; (b) Building that lack many desirable earthquake resistant feature; (c) Building that lack many desirable earthquake resistant feature*

These RC constructions are mostly non-engineered and this observation is valid uniformly for housing as well as critical and lifeline buildings and structures. Unregulated development in the Himalayan region indicates that RC frame buildings are constructed without even designing them for gravity loads, resulting in the construction of old fashioned pad foundations, very slender columns and a long typical beam were observed throughout the state (Figure 1(b) and 1(c)). Very few studies (Kumar 1996; Paul et al, 1997; Kumar et al., 1998; Detlof von Winterfeldt et al., 2003; Birajdar et al., 2004; Kumar et al, 1999) have been undertaken in the past to understand the behaviour of buildings on the hill slope. In this study, the seismic behaviour of step back configuration of hill building is compared with that of the regular building on the flat ground.

Nevertheless, the comparative study of the behaviour of these buildings of same mass is still lacking. Hence by equating the seismic weight of the regular building on flat ground to that of the respective hill building, their seismic behaviours were compared by performing a modal analysis and a linear dynamic analysis using spectrum compatible time history.

2. Behaviour of Building in Hill Slope

The behaviour of a building during an earthquake depends on various factors like stiffness, lateral strength and configurations of the building. Buildings in hill slope have a typical structural configuration. Subsequent floors in building step back (Figure 2) towards the hill slope, resulting in unequal column height at a particular storey. This causes stiffness irregularity in both the directions. The steep slope is another common type of structural configuration that is found on hills (Figure 2) where the foundations are provided at two levels.

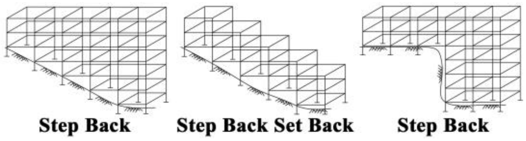

Figure 2: *Hill building configuration*

Building on hill slope with a symmetric plan, when subjected to an earthquake in cross-slope direction; besides stiffness irregularity building is subjected to torsion, due to non-coincident of the centre of stiffness and centre of mass at each floor level. The torsion in these building is more complex than the building on the flat ground.

Building on hill slope with a symmetric plan, when subjected to tremor in along-slope direction are not subjected to torsion, but the shorter columns on the uphill side of a storey attract more lateral force, which is usually higher than their capacity resulting in shear failure.

3. Building Configuration

In the present study, a three-dimensional space frame analysis is carried out on a 6 storey RC frame building with step back, step back set back and steep slope configuration. To compare the behaviour of regular building resting on the flat ground a 6 storeys building having plan and weight same as that of the respective hill building was considered (Figure 3). The seismic weight of the regular building on flat ground is equated to that of the respective hill building (Table 1).

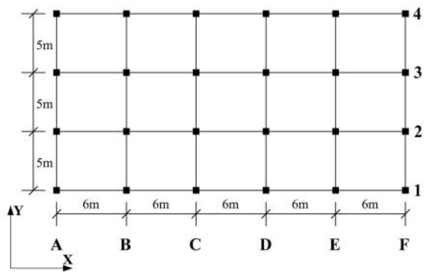

Figure 3: *Plan of the building*

The Type A building is stepping back at every floor level on the slope, up to 4 storeys and has two storeys above road level (Figure 4(a)). The Type B building is stepping and setting back at every floor level (Figure 4(b)). The Type C building is stepping back at fourth-floor level only and has two storeys above road level (Figure 4(c)). The elevation of the regular building resting on flat ground is shown in Figure 4(d).

Table 1: *Weight comparison of building*

Hill Building	Regular Building	Weight kN
Type A	Type A1	31777
Type B	Type B1	19362
Type C	Type C1	28811

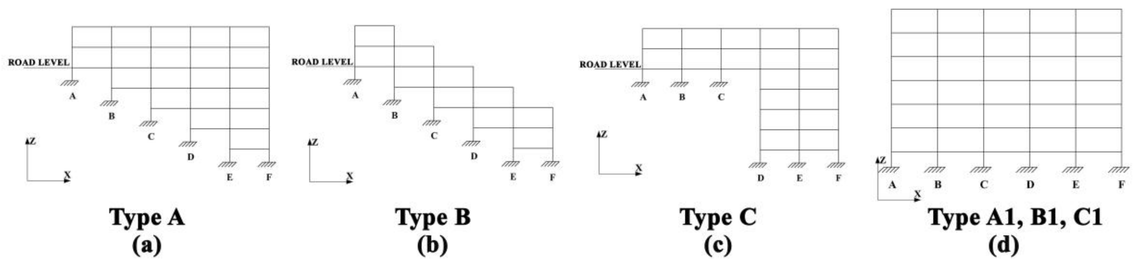

Figure 4: *Elevation of the considered building (a) Type A (b) Type B (c) Type C (d) Type (A1, B1 and C1)*

The storey heights have also been considered uniform as 3 m and the depth of footing below ground level is taken as 2 m for all the building, assuming rock is available at that depth. The foundation is been considered fixed. The cross sections of beams and column are kept uniform as 250mm × 450mm and 500mm × 500mm respectively; the thickness of the slab is taken as 150mm. The in-plane rigidity of floor slabs has been simulated using rigid diaphragm constraints.

4. Seismic Input

To compare the dynamic behaviour of building on hill slope under various seismic excitations. The time histories as given in strong motion database of Pacific Earthquake Engineering Research Centre (http://peer.berkeley.edu/smcat/) are scaled using wavelet transform to match the response spectrum of Indian seismic zone V. A linear dynamic analysis was performed on the spectrum compatible scaled time history for the corresponding matched value of spectral acceleration. (Joshua et. al., 2014)

5. Modal Analysis

After equating the mass to differentiate the behaviour of the hill building with a control structure a modal analysis was performed to compare the time period and cumulative modal mass participation ratio.

The comparison of first three mode shapes for the hill building with their corresponding control structure is shown in Figure 5 to 10. Table 2 shows the cumulative modal mass ratio for different type of building.

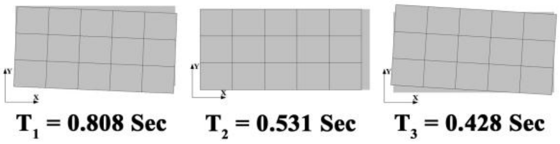

Figure 5: *Mode shape of Type A configuration*

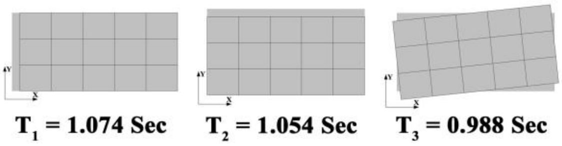

Figure 6: *Mode shape of Type A1 configuration*

Table 2: *Comparison of cumulative modal participating mass ratios (P_K) for different type of building*

Mode	Type A Direction		Type A1 Direction		Type B Direction		Type B1 Direction		Type C Direction		Type C1 Direction	
	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y
1	0	55.02	75.31	0	31.21	0	75.22	0	0	52.24	75.27	0
2	51.92	55.02	75.31	75.34	31.21	51.97	75.22	75.25	43.12	52.24	75.27	75.3
3	51.92	65.63	75.31	75.34	31.21	54.02	75.22	75.25	43.12	62.8	75.27	75.3
4	51.92	78.01	85.58	75.34	31.21	71.29	85.59	75.25	43.12	81.06	85.59	75.3
5	85.82	78.01	85.58	85.64	31.21	71.29	85.59	85.65	82.54	81.06	85.59	85.65
6	85.82	79.15	85.58	85.64	80.16	71.29	85.59	85.65	82.54	84.85	85.59	85.65
7	95.27	79.15	90.05	85.64	93.39	71.29	90.17	85.65	82.54	84.89	90.1	85.65
8	95.27	85.3	90.05	90.08	93.39	73.45	90.17	90.2	84.3	84.89	90.1	90.13
9	95.27	85.51	90.05	90.08	93.39	77.61	90.17	90.2	90.9	84.89	90.1	90.13
10	96.8	85.51	92.67	90.08	94.38	77.61	92.9	90.2	90.9	89.23	92.76	90.13
11	96.8	96.87	92.67	92.69	94.38	81.71	92.9	92.91	90.9	89.24	92.76	92.77
12	96.8	96.87	92.67	92.69	94.38	95.97	92.9	92.91	90.9	90.88	92.76	92.77

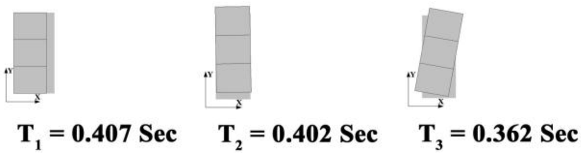

Figure 7: *Mode shape of Type B configuration*

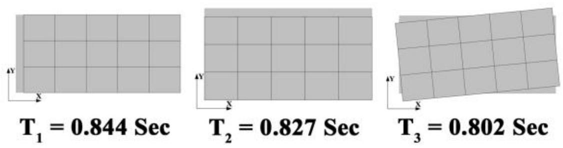

Figure 8: *Mode shape of Type B1 configuration*

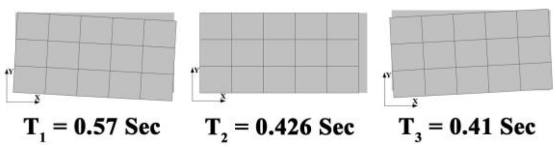

Figure 9: *Mode shape of Type C configuration*

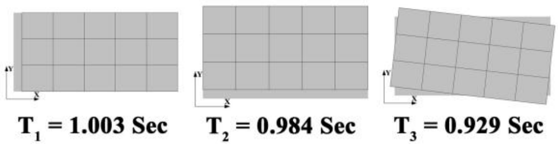

Figure 10: *Mode shape of Type C1 configuration*

6. Linear Dynamic Analysis

After equating the mass to unveil the behaviour of hill building with an control structure a linear dynamic analysis is performed. The results from the linear dynamic analysis were presented in the accompanying tables and figures.

Figure 11 to 16 shows the variation of column force in hill building due to earthquake force along X and Y direction, which is remarkably different from their corresponding control structure. The dynamic response of building in term of maximum absolute shear force in the column at ground level for frames due to earthquake force along X and Y direction is shown in Table 3 and 4.

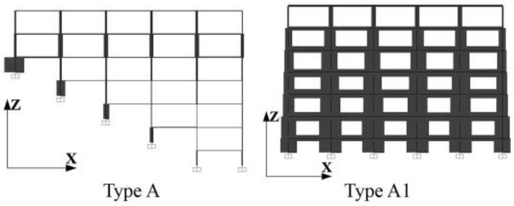

Figure 11: *Variation of column force along the height for earthquake force along X-direction*

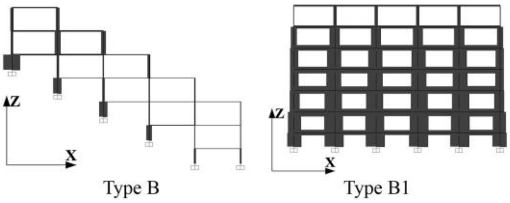

Figure 12: *Variation of column force along the height for earthquake force along X-direction*

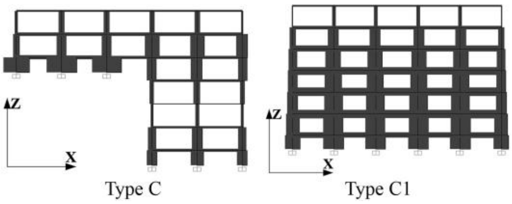

Figure 13: *Variation of column force along the height for earthquake force along X-direction*

Table 3: *Dynamic response of the building due to earthquake force in X direction*

Type of building	Maximum absolute shear force in the column at ground level in kN	
	Frame A	**Frame F**
Type A	2399.25	96.93
Type A1	242.89	242.89
Type B	1132.37	98.55
Type B1	183.73	183.73
Type C	865.88	348.83
Type C1	225.76	225.76

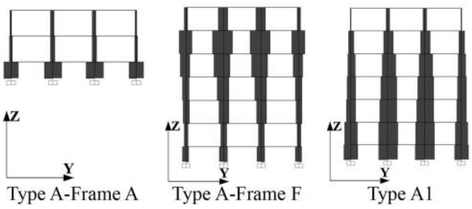

Figure 14: *Variation of column force along the height for earthquake force along Y-direction*

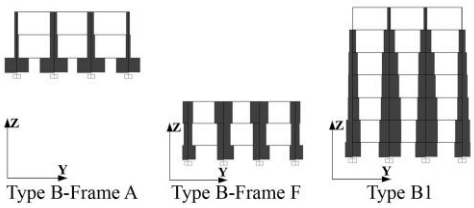

Figure 15: *Variation of column force along the height for earthquake force along Y-direction*

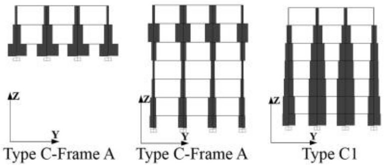

Figure 16: *Variation of column force along the height for earthquake force along Y-direction*

Table 4: *Dynamic response of the building due to earthquake force in Y direction*

Type of building	Maximum absolute shear force in the column at ground level in kN	
	Frame A	**Frame F**
Type A	1041.39	152.74
Type A1	344.73	344.73
Type B	946.73	203.68
Type B1	269.55	269.55
Type C	958.68	409.01
Type C1	328.81	328.81

Figure 17 and 22 shows the variation of torsion force in the respective structure due to earthquake force along X and Y direction. Table 5 and 6 shows the top storey displacement and maximum absolute torsion force due to earthquake force along X and Y direction.

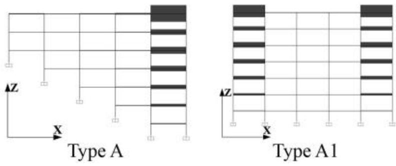

Figure 17: *Variation of torsion force due to earthquake force along X-direction*

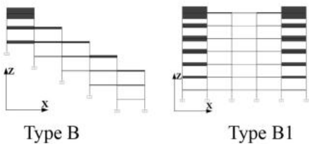

Figure 18: *Variation of torsion force due to earthquake force along X-direction*

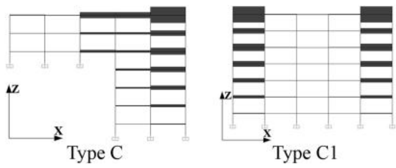

Figure 19: *Variation of torsion force due to earthquake force along X-direction*

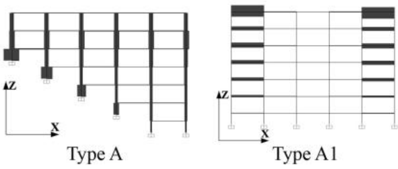

Figure 20: *Variation of torsion force due to earthquake force along Y-direction*

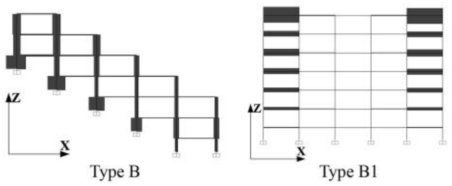

Figure 21: *Variation of torsion force due to earthquake force along Y-direction*

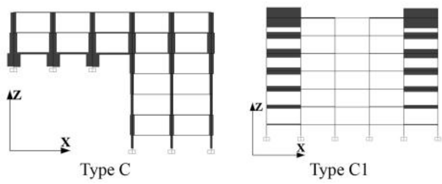

Figure 22: *Variation of torsion force due to earthquake force along Y-direction*

Table 5: *Dynamic response of the building due to earthquake force in X direction*

Type of building	Top storey displacement in mm	Maximum absolute torsion force	
		Member type	Magnitude in kNm
A	75	Beam	0.0021
A1	138.5	Beam	0.0007
B	56.1	Beam	0.0006
B1	103.8	Beam	0.0003
C	60.3	Beam	0.002
C1	128.7	Beam	0.0005

Table 6: *Dynamic response of the building due to earthquake force in Y direction*

Type of building	Top floor displacement in mm		Maximum absolute torsion force	
	Frame			
	A	F	Member type	Magnitude in kNm
A	57.4	144.7	Column	136.49
A1	136	136	Beam	0.0012
B	52.9	26.1	Column	77.96
B1	102	102	Beam	0.00071
C	48.5	114.4	Column	102.64
C1	126.1	126.1	Beam	0.00091

7. Nonlinear Static Analysis

A three-dimensional model created in SAP2000 is used to carry out nonlinear static analysis. The beam and column were modelled as a nonlinear (material nonlinearity) frame element with lumped plasticity by defining plastic hinges at both ends of the frame.

SAP2000 implements the plastic hinge properties described in FEMA-356. As shown in Figure 23, five points labelled A, B, C, D and E defines the force–deformation behaviour of a plastic hinge.

The values assigned to each of these points vary depending on the type of element, material properties, longitudinal and transverse steel content, and the axial load on these elements. Initially, a force controlled gravity push is carried out followed by a displacement controlled lateral push using SAP2000.

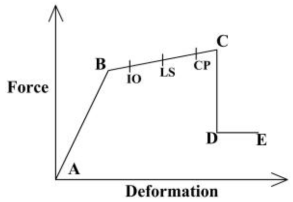

Figure 23: *Force Deformation Plastic Hinge*

In a displacement-controlled push, the displacements are increased monotonically until either the displacement of a predefined control node in the building exceeds a target value or the building has a collapse mechanism.

The building is pushed in lateral directions until the formation of collapse mechanism. For convenience, the control node is taken at the design centre of mass at the roof in these buildings. The target displacement is intended to represent the maximum displacement likely to be experienced during the earthquake.

Pushover analysis is carried out on the hill building and their corresponding control structure, aids in identifying the possible failure mode, inelastic base shear and inelastic displacement that the structure is capable of resisting. The results of the nonlinear static analysis were presented in the accompanying table and figures.

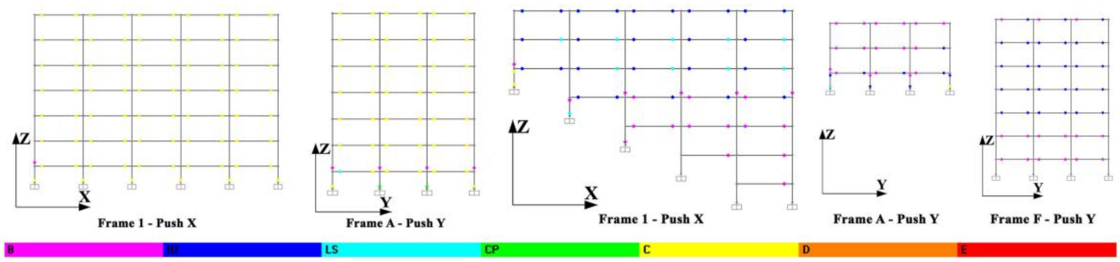

Figure 24: *Hinge states in the Type A and Type A1 configuration*

Figures 24 to 26 shows the plastic hinge distribution observed in hill building with their corresponding control structure subjected to independent push in along-slope and cross-slope directions. The performance point of these building was tabulated in Table 7.

Figure 27 and 28 shows the comparison of capacity curve (base shear versus roof displacement) when subjected to independent push along both the direction.

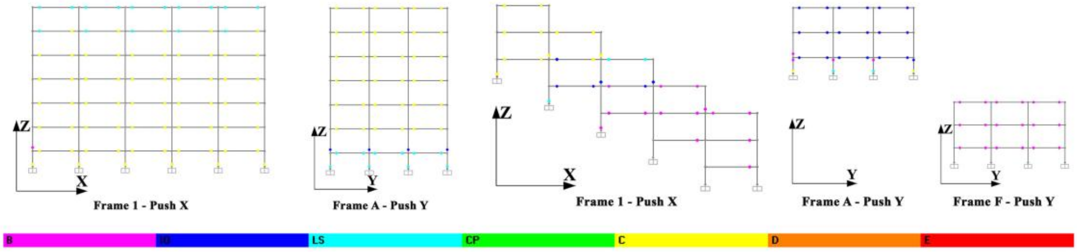

Figure 25: *Hinge states in the Type B and Type B1 configuration*

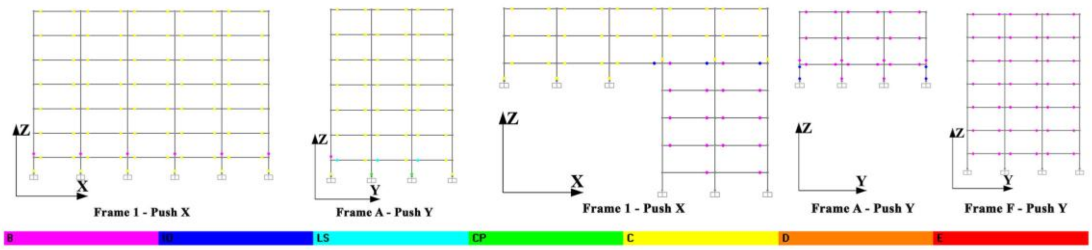

Figure 26: *Hinge states in the Type C and Type C1 configuration*

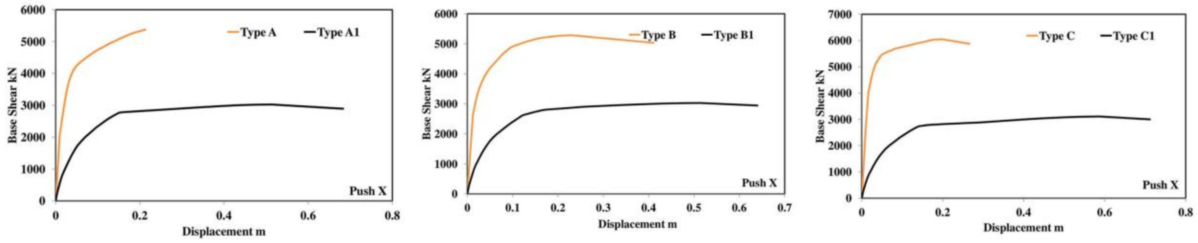

Figure 27: *Comparison of capacity curve for push along X direction*

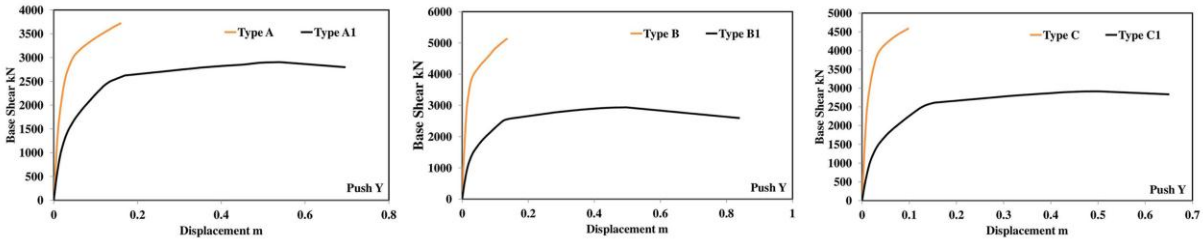

Figure 28: *Comparison of capacity curve for push along Y direction*

Table 7: *Performance point of hill building with their corresponding control structure*

Type of building	**Type A**		**Type A1**		**Type B**		**Type B1**		**Type C**		**Type C1**	
	Direction											
	X	**Y**	**X**	**Y**	**X**	**Y**	**X**	**Y**	**X**	**Y**	**X**	**Y**
Base shear (kN)	1325	949	611	694	757	1019	528	611	1586	1389	588	673
Deflection (mm)	6.2	6.4	11	11	3.5	3.7	8.8	8.6	5.9	5.6	10	10

8. Discussion of Result

The seismic behaviour of these buildings was studied by performing a modal analysis, linear dynamic analysis using spectrum compatible time history and a pushover analysis. The results were discussed below:

8.1. Time period

The difference in stiffness illustrates the corresponding variation in fundamental time period and it is affirmative that the regular building on flat ground (Type A1, Type B1, Type C1) is 1.33, 2.07 and 1.57 times flexible than the respective hill building (Type A, Type B, Type C) of identical weight. Further it is observed that the Type A configuration is flexible that the other hill building.

8.2. Cumulative modal mass participation ratio

As per Clause 7.8.4.2 of IS 1893 (Part I): 2002 it is being stated that for a considered direction of earthquake shaking the summation of modal masses of all modes considered should be at least 90 percent of the total seismic mass.

From Table 2 it is observed that 90% participation is attained at eleventh mode for Type A and twelfth mode for Type B and Type C building. However, it is observed that 90 percent participation is attained at eighth mode for the regular building on the flat ground. This confirms the energy dissipation capacity of regular building on flat ground is higher than the respective hill building. Further, it is observed that Type A building has higher energy dissipation capacity than other hill building.

8.3. Fundamental mode shape

The fundamental mode shape for the regular building on flat ground (Type A1, Type B1, Type C1) undergoes translational mode in X-direction. In hill building, irregular variation in mass and stiffness along the vertical and horizontal surface, results in non-coincident of the centre of mass and centre of stiffness at each storey. When subjected to lateral loads, these buildings generally undergo torsional response. The fundamental mode shape of Type A and Type C building experience twisting on the flexible side (Frame F) of the building. However, the fundamental mode shape of Type B building has a translational mode in X-direction and the subsequent mode undergo torsion response about the Z axis.

8.4. Linear dynamic analysis

8.4.1. Column force

When subjected to earthquake force along X direction, it is evident that ground level column in frame A of hill building, being rigid attracts more lateral force (Table 3, Figure 11 - 13) when compared with the corresponding columns in a regular building which has a uniform stiffness throughout the frame.

When subjected to earthquake force along Y direction, in addition to stiffness irregularity, the building is subjected to torsion, where the ground level columns of the top three storeys in hill building configurations have much higher shears than the storeys below (Table 4, Figure 14 - 16) when compared with the corresponding columns of the regular building.

8.4.2. Deflected shape

From fundamental time period, it is observed that the regular building on flat ground is flexible than the respective hill building of identical weight. Hence, when subjected to ground motion regular building endures larger displacement when compared with the respective hill building (Table 5 and Table 6).

8.4.3. Torsion

Hill slope building with a symmetric plan, when subjected to earthquake force in X direction are not subjected to torsion. Table 5, Figure 17 - 19 shows the occurrence of torsional force in the flexural member of both the building with negligible magnitude.

When subjected to earthquake force in Y direction hill buildings are subject to torsion. Table 6, Figure 20 - 22 shows the occurrence of high magnitude torsional force in the column of hill building and negligible magnitude of torsional force in the flexural member of the regular building.

8.5. Plastic hinge distribution

When subjected to lateral push along X direction (Figure 24, 25 and 26) the shorter columns in the uphill side, being stiffer attract more lateral force resulting in the formation of collapse hinges in the column.

Buildings in hill slope with the symmetric plan, when subjected to lateral push along Y-Direction (Figure 24, 25 and 26); in addition to stiffness irregularity, the building is subjected to torsion. Frames on downhill side being flexible hinges are developed only in beams whereas; Frames on uphill side being rigid hinges were developed in frame member subjected to bending and axial load.

When these regular building are pushed independently along X and Y direction (Figure 24, 25 and 26) collapse hinges developed in almost in every beam emphasising the strong column weak beam concept.

8.6. Pushover curve with performance point

The lateral load-deformation curves of these buildings (Figure 27 - 29) show that the ductility (displacement) of regular building is superior to respective hill slope building (Table 7). It is further observed that torsion reduces the ductile capacity of the building when subjected to lateral push along Y direction.

9. Conclusion

In this study, the behaviour of three typical configurations of hill building having weight same as that of the respective regular building resting on the flat ground. The seismic behaviour of these buildings was studied by performing a modal analysis and a linear dynamic analysis using spectrum compatible time history followed by a pushover analysis.

The conclusions drawn from the above study were summarised below:

- From time period, it is observed that the regular building on flat ground is flexible than the respective hill building
- From the cumulative modal mass participation ratio is it evident that the energy dissipation capacity of regular building on flat ground is higher than the respective hill building
- Among the hill building configuration from time period and cumulative modal mass participation ratio it is also noticed that Type A building is flexible than other hill building configuration

- The fundamental mode shape of Type A and Type C building experience twisting mode whereas, Type B building experience translational mode in X-direction and the subsequent mode undergo torsion response about Z axis, causing adverse effect on the structure
- If the building is subjected to earthquake force; column in the uphill side of hill building, being rigid attracts more lateral force whereas column in the downhill of hill building, being flexible attracts lesser lateral force
- Flexibility of regular building endures larger displacement when compared with the respective hill building
- When earthquake force acts along X direction; both the building experience torsional force in flexural member with lesser magnitude
- When subjected to earthquake force along Y direction; hill building experience torsional force of higher magnitude in column and lesser magnitude of torsional force in flexural member of regular building
- For lateral push along X direction the shorter columns in uphill side being stiffer attract more lateral force resulting in the formation of collapse hinge
- When subjected to lateral push along Y-Direction; Frame on downhill side being flexible hinges formation occurs in beams. Whereas, uphill side frame being rigid hinges are developed in flexural member and frame members subjected to bending and axial load
- When regular buildings are pushed independently collapse hinges develops almost in every beam emphasising the importance of strong column-weak beam concept
- From lateral load-deformation curves, it is observed that the ductility of regular building on flat ground is better than the respective hill building having equivalence in seismic weight

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