Seismic Behavior of Buildings Located on Slopes - An Analytical Study and Some Observations From Sikkim Earthquake of September 18, 2011

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SUMMARY:
The buildings in hilly areas have to be configured differently due to scarcity of flat ground. This paper presents some observations about seismic behaviour of hill buildings during the Sikkim earthquake of September 18, 2011. An analytical study is also performed to investigate the peculiar seismic behaviour of hill buildings. Dynamic response of hill buildings is compared with that of regular buildings on flat ground in terms fundamental period of vibration, pattern of inter-storey drift, column shear, and plastic hinge formation pattern. The seismic behaviour of two typical configurations of hill buildings is investigated using linear and non-linear time history analysis. It is observed that hill buildings have significantly different dynamic characteristics than buildings on flat ground. The storeys immediately above the road level, in case of down-hill buildings, are particularly vulnerable to earthquake action. The analytical findings are corroborated by the damage pattern observed during Sikkim earthquake.

Keywords: Hill Slopes, Frame Buildings, Dynamic Characteristics, Torsional Coupling, Nonlinear Dynamic Analysis

1. INTRODUCTION

Sikkim earthquake of September 18, 2011 was the first earthquake in India which exposed the RC frame buildings on hill slopes to ground shaking and performance of such buildings in this rather moderate ground shaking was far from satisfactory. Due to scarcity of flat land in hilly areas, majority of the buildings is constructed on the hill slopes with irregular structural configuration having foundations at different levels. Such buildings pose special structural and constructional problems. Dynamic characteristics of hill buildings (the term has been used in this paper for buildings located on hill slopes) are significantly different from the buildings resting on flat topography, as these are irregular and unsymmetrical in both horizontal and vertical directions. The irregular variation of stiffness and mass in vertical as well as horizontal directions, results in centre of mass and centre of stiffness of a storey not coinciding with each other and not being on a vertical line for different floors. When subjected to lateral loads, these buildings are generally subjected to significant torsional response. Further, due to site conditions, buildings on hill slope are characterised by unequal column heights within a story, which results in drastic variation in stiffness of columns of the same storey. The short, stiff columns on uphill side attract much higher lateral forces and are prone to damage. Very few studies (Kumar 1996; Paul and Kumar 1997; Kumar and Paul 1998; Detlof von Winterfeldt et al. 2003; Birajdar and Nalawade 2004) have been undertaken in the past to understand the behaviour of buildings on hill slopes, where the focus has been mainly on the stability of slopes. This paper examines the dynamic characteristics and seismic behaviour of hill buildings using modal, and linear and nonlinear time history analyses. The findings of the analytical study have been corroborated by observations during damage survey after Sikkim earthquake.

2. CONFIGURATION OF BUILDINGS ON HILL SLOPES

Buildings constructed in hilly areas have peculiar structural configurations. Successive floors of such buildings step back towards the hill slope and sometimes, the buildings also set back, as shown in the Figure 2.1. The stepping back of building towards hill slope results in unequal column heights in the same storey, which causes severe stiffness irregularities in along- and cross-slope directions. When subjected to lateral loads in cross-slope direction, even the buildings with symmetric rectangular configurations are subjected to significant torsional coupling due to varying lateral stiffness of uphill and downhill side frames. The torsional behaviour of these buildings is much more complex than that of buildings on flat ground due to shifting of centre of stiffness and centre of mass with floor level. Under along-slope excitation, the buildings having a symmetric configuration are not subjected to torsion, but the shorter columns on uphill side of a storey take the major share of the storey shear, which is usually much higher than their capacity and may result in shear failure.

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(a) (b)

Figure 2.1. Hill building configurations: (a) Step back building; (b)Set back and Step back building

Another common type of structural configuration that is found on hills where buildings are located on steep slopes/vertical cuts, is shown in Figure 2.2. In this case, the foundations of the building are provided at two levels (Figure 2.2): (i) at the base downhill, and (ii) at the road level. These buildings have a few storeys above the road level and several storeys below. These buildings are also subjected to severe torsional irregularity in cross-slope direction, and the short columns at road level are subjected to very high shear force, under along-slope actions.

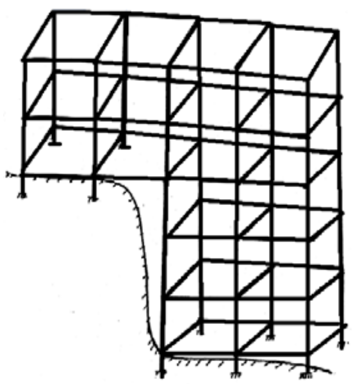


Figure 2.2. Building configurations at vertical cuts/steep slopes

3. ANALYTICAL STUDY

In the present study a 9-storey RC frame building with two different hill configurations described above, has been considered. The building has 6 storeys below the road level and three storeys above the road level. To compare the behaviour with regular buildings, two regular buildings resting on flat ground with 3 and 9 storeys and having the same plan (Figure 3.1) as the hill buildings are also considered. The first building (denoted as ‘Type S-I’) is stepping back at every floor level on a slope of about 45°, up to six storeys and has three storeys above the road level. Second building (denoted as ‘Type S-II’) is stepping back at sixth floor level only and has three storeys above road level. The 9 and 3 storeyed regular buildings on flat ground are labelled as ‘Type P-III’ and ‘Type P-IV’, respectively. The plan and elevations of different building configurations are shown in Figures 3.1 and 3.2.

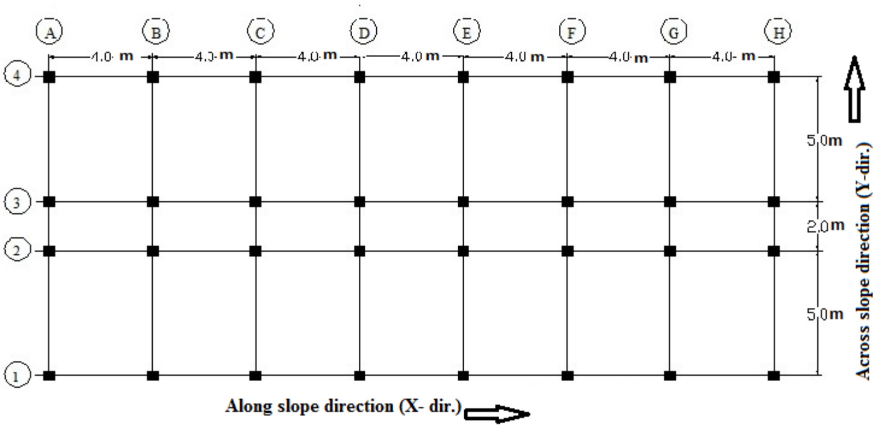


Figure 3.1. Plan of the buildings considered in the study

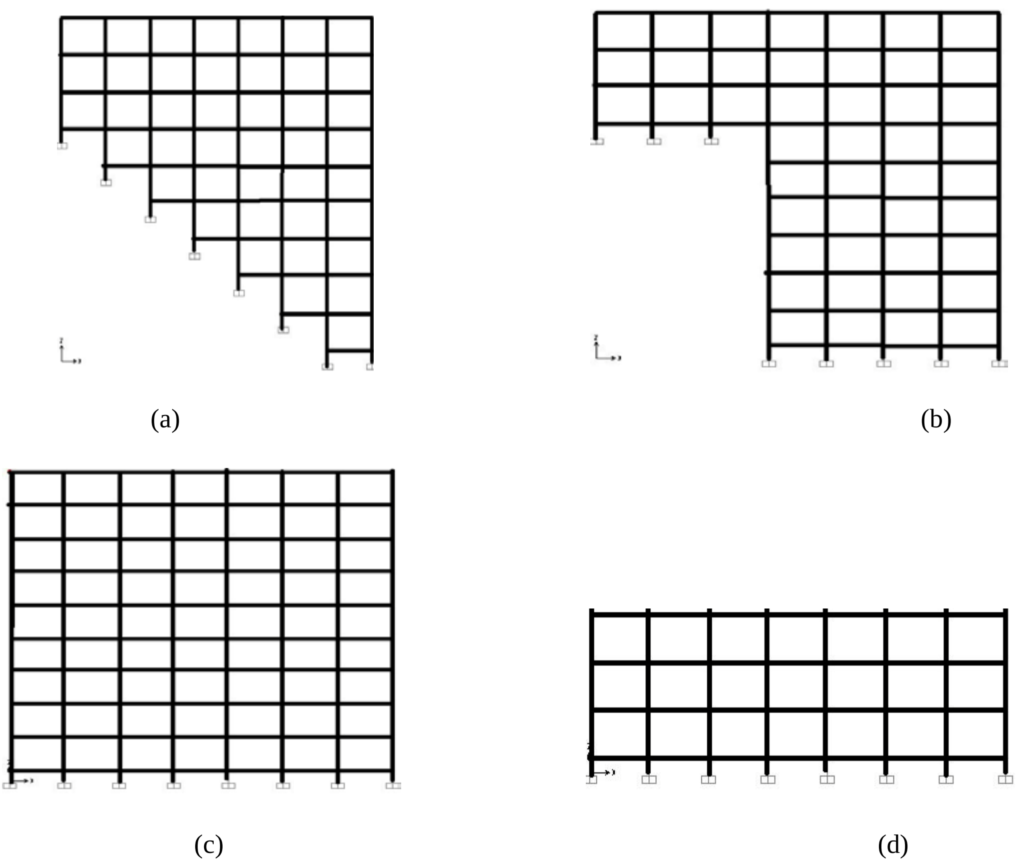


Figure 3.2. Elevations of the considered buildings: (a) Type S-I; (b) Type S-II; (c) Type P-III; (d) Type P-IV

The buildings are designed for Seismic Zone IV (the seismic zone of Sikkim) as per Indian seismic design code (BIS 2002). To facilitate comparison, size of the columns and beams is kept uniform as 500x500 mm, and 400x400 mm, respectively, for all buildings. The storey heights have also been considered uniform as 3 m in all the buildings. The analytical model has been developed based on cracked sections stiffness as per guidelines of ASCE-41 (2006). The in-plane rigidity of floor slabs has been simulated using rigid diaphragm constraints. The foundations of the buildings have been considered as fixed at a depth of 1 m below the ground surface, assuming that rock is available at that depth.

The buildings have been analysed for a set of five ground motions (Table 3.1) taken from strong motion database of Pacific Earthquake Engineering Reasearch Center (http://peer.berkeley.edu/smcat/). The time histories are scaled using wavelet transform (Mukherjee and Gupta 2002) to match the response spectrum of Indian Seismic Zone IV as shown in Figure 3.3.

Table 3.1. Earthquake records used in the analysis

S. No.	Event	Magnitude	PGA [g]	PGV [cm/sec]	PGD [cm]
1.	1999 Chi-Chi	M7.6	0.266	38.331	38.331
2.	1979 Imperial Valley	M6.5	0.289	19.915	10.97
3.	1994 Northridge	M6.7	0.249	19.381	6.824
4.	1971 San Fernando	M6.6	0.33	56.3.5	60.017
5.	1995 Kobe	M7.2	0.28	16.369	8.067

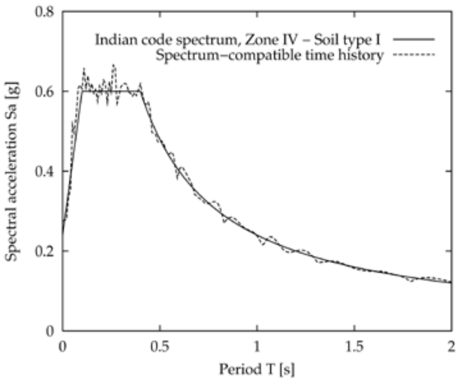


Figure 3.3. Indian code response spectrum for seismic zone IV and matched response spectrum of a typical scaled time history.

3.1 Dynamic Characteristics

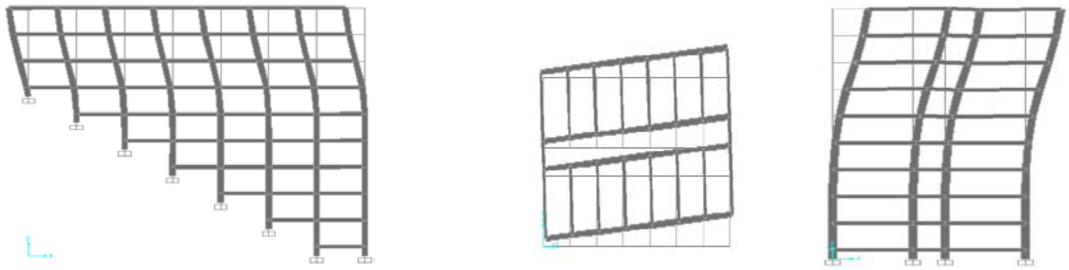
Fudamental periods and dyanamic mass participation ratios in the first three modes are shown in Tables 3.2-3.3 for all four building configurations, considered. The fundamental mode shapes in the two directions of hill building configurations, Type S-I and Type S-II are shown in Figures 3.4 and 3.5, respectively. Due to irregularity of configurations, the mass participation in fundamental mode in case of buildings on slopes is much lower than the regular buildings. The Type S-I and Type S-II buildings show pure translational modes in along-slope direction, but the modes are torsionally coupled in cross-slope direction. Further, the fundamental period of 9 storey hill buildings (Type S-I and S-II) is close to the fundamental period of Type P-IV (3 storey regular configuration) building.

Table 3.2. Fundamental periods (T) and Modal Participating Mass Ratios (P_K) in along-slope direction

Mode	Type S-I		Type S-II		Type P-III		Type P-IV	
	T(sec)	P_k (%)	T(sec)	P_k (%)	T(sec)	P_k (%)	T(sec)	P_k (%)
1	0.683	41.78	0.604	17.54	1.78	75.00	0.633	69.90
2	0.120	25.0	0.536	56.8	0.58	9.00	0.180	9.00
3	0.10	11.0	0.184	5.0	0.33	3.00	0.072	10.00

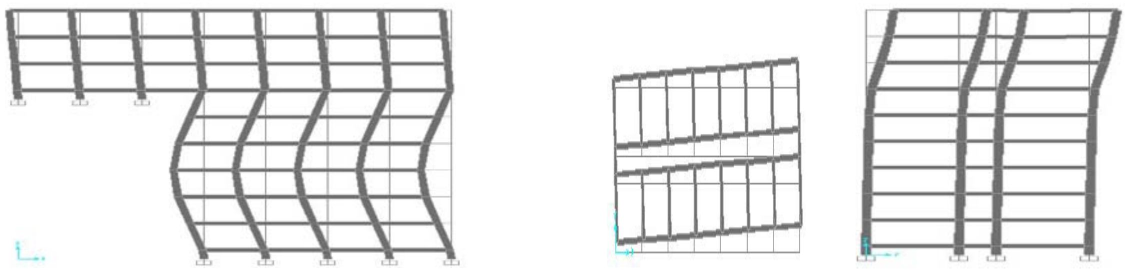
Table 3.3 Fundamental periods (T) and Modal Participating Mass Ratios (P_K) in cross-slope direction

Mode	Type S-I		Type S-II		Type P-III		Type P-IV	
	T(sec)	P_k (%)	T(sec)	P_k (%)	T(sec)	P_k (%)	T(sec)	P_k (%)
1	1.05	45.78	0.78	38.00	2.243	73.00	0.76	69.90
2	0.68	5.00	0.64	25.00	0.71	9.00	0.21	9.00
3	0.36	16.46	0.60	14.00	0.38	3.00	0.081	10.00



(a) (b)

Figure 3.4. Fundamental mode shapes of configuration Type S-I : (a) along-slope direction; and (b) cross-slope direction

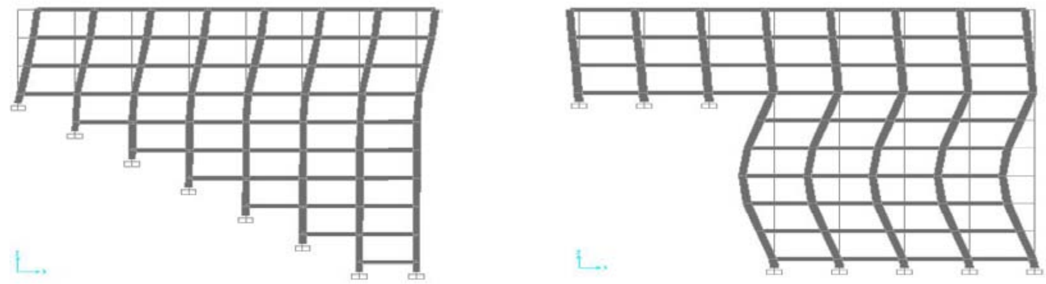


(a) (b)

Figure 3.5. Fundamental mode shapes of configuration Type S-II : (a) along-slope direction; and (b) cross-slope direction

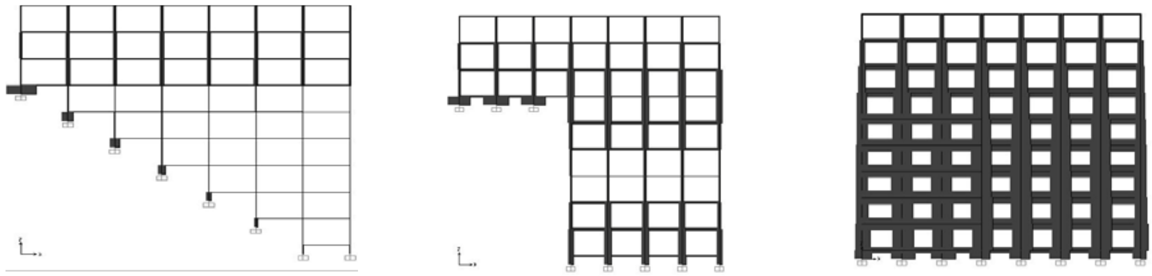
3.2 Linear Dynamic Response

The deflected shapes of hill building configurations, Type S-I and Type S-II, due to excitation along the slope are shown in Figure 3.6. It is observed that no significant lateral displacement occurs below the sixth floor level (road level) in Type S-I building, due to high rigidity of short columns. The deflected shape of the Type S-II building is similar to a vertical cantilever propped at sixth floor level. Accordingly, almost all of the storey shear below sixth floor level is resisted by short columns (Figure 3.7) in case of Type S-I configuration. In case of Type S-II configuration, the columns in the bottom storey and storeys immediately above and below the road level (sixth and seventh storey) are subjected to the maximum forces. As shown in Figure 3.7, the variation of column forces in hill building configurations is remarkably different than that in case of regular (Type P-III) building configurations.



(a) (b)

Figure 3.6. Deflected shapes of hill building configurations due to along-slope excitation: (a) Type S-I; and (b) Type S-II configuration.



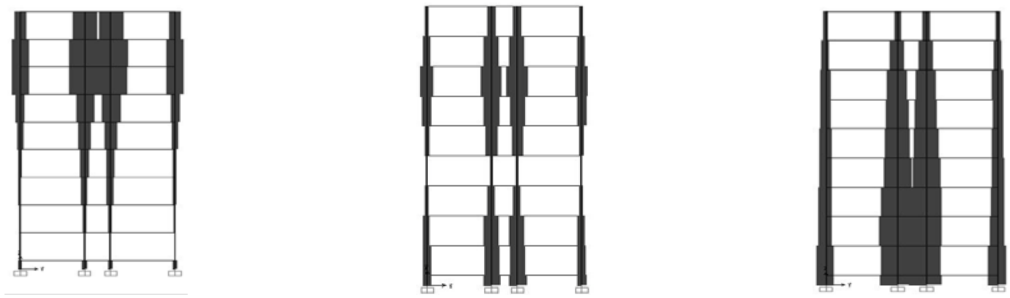
(a) (b) (c)

Figure 3.7. Variation of column shear along the height of the building due to along-slope excitation: (a) Type S-I; (b) Type S-II; and (c) Type P-III configuration.

The deflected shapes of the hill building configurations (Type S-I, and S-II) under cross-slope excitation are shown in Figure 3.8. The Figure also shows the deflected shape of the regular 9 storey building (Type P-III) for the purpose of comparison. It can be observed that the deflected shape of the hill building configurations is significantly different than regular buildings and similar pattern is observed for column shears, where the columns of the top three storeys in hill building configurations have much higher shears than the storeys below and the corresponding columns in the regular building (Figure 3.9). The effect of torsion irregularity in the hill building configurations can be represented by the ratio of maximum to average interstorey drifts ($\Delta_{max}/\Delta_{avg}$) in a storey, as shown in Figure 3.10. In Type S-I building, torsion is observed in all the storeys whereas in Type S-II building, torsion is observed in top three storeys only. Further, the torsion is most significant at road level (6^{th} storey) in both Type S-I and Type S-II buildings.

(a) (b) (c)

Figure 3.8 Deflected shapes of different building configurations, under cross-slope excitation: (a) Type S-I; (b) Type S-II; and (c) Type P-III configuration.



(a) (b) (c)

Figure 3.9. Variation of column shear along height of different building configurations, due to excitation in cross-slope direction: (a) Type S-I; (b) Type S-II; and (c) Type P-III configuration.

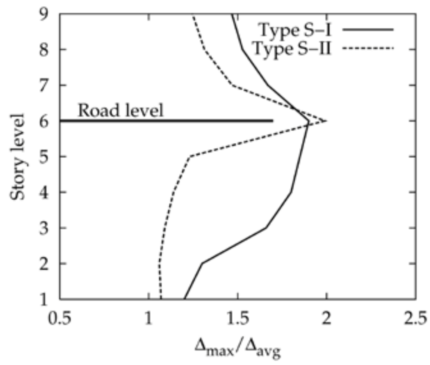
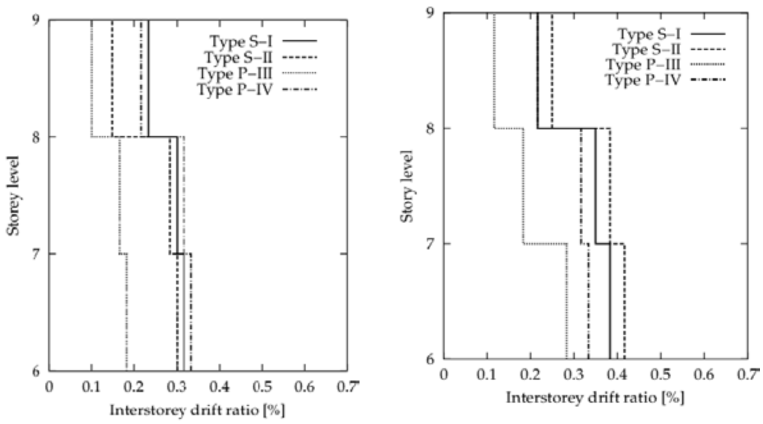


Figure 3.10. Variation of $\Delta_{max}/\Delta_{avg}$ along height in hill building configurations Type S-I, and Type S-II, due to seismic excitation in cross-slope direction.

To compare the seismic response of hill buildings with regural building configurations, interstorey drift in the top three storeys of all the four strucural configurations considered herein, is shown in Figure 3.11. It can be observed that interstorey drifts in the top three storeys of the hill buildings are quite close to those in the 3 storey regular building (Type P-IV) rather than those in the 9 storey building (Type P-III).



(a) (b)

Figure 3.11 Interstorey drift ratio in the top three storeys along column line H1, for different building configurations: (a) along-slope direction; (b) cross-slope direction.

3.3 Nonlinear Dynamic Response

Figures 3.12 and 3.13 show the hinge patterns observed in hill building configurations Types S-I and S-II, respectively, subjected to independent excitation in along-slope and cross-slope directions. In Type S-I configuration, most of damage is observed in the top three storeys, where plastic hinges are developed in both beams and columns. The columns on rigid side exceeded the collapse limit state, even though the building was designed for earthquake forces. In the storeys below sixth floor level, hinges are developed only in the short columns and adjacent beams. The hinges in top three storeys develop a mechanism indicating collapse of these storeys. Under cross-slope excitation, hinges are formed in beams as well as columns (Figure 3.12(b)) in the rigid side frame, whereas on the flexible side, the hinges are developed only in beams (Figure 3.12(c)). Failure occurs due to shorter columns on sixth storey reaching the collapse limit state.

In Type S-II configuration subjected to along-slope excitation, hinges are developed in beams of the most of the storeys and in columns at the base and at the road level (Figure 3.13(a)). Similar hinge pattern is also observed under cross-slope excitation, where the beams and columns on the rigid side reach the collapse limit state.

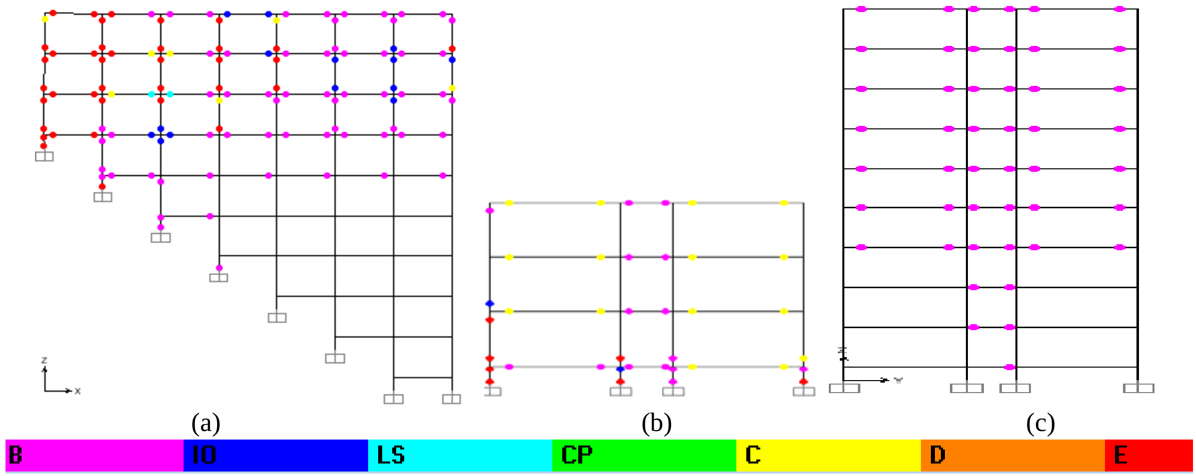


Figure 3.12. Hinge pattern of the hill building configuration Type S-I: (a) along-slope excitation; (b) cross-slope excitation (rigid side); and (c) cross-slope direction (flexible side).

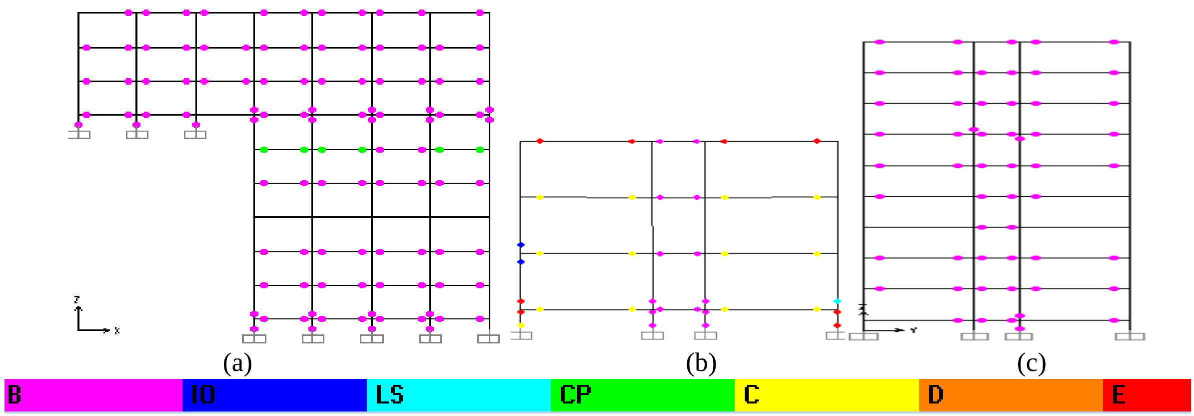


Figure 3.13 Hinge pattern of the hill building configuration Type S-II: (a) along-slope excitation; (b) cross-slope excitation (rigid side); and (c) cross-slope direction (flexible side).

4. OBSERVATIONS DURING SIKKIM EARTHQUAKE

Sikkim is one of the most rapidly growing states of India, where the RC frame buildings are the prevalent building typology in most of the towns. A joint team of IIT Roorkee, and NORSAR, Norway surveyed the damage in Gangtok (the capital town of Sikkim) and other major towns of Sikkim after the M6.9 earthquake of September 18, 2011. Although, the city of Gangtok was more than 100 km from the epicenter, several buildings (including RC frame buildings) were damaged and two RC frame buildings collapsed in Gangtok. The collapse of one of the RC frame building was peculiar as the columns of sixth storey (at the road level) failed (Figure 4.1), whereas the storeys below were intact. This unusual failure of RC frame building motivated the authors to take up the analytical study summarized above to understand seismic behavior of RC frame buildings on hill slopes. The configuration of the observed building was similar to the Type S-II configuration discussed earlier. It can be observed that the analytical study explains the damage pattern showing that the storeys at road level are most prone to the damage during earthquake.

Figure 4.1 Failure at sixth storey level of a ten storey hill building during Sikkim earthquake of September 18, 2011

CONCLUSION

The Sikkim earthquake highlighted the peculiar failure pattern of hill buildings. The behaviour of hill buildings differs significantly from the regular buildings on flat ground. The hill buildings are subjected to significant torsional effects under cross-slope excitation. Under along-slope excitation, the varying heights of columns cause stiffness irregularity, and the short columns resist almost all of the storey shear. The linear and non-linear dynamic analysis shows that the storey at road level, in case of downhill buildings, is most susceptible to damage. The findings from the analytical study are supported by the observation of the damage pattern in a 10 storey RC frame building, which collapsed during Sikkim earthquake. The building had a structural configuration similar to that considered in the present study, and damaged in exactly similar manner as predicted by the analytical study.

REFERENCES

ASCE-41. 2006. Seismic Rehabilitation of Existing Buildings. In *ASCE/SEI 41*: Structural Engineering Institute.

Birajdar, B. G., and S. S. Nalawade. 2004. Seismic Analysis of Buildings Resting on Sloping Ground. In *Thirteenth World Conference on Earthquake Engineering (13WCEE)*. Vancouver, Canada.

BIS. (2002). IS 1893 (Part 1) Indian Standard criteria for Earthquake Resistant Design of structures, *Part 1: General Provisions and buildings (Fifth Revision)*. New Delhi, Bureau of Indian Standards.

Detlof von Winterfeldt, Nels Rosewnd, and Alica Kitsuse. 2003. Framing Earthquake Retrofitting Decisions: The case of Hillside Homes in Loss Angeles. Pacific Earthquake Engineering Reasearch Center.

Kumar, S., and D.K Paul. (1998). A Simplified Method for Elastic Seismic Analysis of Hill Buildings. *Journal of Earthquake Engineering* **2:(2)**, 241-266.

Kumar, Satish 1996. Seismic analysis of setback and setback buildings, Earthquake engineering, University of Roorkee, Roorkee.

Mukherjee Sushovan, and Vinay K. Gupta. (2002). Wavelet-based generation of spectrum-compatible time-histories. *Soil Dynamics and Earthquake Engineering* **22:(9–12)**, 799-804.

Paul, D. K., and Kumar S. (1997). Stability analysis of slope with building loads. *Soil Dynamics and Earthquake Engineering* **16:(6)**, 395-405.