SEISMIC RISK ASSESSMENT IN HILLY AREAS: CASE STUDY OF TWO CITIES IN INDIAN HIMALAYAS

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Abstract: Past earthquakes in India and other countries have shown that hilly areas are subjected to higher losses as compared to the flat areas. This is due to combination of a number of factors, including topographic amplification, earthquake triggered ground failure hazard and higher vulnerability of hill buildings due to irregular structural configurations. This study identifies the role of these parameters through a case study of two cities in Indian Himalayas. An extensive field survey of the test-bed cities is conducted to identify different structural configurations prevalent in Indian Himalayas. Topographic amplification factors using three codes which deal with this issue, are compared and it is found that the Italian code (ICMS 2008) results in the most conservative amplification factors at the ridge. Seismic performance of the most commonly found hill building configuration is studied using Incremental dynamic analysis. The analysis shows that the hill buildings collapse at much lower PGA than their flat terrain counterparts, designed for the same hazard level, using Indian codes.

1. Introduction

Indian Himalayas are not only the youngest mountains in the world, these are also among the most seismically active areas of the world. Several devastating earthquakes have been experienced in Indian Himalayas, in the past (Figure 1(a)). The Indian Seismic Zonation Map (Figure 1(b)) classifies this region into Zones IV and V, the highest seismicity zones in India.

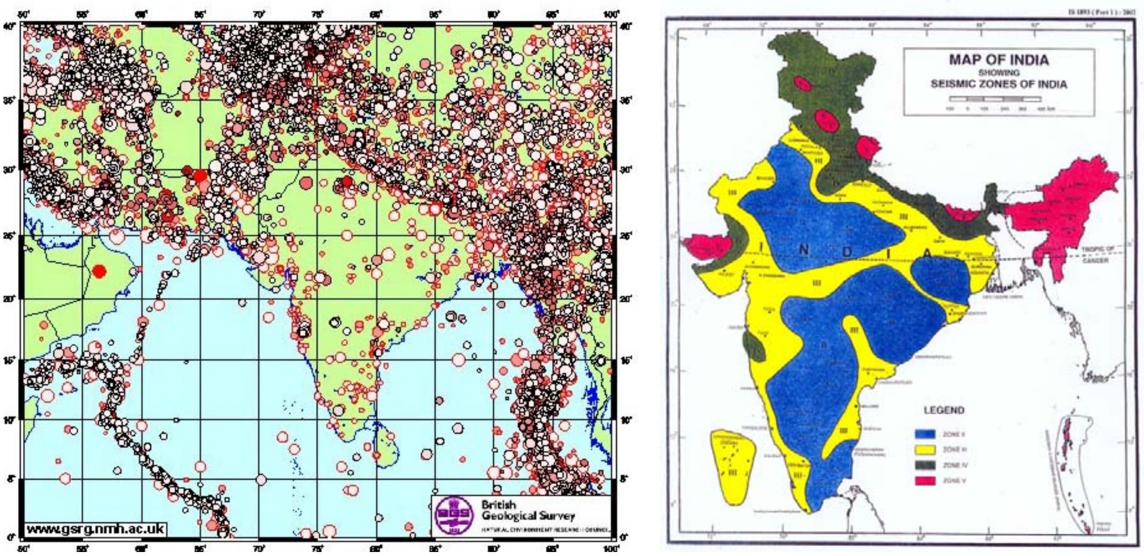

Figure 1. Seismicity of Indian Himalayas: (a) Past earthquakes (M >3),
(b) Seismic Zonation Map of India.

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Due to rapid urbanization in the recent decades, the seismic risk scenario has rapidly changed in this region. Due to migration of population from villages to cities, a few locations are subjected to very high population pressure, which forces people to occupy unstable hill slopes. Further, a large number of multi-storey buildings are replacing the old low-rise timber dominant construction. To suite the sloping terrain, these buildings have very irregular configurations, which result in complex seismic behaviour, not anticipated by the current seismic design codes. Moreover, these multi-storey buildings, are often constructed without any consideration for seismic forces, and result in collapses during even moderate earthquakes. Figure 2 shows collapse of a multi-storey building in Gangtok which was more than 100 km from the epicentre of the 6.9 Magnitude earthquake of September 18, 2011 (Sharma et al. 2011)

Figure 2 Failure at sixth (road level) storey of a ten storey hill building during Sikkim earthquake of September 18, 2011

Hilly regions have their unique problems which compound to increase the seismic risk in these areas. These include topographic amplification, earthquake triggered ground failure (slope un-stability) hazard, non-conventional and irregular building configurations, lack of good quality construction material and skill, and most importantly inadequacy of building code provisions, which are mainly focussed on the buildings located on flat terrain.

This paper identifies the various factors responsible for high seismic risk in hilly areas, through a rigorous field study of two hill towns in north India Himalayas – Mussoorie and Nainital. Effect of topographic amplification on seismic hazard, and characteristics of building stock and its vulnerability have been discussed.

2. Seismic Risk in Hilly Areas

Hilly areas face a severe risk of loss during earthquakes, which is aggravated by three factors. Firstly, seismic ground motion in hilly areas, particularly at ridges and crests, experiences topograpic amplification due to the geometric features. The majority of building construction in hilly areas is somehow located on slopes or hilltops, due to the scarcity of flat land. Secondly, buildings located on slopes are susceptible to slope failure hazard, as many earthquake-triggered landslides have been observed in the past. In addition to the catastrophic slope failures, large creeping movement of slopes can also take place resulting in damage to the supported building stock. Numerous examples of such damage have been observed during past earthquakes in Indian Himalayas and elsewhere. At last, a crucial factor contributing to the vulnerability of construction on hill slopes, arises from the irregular configuration of ‘hill buildings’ due to foundations located at different levels. The observed irregular configurations typically depict low structural ductility resulting in an increased vulnerability. Figure 3 schematically illustrates these issues. In Indian Himalayas, the vulnerability of the existing housing stock is further exacerbated by the quality of construction materials, workmanship, and deficient design codes neglecting the peculiarities of buildings in hilly areas. However, it is difficult to take into consideration all these issues, at the moment. Present study focusses on the issue of topographic amplification of earthquake ground motions and seismic vulnerability of building configurations evolved to suite their location on hill slopes.

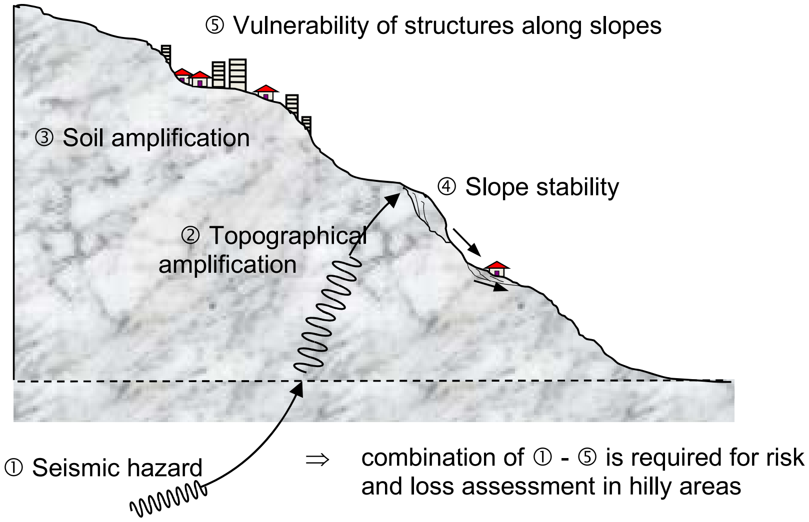


Figure 3 Issues and challenges in seismic risk assessment in hilly areas

After many destructive earthquakes, it could be observed that structural building damage shows unique distributions within the range of topographic features such as slopes and hills. Keeping the effects of landslide or slope instability aside, lower damage extents could be often observed at the foot of a slope, while buildings located on the slope and especially at the slope's ridge showed higher damage concentrations. This effect, known as Seismic Topographic Amplification, is completely different from the well-investigated effects of subsurface topography (sedimentary basin effects) or soil amplification. However, in many cases, it may not be possible to separate the effects of soil amplification (caused by subsoil stratigraphy) from surface topography. This is especially true when the topographic feature mainly consists of sedimentary soil materials (e.g. soil slopes at river banks) or when rock slopes are covered by soft sedimentary layers (as e.g. observed in parts of the Indian Himalayas).

Even though it is now well-known and widely accepted that surface topography can have considerable influence on the frequency and amplitude characteristics of earthquake ground motion and thus on the extent of local structural earthquake damage, this phenomenon received only minor attention by the scientific community for a long time (Lang 2004). A small number of international seismic building codes address the topic of topographic amplification effects. In general, topographic amplification is handled in a very simplified way being solely represented by an additional amplification factor which is to be added to the elastic design spectrum. This factor, often called A_T, requires that the relief can be represented in a simplified 2D shape. Each of the respective design codes mention that irregular complex shapes will require specific studies.

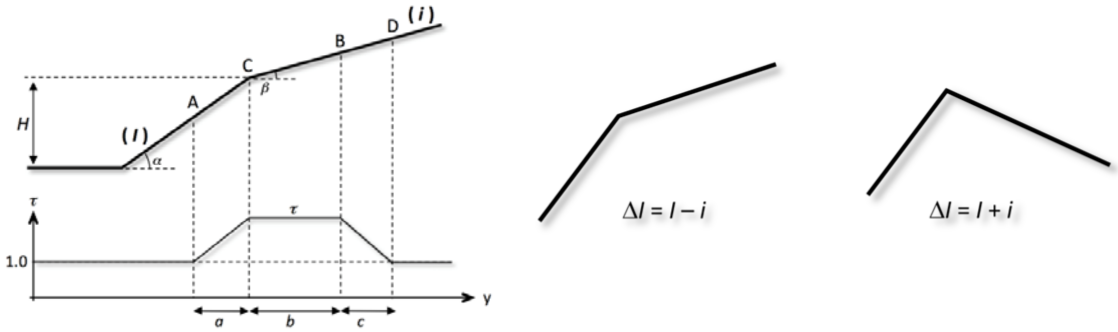
The French code AFPS (Association Française du Génie Parasismique) was probably the first international seismic design code which addressed the phenomenon of topographic amplification. The effect of a site's local topography is accounted for by using a multiplying corrective coefficient τ, called *site response factor* or *topography factor*.

Considering a ridge C (Figure 4) delimiting a downhill slope of gradient I (tangent of slope angle α), an uphill slope of gradient i, and if:

- $H \geq 10\ m$ (H being the height of the ridge above the base of the relief), and
- $i \leq I/3$ (i.e. $\tan\beta \leq 0.33 \cdot \tan\alpha$)

then coefficient τ can be computed as:

$$\begin{aligned} &\tau = 1.00 && \text{for } I - i \leq 0.40 \\ &\tau = 1 + 0.8\,(I - i - 0.40) && \text{for } 0.40 < I - i \leq 0.90 \qquad (1) \\ &\tau = 1.40 && \text{for } I - i \geq 0.90 \end{aligned}$$



(a) (b) (c)

Figure 4 Topographic amplification factor in French code: (a) variation of topographic amplification factor along slope and on the ridge, (b) Ridge ledge, and (c) watershed ledge.

The seismic building code of Italy (ICMS 2008) provides graphs and relations to compute the amplification factor F_a separate for bedrock crests (Figure 5) with slope angles α_i greater or equal to 10°. The amplification factor F_a is applied for periods ranging from 0.1 to 0.5 seconds only. It should be assumed that the material that forms the relief has an average shear wave velocity $V_s \geq 800\ m/s$. Relationships for the various amplification factors are given in Table 1.

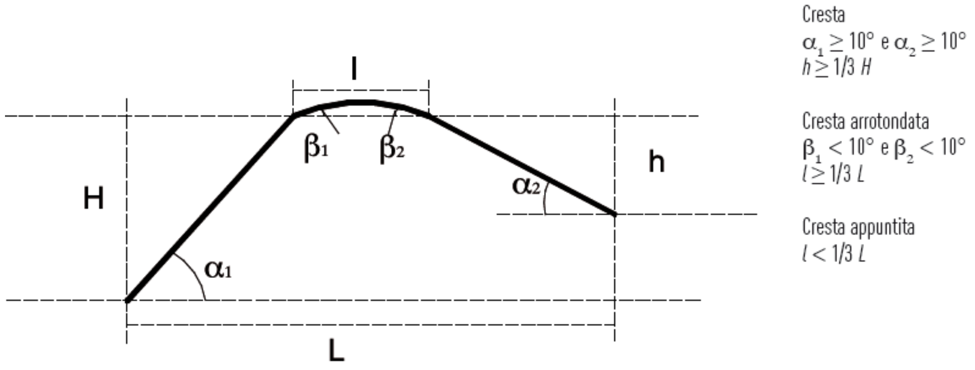


Figure 5. Geometrical parameters of the bedrock crest.

Table 1. Amplification factors for various types of bedrock crests (ICMS 2008).

Sharp crest				**Soft crest**
$L > 350\ m$	$250 < L < 350\ m$	$150 < L < 250\ m$	$L < 150\ m$	$l \geq 1/3 \cdot L$
$\ln(F_a) = 1.11 \cdot H/L$	$\ln(F_a) = 0.93 \cdot H/L$	$\ln(F_a) = 0.73 \cdot H/L$	$\ln(F_a) = 0.40 \cdot H/L$	$\ln(F_a) = 0.47 \cdot H/L$

Eurocode 8 (EN 1998-5:2003, CEN 2004a, 2004b) provides some simplified topographic amplification factors, called S_T. Factors S_T are considered independent of the fundamental period of vibration and are used as a constant scaling factor for the ordinates of the elastic design response spectrum (Table 2). These should be used in cases that the slope belongs to 2D topographic irregularities, such as long ridges and cliffs of heights greater than ~ 30 *m*.

Table 2. Topographic amplification factors according to Eurocode 8.

Description	**Building location**	**Topographic amplification factor S_T**
flat or average slope angles of less than ~ 15°	--	1.0
isolated cliffs and slopes	near the top edge	≥ 1.2 [1)]
ridges with crest widths significantly less than the base width	near the top of the slope	≥ 1.4 [1)] for angles greater than 30°
		≥ 1.2 [1)] for angles 15° to 30°
The value of S_T may be assumed to decrease as a linear function of the height above the base of the cliff or ridge, and to be unity at the base. [1)] Increase by 20% in presence of a loose surface layer.		

Risk assessment methodologies developed worldwide have been invariably focused on plain areas, i.e. without topographic feature. As described in previous sections, hilly areas have their own specific and challenging problems, in terms of topographic amplification, slope instability and peculiar (generally more vulnerable) construction typology. The application of conventional risk computation methods will fail when applied to hilly areas and will generally underestimated the true extent of damage and loss. Therefore, there is a need for the development of a comprehensive methodology for seismic risk assessment in hilly areas considering all the above-mentioned aspects. It will involve development of criteria for hazard microzonation, slope instability microzonation, building typology and vulnerability identification and representation. Figure 6 shows the schematic representation of the proposed methodology for seismic risk assessment in Hilly areas.

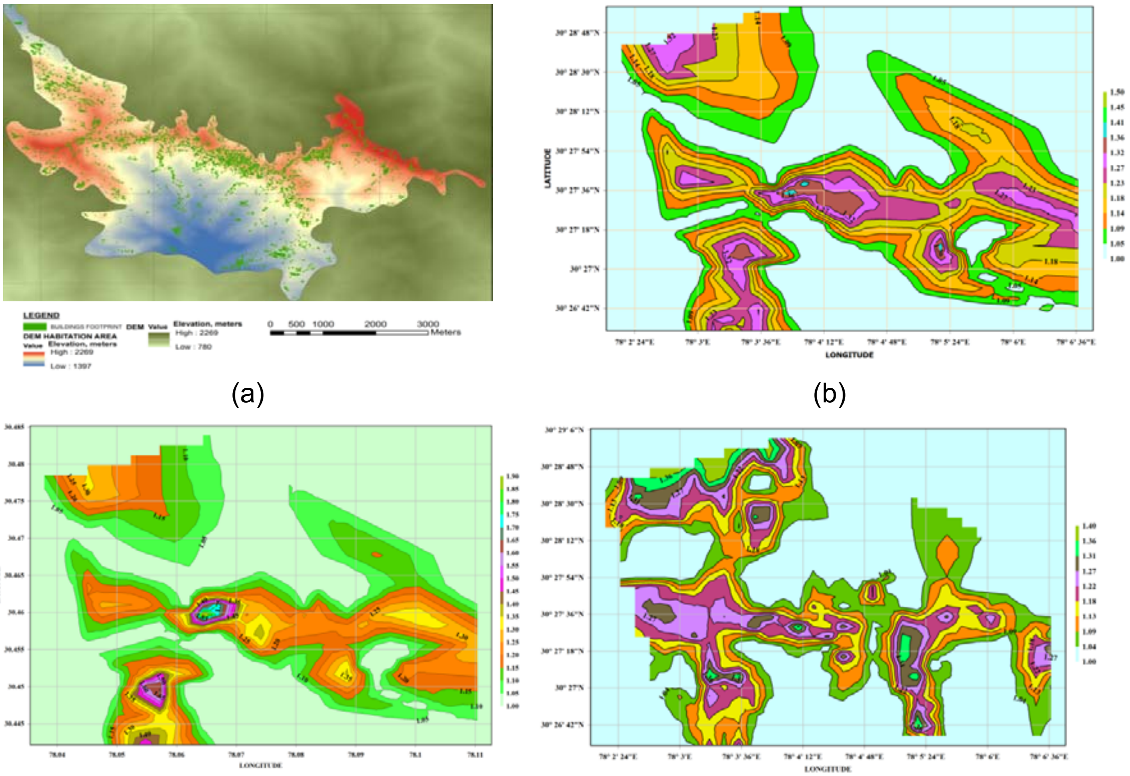
3. Case Study

In the present study, the three aforementioned issues are addressed through a case study of two Himalayan cities in northern India, i.e. Mussoorie and Nainital. Figure 6 shows the satellite imageries of the two cities. Both cities have touristic significance and as a result are subjected to excessive construction activity and high population density. While the city of Mussoorie is located on a ridge of a relatively stronger rocky terrain, the city of Nainital is located around a lake mostly on the deposited debris of past landslides covering the foothill and the slopes of a steep topographic feature.

(a) (b)

Figure 6. Satellite imageries of the test bed cities: (a) Mussoorie, and (b) Nainital

Digital elevation models (DEM) of the two cities were developed using the available topographical maps and satellite data. A number of cross-sections across the main and secondary ridges were considered to compute the amplification factors using the three codes discussed in the previous section. Figure 8 shows the obtained amplification factors. It can be observed from



(a) (b)

(c) (d)

Figure 7. Topographic amplification for Mussoorie: (a) DEM, (b) Amplification factors using Eurocode 8, (c) Amplification factors using Italian code (ICMS), and (d) Amplification factors using French Code (AFPS)

A typology survey of buildings in the cities of Mussoorie and Nainital was conducted under the Indo-Norwegian EQRisk collaboration project. In typology surveys for conventional buildings located on flat ground, vertical (wall type) and horizontal (floor and roof type) load-bearing systems are the main classification criteria (NIBS 2006, Haldar et al. 2013). However, in case of hill buildings, it was observed that identifying wall and roof/floor types only, is not adequate, as the building's geometric configuration also affects its seismic response. Therefore, the geometric configuration was also considered as yet another classification criterion. During the survey, it was observed that in case of steep slopes, it is not possible to have foundations at the same level. In order to create a flat foundation ground, deep cutting of soils or rocks is required. This procedure is not only economically unviable, it also creates vertical cuts into the soil/weathered rock slopes which may dramatically increase susceptibility of slope failures, even without earthquake action. Due to these reasons, there is a general tendency among the local builders in following the terrain of the hill for supporting the buildings. This has given rise to a number of interesting support systems, some of them given in Fig. 8.


(a) (b)

(c) (d)

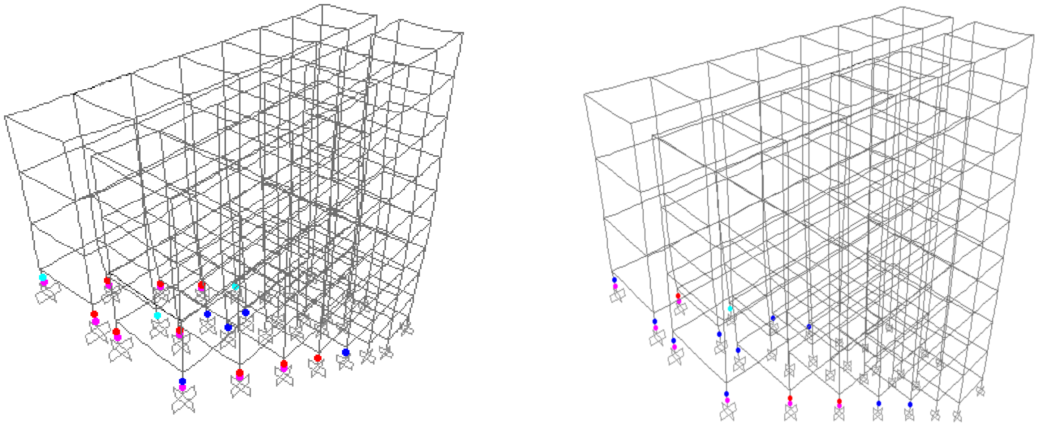
Figure 8. Commonly observed support systems and geometric configurations of buildings in hilly areas in Northern India: (a) downhill side supported on stilts, (b) a flat platform created by a retaining wall on the downhill side, (c) step-back configuration, and (d) step-back and set-back configuration.

The most natural structural configuration is to accommodate the shape of the slope in foundation arrangement through a step-back configuration (Fig. 8(c)). This is basically achieved by providing separate foundations at gradually increasing levels. In some cases, the superstructure, in addition, follows the shape of the slope, resulting in a combination of step-back and set-back configurations (Fig. 8(d)). In case of very steep slopes on rocky terrain, a conventional solution for hill buildings is to provide foundations at two (dual) levels. Few of the columns or walls are supported at or close to the uphill road level, whereas the remaining columns or walls are supported downhill at the toe of the slope (Fig. 8(a)). These buildings may have several stories below and a few above the road level. To create this configuration type, it is required to cut the soil in order to prepare the plane patches of land supporting individual or a group of columns or walls. The vertical cuts in hard rock may sustain themselves against sliding, but in case of soil and weathered rock strata, parts of the buildings have to retain the backfill, resulting in lateral pressure on the vertical building components. Retaining of the soil by the building can be avoided by creating a flat platform above the slope made of landfill, instead of cutting the soil (Fig. 8(b)). However, this comes along with the disadvantage that the filled up platform requires a retaining wall on the downhill side to support the filling. The most convenient, but perhaps the most vulnerable configuration to create flat base for a building is to use columns or posts of varying height, resulting in extremely irregular configurations.

Being the most common geometric configuration, the step-back configuration has been considered for further investigation in the present study. Two design levels of the building have been considered. As many buildings in India are still constructed without any consideration for earthquake forces, the first model is designed for gravity loads only, and designated as ‘GLD’ (Gravity Load Design). The second model is designed according to provisions of the current Indian seismic design code IS : 1893 (2002), which are actually applicable to buildings on flat terrain only. In addition to the usual gravity loads, earthquake forces corresponding to Indian seismic zone IV (Zone Factor 0.24 g) are considered. The model has been detailed for ductility requirements of ‘Special Moment Resisting Frames (SMRF)’ according to IS : 13920 (1993). It is to be noted that the SMRF of Indian code is equivalent to Intermediate Moment Resisting Frame (IMRF) of ASCE 7/ACI 318 in terms of the reinforcement detailing and response reduction factor. This is the most ductile category as per Indian code, and there is no building class in Indian code that would correspond to ‘SMRF’ of ASCE 7.

Nonlinear space frame models of the two buildings are developed (Singh et al. 2012, 2014) using the software SAP 2000 Nonlinear. Beams and columns are modeled using frame elements with lumped plasticity. The rigid diaphragm action of floor and roof slabs is simulated using diaphragm constraints on all the nodes at one floor level. Effective stiffness of the cracked RC members is considered according to ASCE 41 (2007) and so is the joint stiffness. Flexural plastic hinges are assigned at both ends of the beams, whereas P-M2-M3 interactive plastic hinges are assigned at the ends of the columns. Shear hinges are also assigned at the mid-height of the columns, mainly to simulate the shear failure of short columns on the uphill side. The properties of plastic hinges are defined according to ASCE 41 guidelines. The transverse reinforcement categories ‘Non-conforming (NC)’ and ‘Conforming (C)’ are used for ‘GLD’ and ‘SMRF’ buildings, respectively. Shear failure of columns is considered as being force-controlled.

Due to variable column heights, both building models are considered to be irregular in elevation leading to torsional effects. Therefore, both are subjected to bi-directional excitation in order to account for the torsional coupling of the response in the two directions. Incremental nonlinear dynamic (time-history) analysis (Vamvatsikos and Cornell 2002) is performed using the bi-directional components of seven recorded ground motion time histories. It can be observed from Table 3 that the buildings with step-back configuration have much lower seismic capacity than expected. RC frame buildings on flat ground, designed as per Indian codes have been found (Haldar and Singh 2009) to possess sufficient capacity to sustain the Maximum Considered Earthquake (MCE) of the zone for which those have been designed, whereas in case of the considered hill buildings, the buildings are not able to even sustain the Design Basis Earthquake (DBE) though they have been designed for. Their performance is particularly poor in the across-slope direction, being caused by torsional irregularities, resulting in failure at even lower intensities of shaking. The main reason of failure of these buildings, in both the cases of excitation (along and across the slope), is brittle shear failure of short columns at ground level (Figure 9).



(a) (b)

Figure 9. Typical failure pattern of SMRF building model: (a) major component of ground motion applied along the slope, and (b) major component of ground motion applied across the slope.

Table 3. Design and sustained levels of ground shaking

Design Level	Major component of shaking	Design level of shaking		Sustained level of shaking	
		$S_a (T_1, 5\%)$	EPGA	$S_a (T_1, 5\%)$	PGA
GLD	Along-slope	–	–	0.03g	0.04g
	Across-slope	–	–	0.02g	0.03g
SMRF	Along-slope	0.11g	0.12g	0.10g	0.11g
	Across-slope	0.07g	0.12g	0.06g	0.10g

4. Conclusions

Various issues regarding the seismic risk assessment in hilly regions have been identified. Hilly areas are not only subjected to topographic amplification, but higher vulnerability of building stock due to irregular structural configurations. Topographic amplification factors for the test bed city, using the three seismic design codes, which deal with the issue, have been compared. Among the three considered codes, the Italian code (ICMS 2008) predicts the largest amplification factors at the ridge. It has been found that the hill building configurations can sustain much lower PGA, than their counterparts on flat terrain, designed for the same seismic hazard, using the Indian codes.

Acknowledgments

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