2011 Sikkim Earthquake: Effects on Building Stocks and Perspective on Growing Seismic Risk

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SUMMARY
The M6.9 Sikkim Earthquake of Sept. 18, 2011 caused widespread damage in the state and adjoining areas and it exposed the seismic vulnerability of the recently built multi-storied construction. Many building collapses and structural damages were disproportionate to the observed intensity of shaking, primarily due to poor compliance with seismic codes, inferior quality of raw materials and shoddy workmanship. In addition, many unique and inherently poor construction features specific to the affected region significantly added to their structural deficiencies. The event provided ample evidence of growing seismic risk in the region with ever increasing inventory of vulnerable construction. On the other hand, some traditional buildings, like *Shing-Khim* and *Ikra* performed well but the preference for such construction is on steady decline. It is, therefore, important that earthquake-resistant construction practices should be promoted and implemented to mitigate the risk and hence, minimize the damage to property and loss of life.

Keywords: Seismic risk, Seismic vulnerability, Himalayan earthquakes

1. INTRODUCTION: 2011 SIKKIM EARTHQUAKE AND SEISMIC RISK

The M6.9 earthquake hit Sikkim and adjoining areas on Sept. 18, 2011 at 6:11 PM IST with its epicentre located at 27.72°N, 88.06°E, near India-Nepal border, about 68 km NW of Gangtok and at a focal depth of 19.7 km as reported by USGS. The IMD reported the epicentre location at 27.7°N and 88.2°E, with a focal depth of 10.0 km in Sikkim (Fig. 1.1). Three aftershocks of magnitude 5.0, 4.5 and 4.2 were also felt in Sikkim after the main event. In Sikkim the worst affected region was the North District where about 70% of the total deaths were reported. The seismo-tectonic perspective of the earthquake and the field observation of its effects have been studied and reported elsewhere (Rajendran et al., 2011; EERI, 2012; Rai et al., 2012).

This event provided a preview of what is likely to happen in the event of a larger earthquake and highlighted the issue of growing seismic risk in the Himalayan region. Seismic risks are the losses in terms of expected casualties, injuries and economic setback that are likely to result from exposure to seismic hazards. Seismic risk of a region is mainly determined by three factors: (*a*) the level of seismic hazard of that region, (*b*) the exposure of the people and the property to seismic hazard and (*c*) the vulnerability of these properties to the hazard. Seismic hazard is generally measured in terms of potential ground shaking and the possibilities of related effects, such as landslides, tsunami etc.

The loss of life and property caused during an earthquake are limited by the number of people present in stricken areas, and also constrained by the quantity and value of the buildings, infrastructure, and other property in those areas. Seismic risk increases as earthquake-prone regions become more densely populated and urbanized. Indiscriminate expansion of buildings in areas which are more vulnerable to earthquakes, construction of tall buildings on steep slopes in hilly areas increases the seismic risk. The vulnerability of property to seismic hazards is determined by the prevalence and degree of earthquake-resistant construction. Buildings, bridges, dams, road networks, communication lines and other lifeline structures that have been constructed in compliance with the latest seismic codes and standards will be more resistant to earthquake damage. Older and poorly built structures that were constructed under earlier, less-effective codes and not retrofitted to meet modern standards are likely to experience more damage. Levels of earthquake preparedness and disaster resilience determine how vulnerable people are to seismic hazards. Since this region had experienced moderate level earthquake in the past, the common people of Sikkim are aware of the possibility of moderate to large earthquakes in this region. Surprisingly, no consideration for seismic safety of the region in terms of building design and detailing and expansion of buildings has been observed. This paper mainly discusses how various factors, like seismological setting, economical boom leading to large infrastructure development and indiscriminate construction of houses are adding to the seismic risk of the Himalayan region and the 2011 Sikkim earthquake provided a glimpse of this ever growing seismic risk in the region.

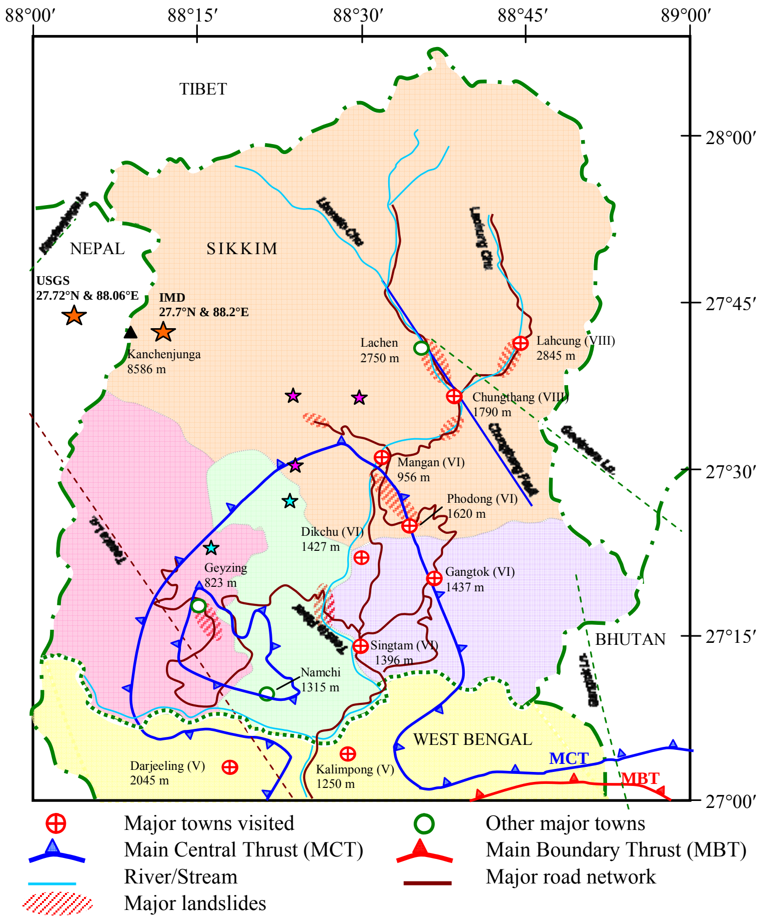
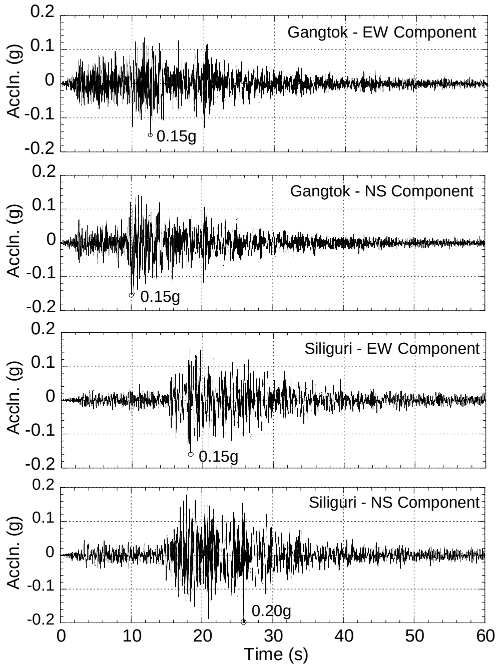


Figure 1.1 Location of epicenter of the earthquake and its aftershocks, Main Central Thrust fault (MCT), Main Boundary Thrust fault (MBT) and the towns visited in India.

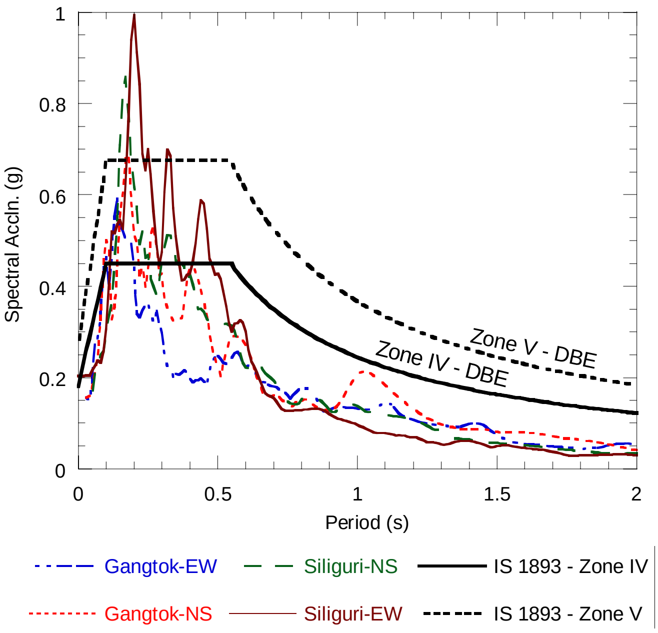
2. SIKKIM: SEISMOLOGICAL SETTING

The entire Himalayan arc is a seismically active region in the Indian subcontinent which has given rise to many earthquakes of M >8.0 since the Great Assam earthquake of 1897 in the north-east. Maximum seismic activity has been seen between the Main Boundary Thrust (MBT) and the Main Central Thrust (MCT). Thrust faults are oriented in E-W direction in the Himalayan region which suggests that the Indian plate is moving underneath the Eurasian plate in N-to NNE-SSW direction. The eastern India-Nepal Himalaya zone has been seismically active with major earthquakes occurring in the north of the MBT. In the Sikkim Himalayas, the MBT and MCT are not parallel, with the MCT arching to create the form of a culmination, an exceptional geologic feature which is believed to be a controlling factor for earthquakes in the region as shown in Fig. 1.1 (Nath et al., 2000; De and Kayal, 2003). Three other moderate earthquakes to have hit the region in the recent times are the M5.9, M6.0 and M5.3 events in 1965, 1980 and 2006, respectively.

In strongly felt areas, the earthquake motions were recorded at Gangtok and Siliguri by strongmotion accelerographs operated by Department of Earthquake Engineering, IIT Roorkee. The PGA values recorded at these locations are 0.15*g* and 0.20*g*, respectively, as shown in Fig. 2.1 alongwith their 5% damped elastic response spectra. Response spectra of these ground motions were also compared with the code prescribed elastic design response spectrum in Zones IV and V for the design basis earthquake (DBE) level (scaled for a general load factor of 1.5). It is clear that in the acceleration controlled regime (i.e., short period range which is typical for low-rise unreinforced masonry and infilled RC frame construction) the ground motion has much higher acceleration demand than the code expected demand in Zone IV. Moreover, in places where heavy damages were observed, such as, Chungthang and Lachung in North Sikkim, the ground motion during this earthquake may have been more severe than those at Gangtok and Siliguri, which are at a distance of 68 km and 119 km from USGS epicenter, respectively. Since Sikkim lies in Zone IV of the Indian seismic code IS 1893-2007 (Fig. 2.2a), it appears that code design forces corresponding to Zone IV in Sikkim is being underestimated and it would be more reasonable to upgrade the region to Zone V and thereby increasing design forces by 50%. This underestimation of hazard by IS 1893 is also noted by earlier researchers (Bilham & Wallace, 2005) on account of ongoing activities and possibility of occurrence of great earthquake in the Sikkim Himalayas (Fig. 2.2b).



(a)



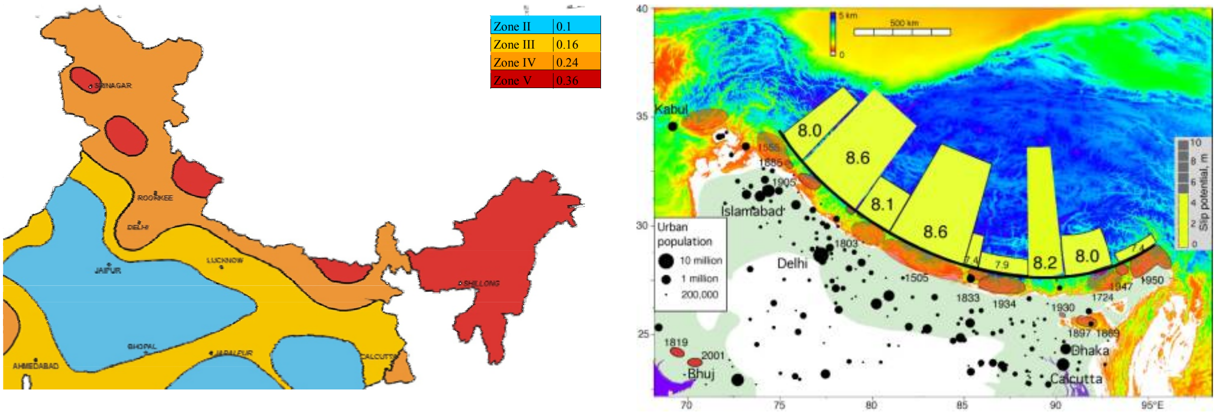
(b)

Figure 2.1 (a) Acceleration time histories for the main shock of September 18, 2011 event recorded at Gangtok and Siliguri (Band pass filtered, 0.1 Hz – 25 Hz) (b) Comparison of 5% damped acceleration response spectra of the recorded ground motions with the Indian seismic code specified elastic design response spectrum in Zone IV and V at DBE level (scaled by 1.5 for factored design loads).

3. POPULATION GROWTH, INFRASTRUCTURE DEVELOPMENT AND EXPOSURE TO SEISMIC HAZARDS

Large areas of Sikkim are restricted to public access; as it is surrounded by three countries namely Nepal, China and Bhutan. The terrain of this region is uneven and landslides occur very often because of the geology and geomorphology of the region. For these reasons the population distribution in

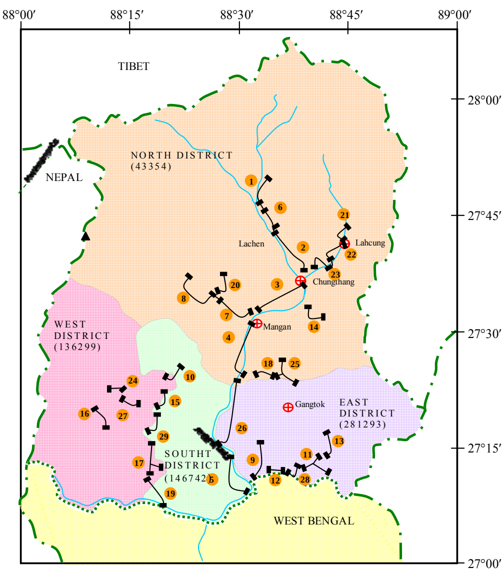
Sikkim is uneven and most of the development in terms of industries and settlement is concentrated at few locations as indicated by population density in Fig. 3.1



(a) (b)

Figure 2.2 (a) Seismic zoning map as Indian (IS 1893) seismic code (b) Possibility of occurrence of great earthquake in the Sikkim Himalayas

Infrastructure development and building pattern are subject to environmental factors such as climatic condition, soil condition etc, subject to practical constraints related to the lack of indigenous resources, income, education, and government policies. The gross domestic product (GDP) of Sikkim in the 2011 financial year was estimated as $1230 million, only 0.08% of the gross GDP of India and constituting the fifth smallest GDP of an Indian state/union territory as per VMW report (2012). However due to small population of the state (about 608 000), the overall prosperity is high and the GDP per capita is $1065 for the financial year of 2011. The pace of urbanisation due to the economic boom brought by tourism has created tremendous infrastructure requirement. This led to the expansion of road network, construction of bridges, building of dams and tunnels for power generation. A total of 28 hydroelectric power plants are proposed to set up in the state in last 15 years. Some are completed and others are under construction or under survey (Fig. 3.1). Among them, six projects along river Teesta which flows across the length of Sikkim are the major facilities with a total power generation capacity of 1047MW.



Poplulation density sq. km	
North	0-60
West	60-150
South	150-200
East	250-350

Figure 3.1 Major Hydro electric power plants and population density distribution in Sikkim

Housing has also evolved and undergone significant transformation in the last 20 years. Earlier, it was common practice in Sikkim to construct residential buildings using bamboo/wood, but the economic development in early nineties prompted the transformation of RC structure from traditional housing. The restriction on the felling of trees for timber, the high maintenance cost of timber structures and the easy availability of loans from the financial institutions for constructing RC buildings have further accelerated this change. Moreover, due to urbanization the tremendous increase in housing requirement and lack of availability of suitable lands forced the people to construct houses in vulnerable areas like sloped ground, sinking area and also improper extension of existing buildings. Most of the buildings do not follow the guidelines regarding number of floors, plan area, etc., provided by the urban development authorities. Most settlement and housing pattern in urban areas is unplanned and inadequately supervised (Fig. 3.2).

(a) (b)

Figure 3.2 Urban settlement and housing pattern (a) Gangtok (East District) and (b) Chungtang (North District)

4. VULNERABILITY TO SEISMIC HAZARD

Assessment based on expected seismic performance of buildings based on engineering computations and design specification shows the vulnerability of the building stocks of a particular region. These uncertainties are due to various reasons like the type of structure, the construction material, construction practices, quality and workmanship, geometrical and structural regularity, local soil condition and also on the state of building.

4.1 Building Typologies

There are mainly three types of building construction practices followed in Sikkim, namely RC frame type with infill walls, *Shing-Khim* type construction and *Ikra* houses. These construction practices are distributed according to the economic development and availability of indigenous raw materials. In modern times, RC frame buildings with masonry infill are prevalent in urban areas. A variety of roof types from lightweight tubular truss to RC slab is in practice. The most common building type in the urban and low altitude areas consists of RC frame. In Gangtok, several nine to ten storey RC buildings were frequently observed whose first three stories are above road level whereas the rest are below the road level supported on sloped ground. RC frame construction has also spread in upper reaches like North district but most of these buildings are not more than three stories. As was frequently observed, concrete blocks both hollow and solid were the prevailing masonry unit in RC frame buildings. Because of its hilly terrain, and lack of transportation, Sikkim lacks a large-scale industrial base. Most of the raw building materials, such as, clay bricks are transported from Siliguri, West Bengal, the nearest town in the plains which serves as a main gateway for road transportation into Sikkim.

Traditional construction in Sikkim mostly consists of *Shing-Khim* (meaning wooden house) and *Ikra* houses (Fig. 4.1a-b). Such houses were constructed using locally available materials. These practices had been observed throughout the affected area and were more in number in Northern districts. S*hing-Khim* houses are single storey structures consisting of wooden planks connected by steel flats with bolts and nails. However, *Ikra* houses are one to two storey timber framed structure filled with specially prepared panels. Infill panels are prepared by bamboo splints woven together with wooden frame and plastered with cement/mud mortar on both faces to have a finished look. In *Shing-Khim* and *Ikra* construction, the superstructure is generally supported on wooden post and an exterior basement wall of R/R masonry was provided for thermal insulation. However, in many cases these houses are constructed on RC columns or simply rested on grade. Pitched roofs made of asbestos or corrugated galvanized iron sheets (CGI) on wooden truss are common in this area because of incessant rain throughout the year with an average annual rainfall of about 3000 mm. Table 4.1 summarises the building typologies which has evoloved in Sikkim over the years.

(a) (b)

Figure 4.1 Types of Buildings in Sikkim (a) *Shing-Khim* house (b) *Ikra* house

Table 4.1. Evolution of housing types in Sikkim

Common Housing types		**Structural System**	
		Beams, Columns and Walls	**Diaphragms for floors and roofs**
Traditional	*Shing-Khim* house	Timber joists, beams and posts, timber stud frame and boarding for wall	Timber joist and boarding for the floor, trussed timber rafters with boarding and asbestos/ CGI sheets
	Ikra house	Timber joists, beams and posts, timber stud frame with infill panels of bamboo splints and cement plaster on both sides	
	Random Rubble masonry building	Exterior load bearing exterior wall having stones laid in mud mortar or weak cement sand mortar	
Modern	RC frame building	RC beam and column as frame unit, infill and partition walls in brick, hollow/solid concrete blocks laid in cement sand mortar	Flat RC slab

4.2 Typical Construction Practices

Modern buildings in RC-frame are mostly planned on rectangular grid of columns at relatively smaller bays which had significantly helped their earthquake resistance, though in some cases irregular grid of columns was observed as shown in Fig. 4.2a. Rising housing demand and limited availability of good land for the construction has forced the adoption of structural configurations, which suffer extensively from many plan and vertical irregularities, for both new buildings as well as unplanned extension of existing buildings (Fig. 4.2b). Indiscriminate use of unsupported partition wall for functional purpose has resulted in various plan irregularities leading to unacceptably large torsional stresses. *Jettying* (horizontal cantilever projection) is often employed in urban areas to create greater floor plan area in upper stories of buildings as shown in Fig. 4.2c. Most of the buildings constructed on sloped land are connected at multiple levels with the ground unlike the houses built on flat lands. The ground motion input at multiple levels of the building cause complex dynamic response, which is usually not analyzed and rarely, accounted for in the design of such structures. In addition, buildings are constructed too close to each other, sometimes with no gap separating adjacent buildings, making them vulnerable to pounding damage (Fig. 4.2d).

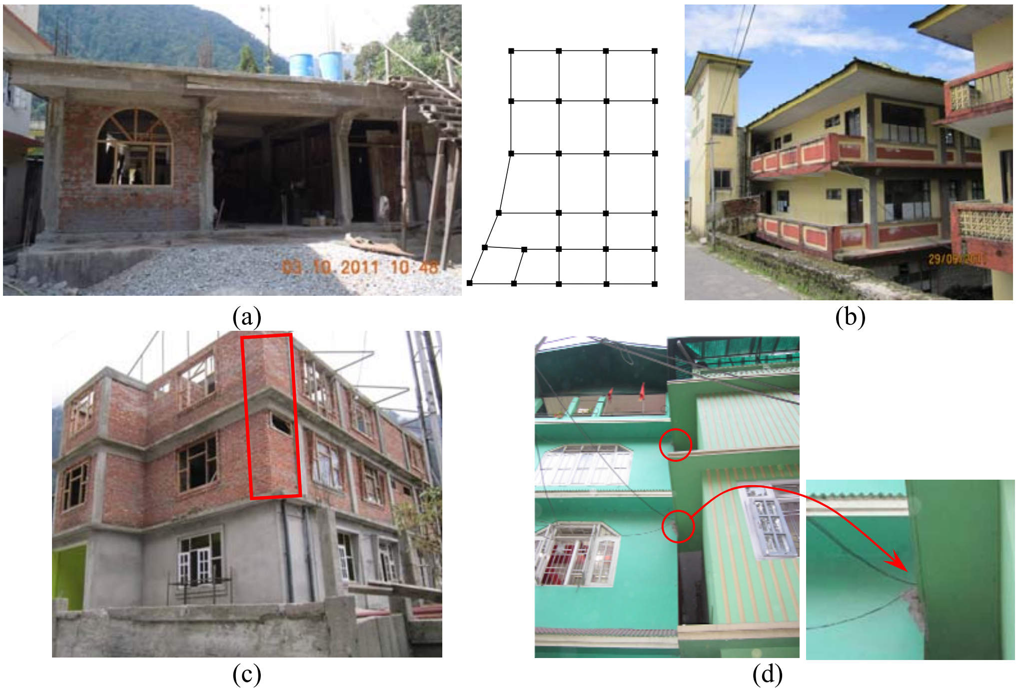


Figure 4.2 Construction practices (a) Building on irregular column grid (b) Multi-level connection of buildings with ground (c) Unsupported masonry wall at corners (d) Adjacency of buildings

The RC buildings are mostly designed to carry gravity load only and no provision is made to resist earthquake loads. Dimension of the columns varies from 200 mm to 300 mm. Main reinforcement bars in beam and columns consist of both mild steel and deformed steel bars. Seismic detailing was not observed in the main components, i.e., beams, columns, beam-column joints of the buildings. Shear reinforcement of insufficient length having ties with 90º hook, lapping of reinforcement at critical section of the beams and columns and splicing of all reinforcement at the same location was observed (Fig. 4.3a-b). Due to ease of construction, the construction joints at columns were located at the critical locations, i.e., at the top and bottom ends of columns as shown in Fig 4.3b. The common deficiencies present in buildings which increase their seismic vulnerability is listed in Table 4.2.

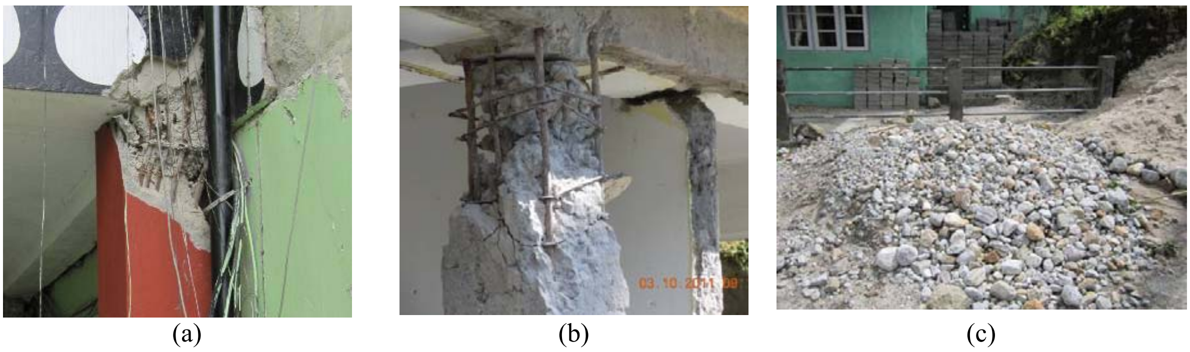


Figure 4.3 Poor detailing (a) Lapping at beam column joint (b) Widely spaced stirrups with 90º hook (c) Inferior quality of construction material

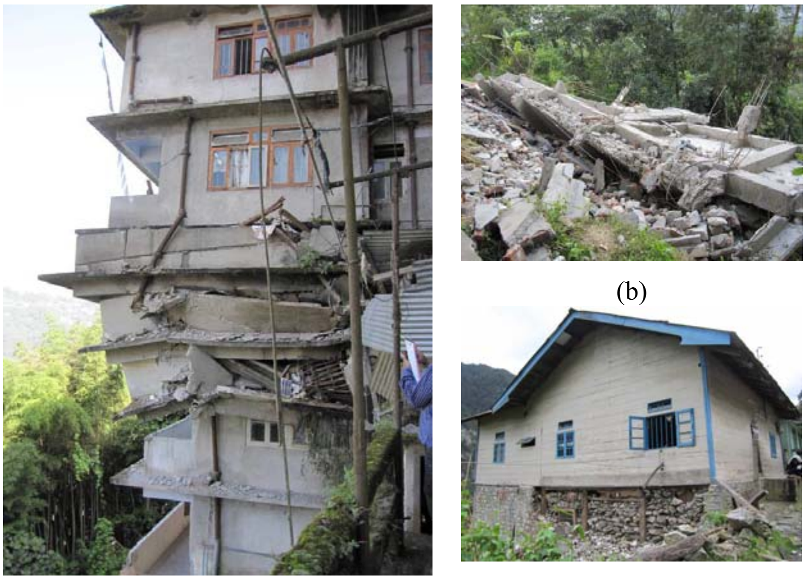
Other common problems are related to poor quality of construction material like inferior and round river stone as coarse aggregate, weak and locally made concrete blocks as infill materials (Fig. 4.3c). Concrete is commonly mixed with hands resulting in heterogeneous batches and inconsistencies between batches. The concrete mix proportion was frequently observed to have high water content in order to increase workability and it is often poured directly into formwork with no vibration or consolidation.

Table 4.2. Common vulnerability of RC buildings in Sikkim

Vulnerability	Features
Irregularities	Vertical irregularities, such as soft and weak storeys, setbacks, jettying of upper floors and unsymmetrical placement of infills, irregular column grid, etc.
Construction practices and workmanship	Inferior quality of construction material
	Cold joint at the ends of the column
	Construction on sloped ground , unstable slopes and weak retaining wall
	Hand mixing of concrete; no control of water/cement ratio, volume batching, improper consolidation of concrete, etc.
Design and detailing	Relatively smaller size columns even for buildings as tall as seven stories
	Presence of short-column due to construction of partial height masonry walls in concrete frames reducing the effective length of column, a factor not accounted for in the design of such columns
	Lack of confining reinforcement, inadequate hook length not bent at 135°
	Improper splicing of bars, lapping near the beam-column joint,
	Buildings with overhanging upper stories over cantilevered beams and columns with corbels, etc.

5. OBSERVED VULNERABILITY: 2011 SIKKIM EARTHQUAKE

The vulnerability to built environment discussed in the previous section got exposed in the recent earthquake. General damage to buildings and other structures agreed well with the intensity of ground shaking observed at various places, with the maximum of VIII in parts of North district, and VI in and around Gangtok on MSK scale. However, unexpected severe damage at an intensity of VI in Gangtok was observed in buildings such as, two multistory buildings in Balwakhani, Gangtok (Fig. 5.1a&b). About 95000 houses have been fully, partially and severely damaged. Out of the fully damaged buildings, about 20% buildings are of RC frame type while only 4% buildings are of traditional type.



(a) (b) (c)

Figure 5.1 (a) Pan-caking of middle two storeys in a 9-storey building, Gangtok (b) Collapse of a building near Balwakhani, Gangtok (c) Collapse of random rubble masonry wall at the foundation level in *Shing khim*.

The traditional buildings, (*Shing-Khim* and *Ikra)*, have better earthquake resistance as observed in the present and past earthquakes (Kaushik et al., 2006). In the present earthquake no major damage was observed and reported in these light weight structures. Damage was only observed at the foundation level to the R/R masonry in most of these buildings as shown in Fig. 5.1(c). Presence of wooden frame at close intervals resulted in an excellent earthquake resistant feature that performed well. Moreover, the closely spaced studs prevent propagation of diagonal shear cracks within any single panel, and reduce the possibility of the out-of-plane failure of panels.

Unlike traditional houses, many government and private RC buildings sustained severe damage and even collapsed mainly due to lack of earthquake-resistant features in combination with poor quality of concrete and construction practices. Most of the RC buildings at major towns suffered damages of some form or the other, the most common being shear and/or flexure failure at column ends, shear failure of beam-column joints, in-plane failure of weak infills and out-of-plane failure of slender walls. Fig. 5.2 shows damage to buildings due to some of these common deficiencies.

Failure of infill walls in RC frame structure was commonly observed due to poor quality of infill material (low density/strength concrete blocks), and poor connection between walls and supporting frame element. Most of these infill walls failed in out-of-plane direction due to their higher slenderness ratio; as thin concrete blocks (80-100 mm), half-brick thick wall and even brick on edge was used. Moreover, indiscriminate use of unsupported partition wall and exterior walls for functional purpose has resulted in unacceptably large torsional stresses causing failure of these walls.

(a) (b) (c)

Figure 5.2 (a)Typical column failure (b) In-plane failure of weak infill masonry and (c) Out-of-plane collapse of concrete block masonry walls.

School and educational buildings in Sikkim are both traditional construction as well as modern RC types. These buildings also suffered extensive damage, with the partial/complete collapse of around 23 school buildings reported in Sikkim alone. Well-built school buildings, such as Tashi Namgyal Academy (TNA) in Gangtok performed satisfactorily as compared to several seismic deficient buildings.

6. GROWING SEISMIC RISK AND POSSIBLE WAYS FOR ITS MITIGATION

The level of damage to building stocks and observed shaking in affected regions of Sikkim indicates that the seismicity of region is underestimated. Moreover, the increasing pace of infrastructure development is not in accordance with the land-use planning and construction practices which help to reduce the seismic vulnerability of the built environment. The Sept. 18, 2011 earthquake was a remarkable event as it demonstrated how seismic risk is rising rather rapidly due to increasing exposure of vulnerable structures in a region of well known significant seismic activity. There is an urgent need to take certain steps to mitigate the effects of growing seismic risk, for example:

- *Good construction practice and quality material* – It is critical to promote good concrete and masonry construction practice and suitable alternative materials.
- *Promotion of earthquake resistant building typologies* – Locally available materials (such as bamboo and other sustainable timber alternatives) and traditional technologies which have

proven their ability to resist earthquake loads should be reinstated and integrated with modern construction practices to have an appropriate design for strong and safe housing. For low rise buildings, new building typologies of proven earthquake performance, such as confined masonry need to be introduced.

- *Compliance to seismic codes* – The state of Sikkim is prone to much greater shaking than caused by the present event; hence compliance to seismic codes can not be ignored. Strict adherence is mandatory to relevant BIS codes for new constructions and documents like IITK-GSDMA guidelines for seismic evaluation and strengthening of existing buildings.
- *Awareness among all stakeholders* – All stakeholders including builders, contractors, engineers, private owners, government officials and public at large must be educated about the importance of geological setting, geotechnical issues and earthquake-resistant construction and their role in mitigating the future seismic risk.

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REFERENCES

Bilham, R. and Wallace, K. (2005). Future M_w>8 earthquake in the Himalaya: Implications from the 26 December 2004 M_w=9 earthquake on India's eastern plate margin. *Special Publication*, Geological Survey of India, **85**, 1-14.

BIS. (2002). IS:1893 Indian Standard Criteria for Earthquake Resistant Design of Structures: Part 1– General Provisions and Buildings, Bureau of Indian Standards, New Delhi. (2002).

De, R. and Kayal, J. R. (2003). Seismotechtonic model of Sikkim Himalaya: Constraint from microearthquake surveys. *Bulletin of Seismological Society of America*, **93:3**, 1395-1400.

EERI. (2012). The M_w 6.9 Sikkim-Nepal Border Earthquake of September 18, 2012: Learning from Earthquakes, *Special Earthquake Report*, Earthquake Engineering Research Institute, Oakland, CA.

Kaushik, H. B., Dasgupta, K., Sahoo, D. R. and Kharel, G. (2006). Performance of structure during the Sikkim earthquake of 14 February 2006. *Current Science,* **91:4**, 449-455.

Nath, S. K., Sengupta, P., Sengupta, S. and Chakrabarti, A. (2000). Site response estimation using strong motion network: A step towards microzonation of Sikkim Himalayas. *Current Science,* **79:9**, 1316-1326.

Rai, D. C., Mondal, G., Singhal, V., Parool, N., Pradhan, T. (2012). Reconaissance repot of M 6.9 Sikkim (Nepal-India Border) Earthquake of 18 September 2011. *Geomatics Natural Hazards and Risk,* **3:2**, 99-111.

Rajendran, K., Rajendran, C. P., Thulasiraman, N., Andrews, R. and Sherpa, N. (2011). The 18 September 2011, North Sikkim earthquake, *Current Science,* **101:11**, 1475-1479.

VMW. (2012). Economy of the Federal States For Year 2011 & Population for Year 2011, [Online], Available: http://unidow.com/india home eng/statewise_gdp.html, [20 April 2012].