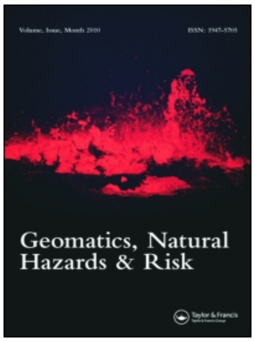

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Reconnaissance report of the M6.9 Sikkim (India–Nepal border) Earthquake of 18 September 2011

DURGESH C. RAI*†, GOUTAM MONDAL†, VAIBHAV SINGHAL†, NEHA PAROOL†, TRIPTI PRADHAN† and KEYA MITRA‡

†Department of Civil Engineering, Indian Institute of Technology Kanpur, Kanpur, India

‡Department of Architecture, Town and Regional Planning, Bengal Engineering and Science University, Shibpur, India

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The M6.9 Sikkim Earthquake of 18 September 2011 caused widespread devastation in the state and adjoining areas from disrupting the road network to damaging structures of commercial, public, and religious values. This event presented another opportunity to further the understanding of earthquake risk of the affected region as well as of the North-Eastern Himalayan region, which have similar patterns of seismicity, built environment and construction practices. The general pattern of damage to structures, landslides, rockfalls, etc. was consistent with the shaking associated with this event. However, collapses of many buildings and damages to structures were disproportionate to the observed intensity of shaking, primarily due to poor compliance with seismic codes, inferior quality of raw materials and shoddy workmanship. Consequently, the seismic risk in the region is growing at an alarming pace with increasing inventory of vulnerable construction. The current event provides a preview of what is likely to happen in the event of a larger earthquake which the Himalayan region has witnessed in the past. This article discusses the construction practice in Sikkim Himalayas and their seismic performance in the recent earthquake, highlighting the vulnerability of inventories and suggests steps to mitigate the seismic risk for future events.

1. Introduction

Field study of the earthquake effects has been crucial in understanding the nature of the natural hazard, its impact and extent of the risk exposure to the society. The lessons learnt will help improve mitigating the seismic risk by ensuring earthquake-resistant construction suitable for the appropriate level of the hazard present, effective emergency response teams, and identifying topics for follow-up research activities in hazard estimation and measures adopted to reduce the vulnerabilities of the built environment (EERI 1986, 1996). The Sikkim earthquake of 18 September 2011 caused widespread devastation in Sikkim and adjoining areas from disrupting the road network to damaging structures of commercial, public, and religious values. The total loss of facilities in Sikkim has been estimated to be about US$ 1.4 billion.

*Corresponding author. Email: dcrai@iitk.ac.in

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This event presented another opportunity to re-evaluate the earthquake risk of the affected region, in particular, and of the North-eastern Himalayan region, in general, which have similar patterns of seismicity, the built environment and construction practices.

2. Earthquake and its seismological setting

The M6.9 earthquake hit Sikkim and adjoining areas on 18 September 2011 at 6.11 PM IST with its epicentre located at 27.72°N, 88.06°E, near Nepal–Sikkim border, about 68 km NW of Gangtok and at a focal depth of 19.7 km as reported by the United States Geological Survey (USGS, www.usgs.gov). The Indian Meteorological Department (IMD, www.imd.gov.in) reported the epicentre location at 27.7°N and 88.2°E, with a focal depth of 10.0 km in Sikkim (figure 1). Tremor which lasted for about 15 s was felt in Nepal, India, Bhutan, Bangladesh and Tibet. Three aftershocks of magnitudes 5.7, 5.1 and 4.6 were also felt in Sikkim within 30 min of the earthquake. About 100 deaths are reported with the maximum of at least 60 in the state of Sikkim.

The whole Himalayan arc has been a seismically active region which has given rise to many earthquakes of $M > 8.0$ in the Indian subcontinent since the Great Assam earthquake of 1897 in the north-east. The maximum seismic activity is 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 at some angle in N- to NNE-SSW direction.

The eastern Nepal–Sikkim Himalaya zone has been seismically active with major earthquakes occurring the north of the MBT. In 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 Sikkim Himalayas (figure 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. Events of 1965 and 1980 were caused by strike-slip movements similar to the recent event of the 18 September, suggesting the presence of transverse tectonics in the region. Sikkim lies in zone IV of Indian seismic code IS: 1893 with expected intensity of VIII (BIS 2002). The recent activities and possibility of occurrence of great earthquake in the Sikkim Himalayas and neighbouring areas have raised concern on the underestimation of hazard by IS 1893 (Bilham 2004, Raju *et al.* 2007).

3. Geological hazard

The earthquake caused more than 300 landslides spreading over approximately 2400 sq. km area from Namchi in the South District to Lachen in the North District of Sikkim state. A large number of landslides were observed at higher altitudes close to the epicentral region (figure 2). Landslides cut off the severely affected areas such as Chungthang and Lachung from the rest and hampered rescue and relief operations. In Lachung, rockslides and mudslides after two days of the main event changed the course of a stream and caused extensive damage as shown in figure 3. Several areas of these cities are prone to ground sinking and have unstable slopes which become more susceptible to failure in the rainfall.

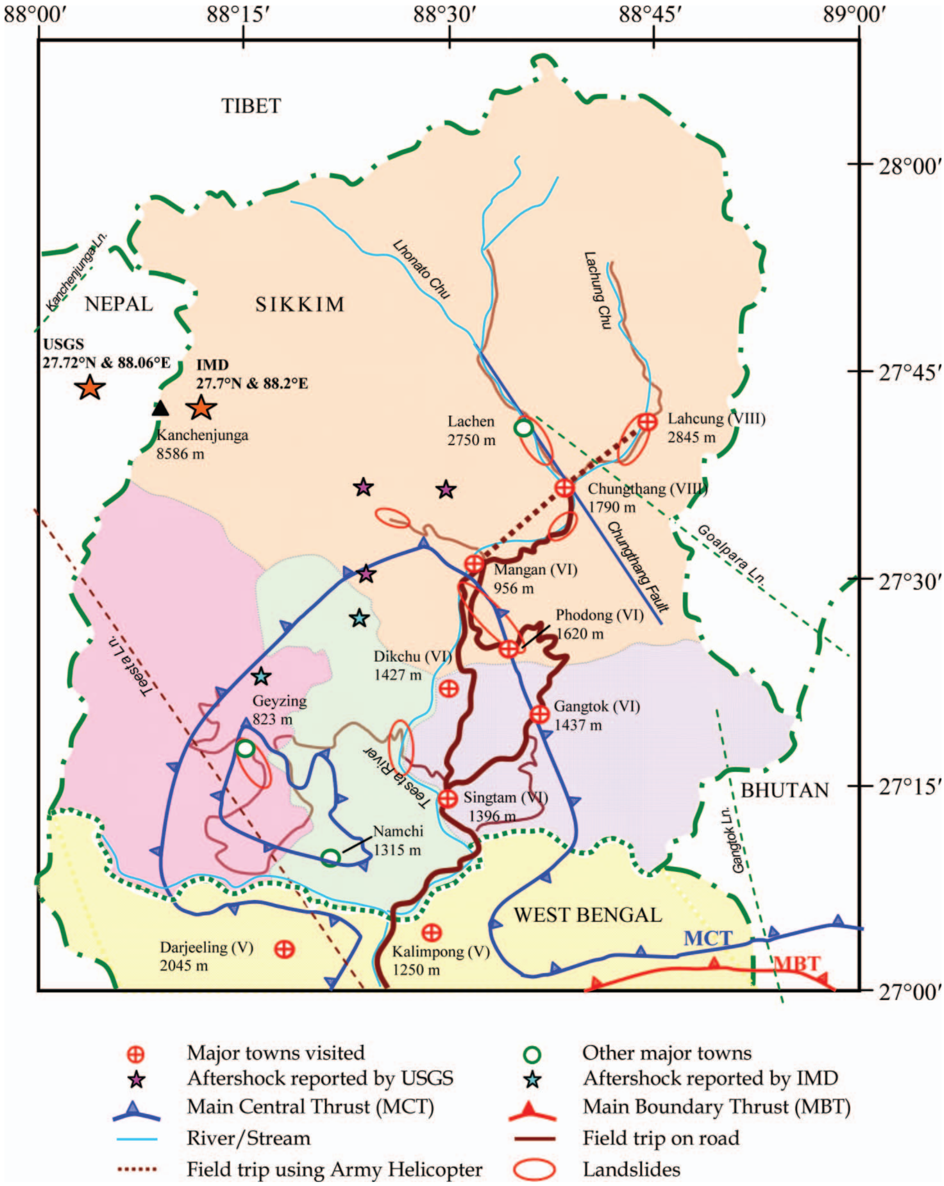

Figure 1. Location of epicentre of the earthquake and its aftershocks, Main Central Thrust fault (MCT), Main Boundary Thrust fault (MBT) and the towns visited in India.

4. Structural damages

General damage to buildings and other structures agreed well with the intensity of ground shaking observed at various places, with the maximum of VIII at Chungthang and Lachung, and VI in and around Gangtok and Mangan on MSK scale. However, unexpected severe damage at an intensity of VI in Gangtok was observed in buildings such as the secretariat building at Tashiling in Gangtok (figure 4). It was a 32-year-old RC frame building infilled with hollow concrete

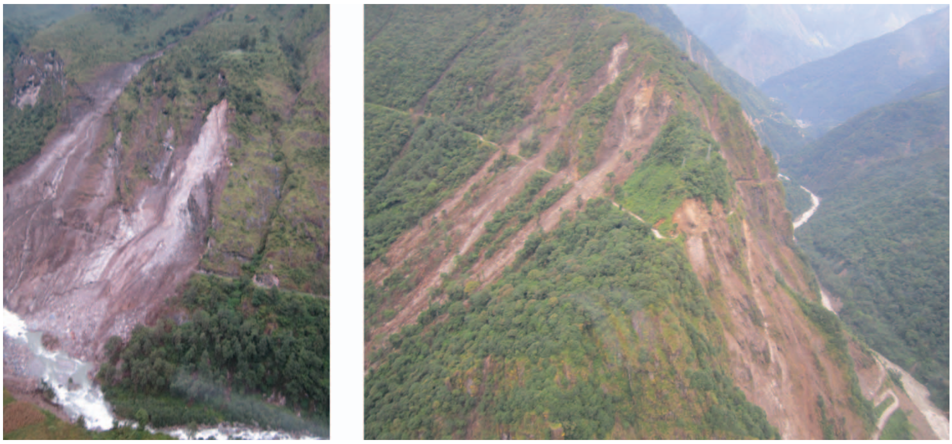

Figure 2. Aerial photograph showing typical landslides en route from Mangan to Chungthang and Lachung.

Figure 3. Damage caused due to rockslide and mudslide at Lachung (*MSK-VIII*).

block. This building suffered damages in columns, infill panel, cladding, etc. Minor damage was also observed in this building during the 2006 Sikkim Earthquake (Mw 5.3). In addition, partial collapse of two multi-story buildings at Balwakhani (figure 5*a* and *b*) and total collapse of a five-storey building at Lumshey Basty (figure 5*c* and *d*) were observed.

Apart from the buildings, the area has a large number of highway and pedestrian bridges on rivers, rivulets and gorges. Only minor damage to a few highway bridges was noticed in the areas visited (figure 6). Abutment of the Palekhola Bridge (*khola* means river) sustained minor damage mainly due to the inadequate support of the seating block which rotated towards the backfill after the partial loss of bearing during the earthquake shaking (figure 6*a* and *b*). Partial collapse of wing walls of the Raykhola Bridge (span 32 m) was observed on both sides (figure 6*c*). Damage to the wing walls was caused by the low strength random rubble (R/R) masonry, poor workmanship and construction. However, the main steel truss bridge performed satisfactorily during this earthquake.

Figure 4. Damage to the state secretariat building at Tashiling in Gangtok (*MSK-VI*).

There are several hydroelectric power plants in Sikkim across the river Teesta and its tributaries. No damage was observed in the dam structure due to earthquake shaking. The hydroelectric power stations performed satisfactorily; the only visible damage was minor cracking in masonry infill walls at various locations in the power stations of Project Teesta-V (513 MW) and Project Rangit (60 MW). Due to landslides, some damages were observed to water conduits, intakes, penstocks of several hydroelectric power plants. The power transmission and distribution network has also been badly affected.

It was common practice in Sikkim to construct residential buildings using bamboo/wood, until the economic development aided by tourism industry got a boost in early nineties. These traditional buildings, also called *Shee-khim* and *Ikra*, have better earthquake resistance as observed in the present and past earthquakes

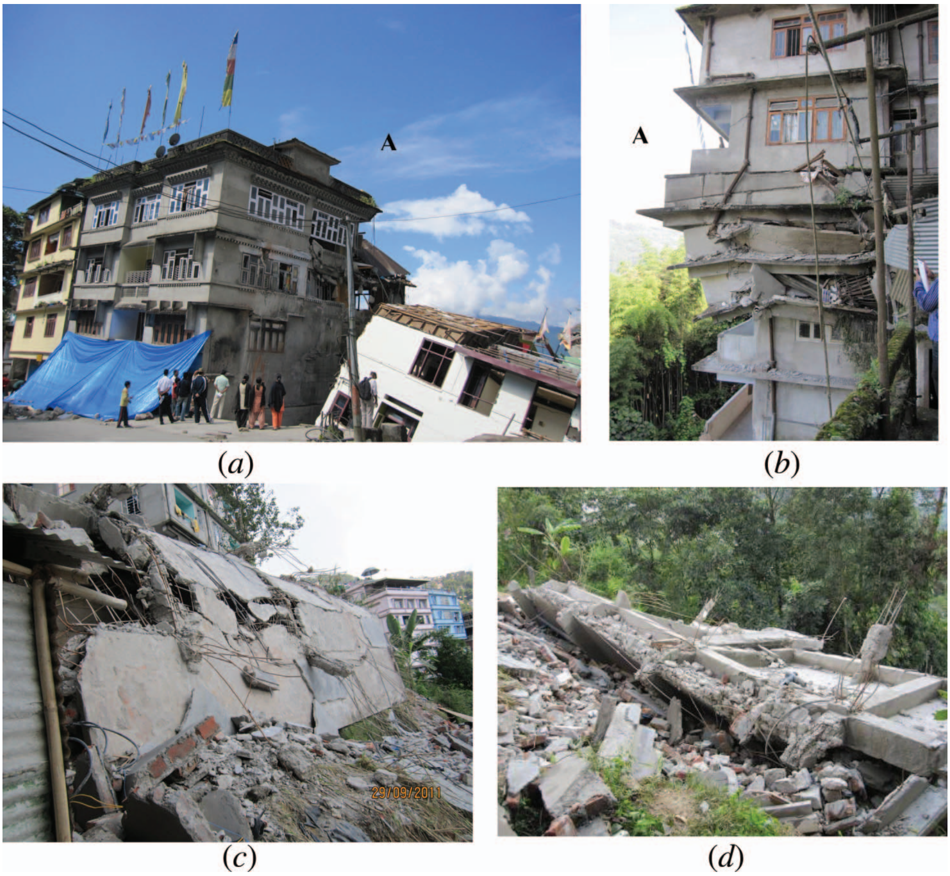

Figure 5. (*a*) Collapse of two multi-storey buildings at Balwakhani in Gangtok (*MSK-VI*); (*b*) view of building A, in figure 5*a*, from backside; (*c*) and (*d*) collapse of a five-storey building at Lumshey Basty in Gangtok.

(figure 7) (Kaushik *et al.* 2006). These practices had been observed throughout the affected area and were more in number in the upper reaches like Lachung. *Shee-Khim* houses are single storey structures consisting of wooden frames and planks. However, *Ikra* houses are one–two storey timber framed structure filled with specially prepared infills made of bamboo splints and plastered with cement/mud mortar. In the present earthquake, no major damage was observed and reported in such houses. Presence of wooden frame at close intervals resulted in an excellent earthquake-resistant feature that performed well.

Unlike traditional houses, many government and private RC buildings sustained severe damage and even collapsed due to lack of earthquake-resistant features, such as ductile detailing in RC beams and columns (adequate confining reinforcement and stirrups with sufficient hook length bent at 135°), proper splicing of bars, and lapping of reinforcement away from beam–column joint, etc. Many unique and inherently poor construction features, such as weak and very slender partition walls in brick/block masonry or in lightly reinforced/plain concrete, extended floor plans in upper stories supported on cantilevered beams and slabs, construction on sloped ground,

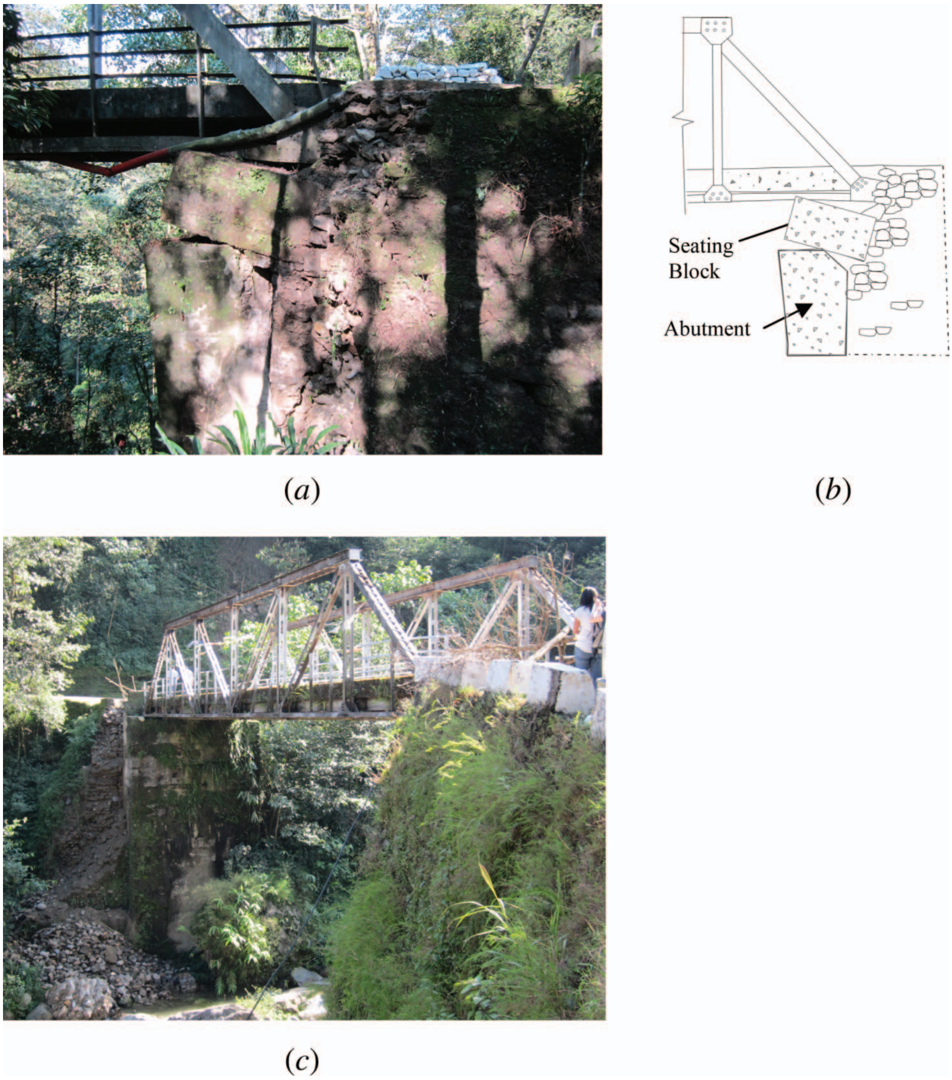

Figure 6. (*a*) Failure of seating block overhanging the abutment of Plaekhola Bridge, (*b*) schematic of the failure of seating block at Plaekhola Bridge and (*c*) damage to the wing wall of steel truss bridge on Raykhola.

unstable slopes, weak retaining walls, poor construction material, etc. significantly added to the seismic vulnerability of these structures. Most of the RC buildings at Gangtok and Chungthang 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 (figures 8 and 9). In addition, buildings are constructed too close to each other, sometimes with no gap at all between adjacent buildings and this resulted in damage due to pounding of buildings (figure 10).

School and educational buildings in Sikkim are of traditional and modern RC types. These buildings also suffered extensive damage, with the partial/complete collapse of around 23 school buildings reported in Sikkim alone. In Chungthang,

(a) (b)

Figure 7. Traditional construction type: (*a*) *Ikra* house and (*b*) *Shee-Khim* house.

(a) (b)

Figure 8. (*a*) and (*b*) Typical failure at column ends (widely spaced stirrups with 90° hooks, cold junction at the column top, poor concrete quality).

pancake collapse was observed in the third storey of a five-storey RC school-cum-residential building (figure 11). Well-built school buildings such as Tashi Namgyal Academy (TNA) in Gangtok performed satisfactorily as compared to the buildings deficient in earthquake-resistant designing and built during the colonial period in Kalimpong, West Bengal (figure 12).

The poor earthquake performance of cultural heritage such as monasteries is a source of concern as almost all historic religious structures suffered varying degree of damages in this earthquake. The exterior walls of monastery temples are constructed of stone masonry mostly random rubble while the interior building frame is constructed of timber using single post beam system. Heavy damages have been

Figure 9. (*a*) In-plane failure of weak infill masonry and (*b*) out-of-plane collapse of concrete block masonry walls.

Figure 10. Pounding damage to adjacent buildings at Gangtok (*MSK-VI*).

Figure 11. Five-storey school cum residential building in Chungtang (*MSK-VIII*).

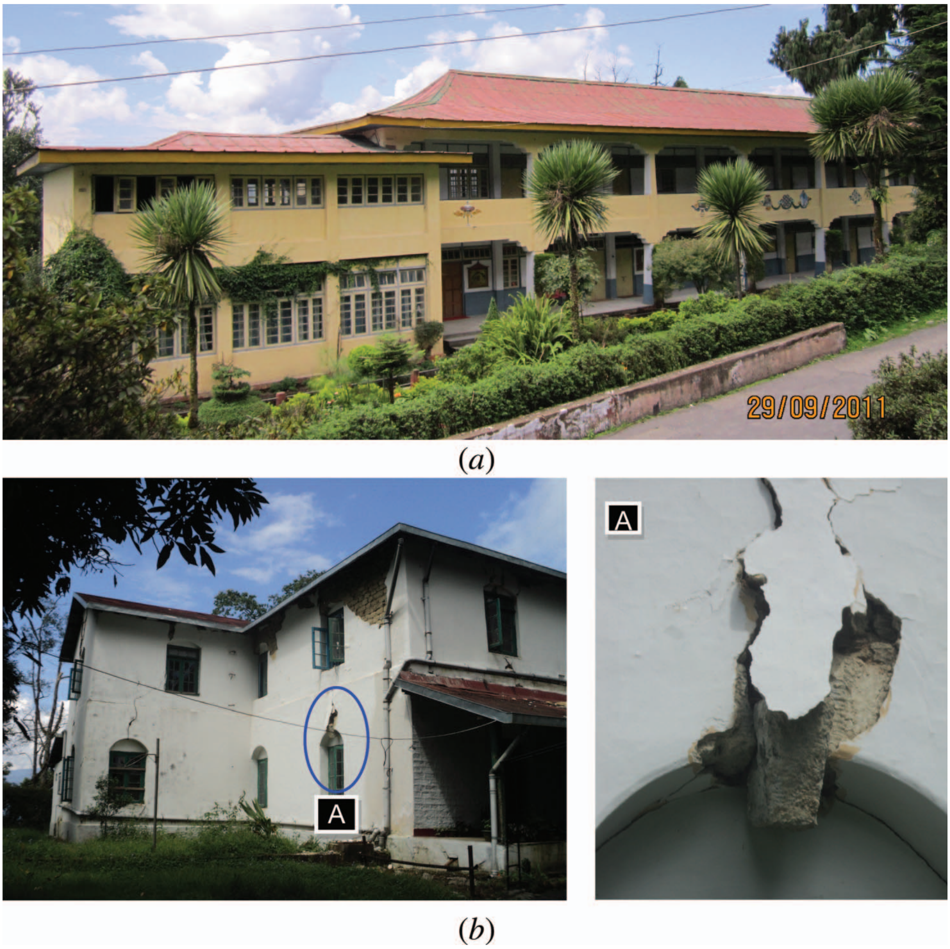

Figure 12. (*a*) Well-built school building of Tashi Namgyal Academy (TNA) in Gangtok (*MSK-VI*) performed well in the recent M6.9 event and (*b*) dormitory in Dr. Graham's Homes suffered extensive damage in gable wall and arch in building with re-entrant corner, Kalimpong (*MSK-V*).

observed to exterior walls at several monastery temples at Mangan and Lachung (figure 13). In Kalimpong, two brick spires of the historic Mac Farlene Church have collapsed and the tall load bearing walls at the gable end of the building have numerous cracks (figure 14).

5. Rescue and relief

Immediately after the earthquake, relief workers including personnel from the Army, National Disaster Response Force (NDRF) and Police were deployed to the severely affected areas. About 15 choppers from Indian Army were used for carrying out various rescue and relief operations in the areas which got completely cut off from the major towns due to landslides. In Chungthang alone the Indian Army carried out 500 sorties and had landed about 70 times a day in the initial period for bringing supplies and evacuating stranded and injured persons. Ten NDRF teams consisting of 403

Figure 13. (*a*) Satisfactory performance of King's monastery in Gangtok (*MSK-VI*) and (*b*) partial collapse of Ringhem Choling Monastery at Mangan (*MSK-VI*).

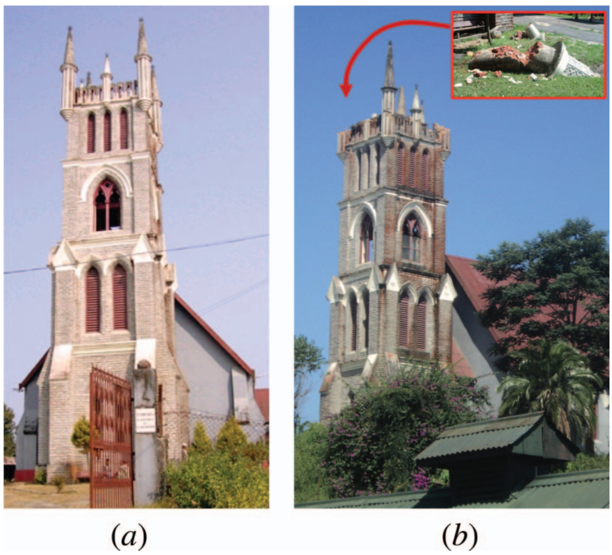

Figure 14. Collapse of brick spires of Mac Farlene Church at Kalimpong (*MSK-V*): (*a*) before the earthquake (Photo: http://mntravelog.com/tag/macfarlane-memorial-church/) and (*b*) after the earthquake.

personnel carried out relief work across Sikkim in Gangtok, Mangan, Ramam, Lingzya, Dzongu, Chungthang and Lachung. Over 5000 people have been provided shelter in this operation. Safe drinking water sources in the region were affected and in addition to distribution of water purification tablets, a water purification unit was installed in Chungthang with the help of the Indian Army. Many organisations provided non-food items like woollen blankets, stoves, tarpaulin for tents, etc.

6. Implication for future action

Rough terrain, complex topography and remote locations pose serious challenge for sound and quality construction in hilly areas. In addition, lack of awareness in the general public about the seismic vulnerability of the area have led to haphazard planning of towns and construction on sites prone to landslides and sinking (ground settlement). Unavailability of raw building materials and the expensive transportation cost have caused use of various substandard construction materials. It is critical to promote good concrete and masonry construction practice and suitable material for light or strong partition walls. For low rise buildings, new building typologies of proven earthquake performance, such as confined masonry need to be introduced (Brzev 2007). All stakeholders must be educated about importance of earthquake-resistant construction and its role in mitigating future risk. Locally available materials (such as bamboo and other sustainable timber alternatives) and traditional technologies should be reinstated and integrated with modern construction practices. Important structures such as schools and hospitals which are vital in the post-earthquake relief and rescue efforts and important historic structures like monasteries must be built earthquake-resistant on a high priority. However, adhoc retrofitting practices of questionable performances and impromptu remedies do not serve the purpose of safeguarding the structure and making it resistant to future seismic activities.

7. Summary

The damage to built environment, economic loss and human casualties caused by Himalayan earthquakes are increasing rather proportionally with the growth of settlements and population. The general pattern of damage to structures, landslides, rockfalls, etc. is consistent with the shaking associated with the recent M6.9 event, except a few dramatic building collapses due to faulty construction practices followed in modern RC and masonry structures. These practices include no confinement of reinforcement at beam and column ends, no shear reinforcement (stirrups) in joint regions, stirrups of very small diameter bar and inadequate tying, 90° hook and insufficient length of such hooks, construction (cold) joint at top end of the column near beam–column joint, splicing at member ends instead of at the middle, hand mixing of concrete, etc. Traditional constructions like *Shee-khim* and *Ikra* performed satisfactorily during this earthquake. Many Buddhist temples were seen to be deficient in lateral strength and need to be safeguarded against future tremors. Despite the available knowledge base, the local community is not adequately prepared due to lack of earthquake-resistant construction practices. There was ample evidence during the present earthquake to indicate that the seismic risk has risen to unacceptable levels in the region. This trend may lead to a large-scale disaster, if the growing seismic risk is not mitigated by promoting the elements of seismic safety and the earthquake-resistant construction practices.

Acknowledgements

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