The *M* 6.9 Sikkim (India–Nepal Border) earthquake of 18 September 2011

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The *M* 6.9 Sikkim earthquake of 18 September 2011 was a remarkable event in the long history of the Himalayan earthquakes which presented a unique opportunity to reflect on the unacceptable rising trend of the seismic risk in the hilly regions. Many dramatic collapses and damages were disproportionate to the observed intensity of shaking and can be attributed to poor construction material, deficient workmanship and lack of compliance with seismic codes and earthquake-resistant construction practices. Many private and governmental buildings were constructed neglecting the seismic design and detailing requirements necessary in the Zone IV of the Indian seismic code IS 1893. The traditional construction practices prevalent in the area performed rather satisfactorily due to their inherent earthquake-resistant features. Old monastery temple structures of distinctive construction in stone masonry and timber suffered varying degree of damage to masonry walls ranging from minor damages to partial collapse. This event should be regarded as a preview of what is likely to happen in the event of a greater shaking expected for the region and should hasten the community to take necessary steps in identifying seismic vulnerabilities and improving construction practices through an effective intervention.

Keywords: Earthquake effects, Himalayan earthquake, seismic risk.

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. It is, therefore, a ritual in the scientific community to perform a quick assessment of general damage survey and document initial important observations before they can be altered. These have proved useful in assessing success of the built environment in resisting seismic forces, the need and extent of rehabilitation programmes, and effectiveness of emergency response for rescue and relief. 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[1,2]. The India–Nepal border earthquake of 18 September 2011 caused widespread devastation in Sikkim and its adjoining areas from disrupting the road network to damaging structures of commercial, public and religious importance. This event presented another opportunity to further the understanding of earthquake risk in the affected region and also in the northeastern Himalayan region, which has similar patterns of seismicity, built environment and construction practices.

The *M* 6.9 earthquake hit Sikkim on 18 September 2011 at 6 : 11 p.m. IST with its epicentre located at 27.72°N, 88.06°E, near the 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 (Figure 1). However, later estimates for location and depth indicate some variation in these initially reported values[3]. It was a shallow-focus event, which was felt in Nepal, India, Bhutan, Bangladesh and China. Tremors which lasted for about 30–40 s were also felt in Assam, Meghalaya, Tripura, parts of West Bengal, Bihar, Jharkhand, Uttar Pradesh, Rajasthan, Chandigarh and Delhi in India. In Tibet, the earthquake was felt as far as in Shigatse and Lhasa. Three aftershocks of magnitude 5.0, 4.5 and 4.2 were also felt in Sikkim after the main event. About 100 deaths were reported with maximum of at least 60 in Sikkim. In Sikkim the worst-affected region was the North District, where about 70% of the total deaths was reported.

The whole 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 the 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 Himalayan 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 form a culmination, an exceptional geologic feature which is believed to be a controlling factor for earthquakes in the region (Figure 1)[4,5]. Three other moderate earthquakes that have hit the region in recent times are the *M* 5.9, *M* 6.0 and *M* 5.3 events in 1965, 1980 and 2006 respectively. Events of 1965 and 1980 were caused by strike-slip movements, suggesting the presence of transverse tectonics in the region. However, the *M* 5.3 earthquake of 2006 was reported to be a thrust-fault event[4,6]. The USGS initial focal mechanism solution indicates that

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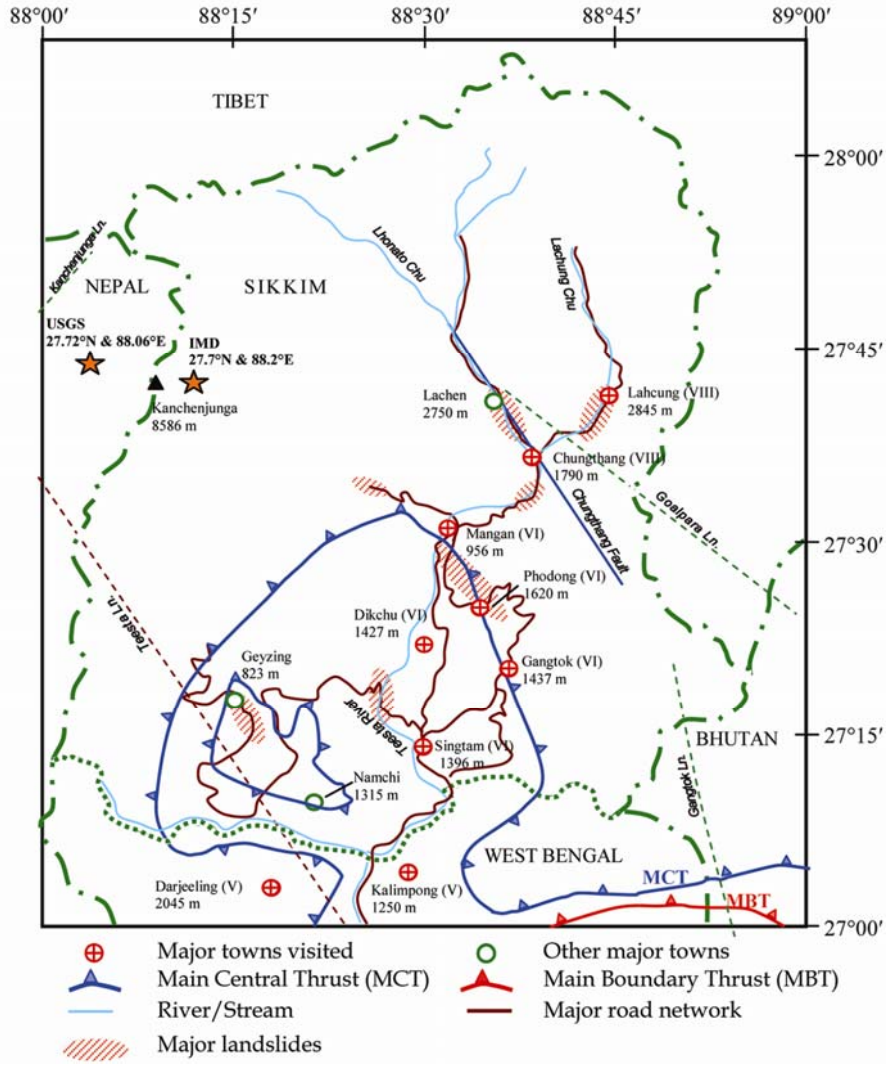

Figure 1. Location of epicentre of the Sikkim earthquake and its aftershocks, Main Central Thrust fault, Main Boundary Thrust fault and the towns visited in India.

the 18 September event was due to strike-slip movement, whereas the IMD report suggests a reverse-faulting mechanism at the thrust interface. The contradiction on focal mechanism needs to be studied in detail for more accurate probabilistic assessment of such events in the future[3].

The earthquake motions were recorded at Gangtok and Siliguri by strong motion accelerographs operated by DEQ, IIT Roorkee (http://pesmos.in/2011/). The PGA values recorded at these locations are 0.15 *g* and 0.20 *g* respectively (see Figure 2 *a* for acceleration time histories). Sikkim lies in zone IV of the Indian seismic code IS 1893–2002 (ref. 7). In Figure 2 *b*, response spectra of these ground motions were 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 respectively, from the USGS epicentre. It appears that code design forces corresponding to zone IV in Sikkim are being underestimated and it would be more reasonable to upgrade the region to zone V resulting in 50% increase in the design forces. This underestimation of hazard by IS 1893 has also been noted by earlier researchers on account of ongoing activities and possibility of occurrence of a great earthquake in the Sikkim Himalayas[8].

During 29 September to 5 October 2011, the present authors visited (by road) Darjeeling, Kalimpong and

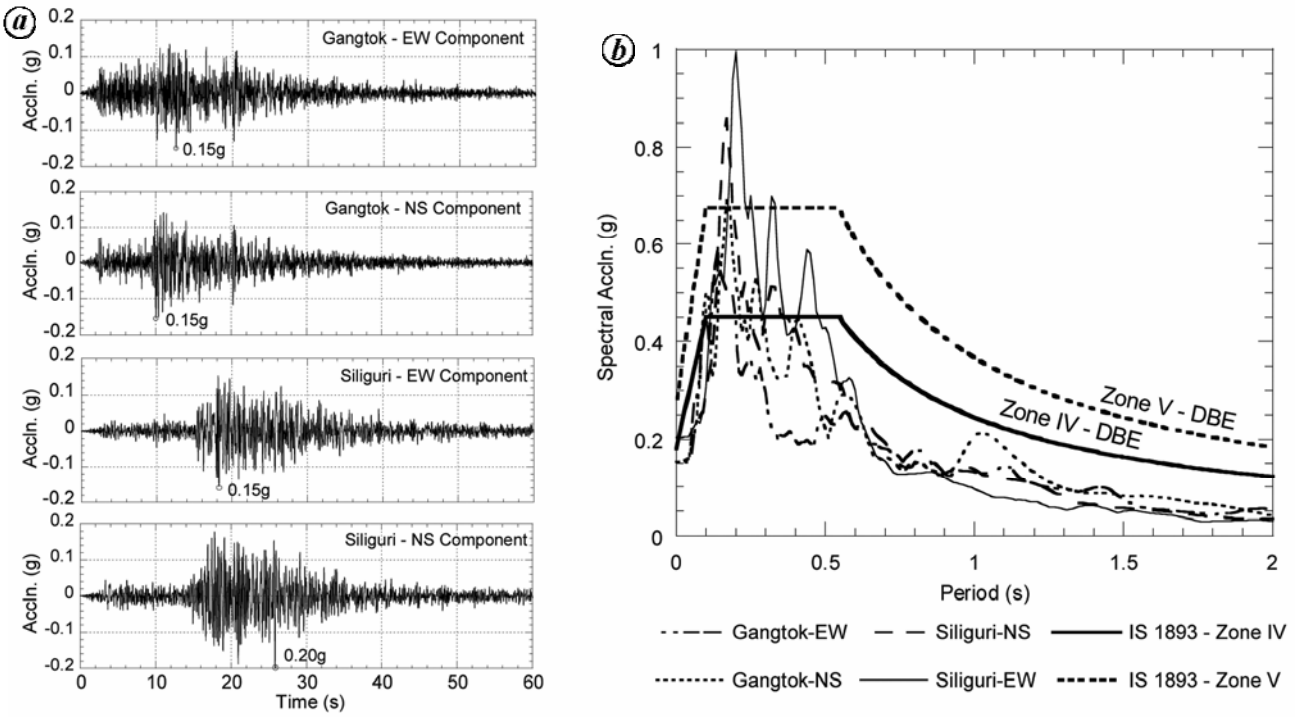

Figure 2. ***a***, Acceleration time histories for the main shock of the 18 September 2011 event recorded at Gangtok and Siliguri (band-pass filtered, 0.1–25 Hz). ***b***, Comparison of 5% damped acceleration response spectra of recorded ground motions with the Indian seismic code-specified elastic design response spectrum in zones IV and V for the design basis earthquake (scaled by 1.5 for factored design loads).

Figure 3. Aerial photographs showing typical landslides enroute from Mangan to Chungthang and Lachung.

Figure 4. Aerial photograph of Chungthang town showing surrounding mountainous terrain and river valley.

places along NH 31A from Gangtok to Mangan, and also Chungthang and Lachung (by Choppers) (major towns visited are marked in Figure 1). They also travelled through the tunnels being constructed for the Teesta hydroelectric projects, as roads were blocked from Chungthang to Mangan. More than 300 landslides spreading over approximately 2400 sq. km area from Namchi in the south to Lachen in the north were reported after this earthquake[3]. A large number of new landslides/rockslides were observed at higher altitudes close to the epicentral region (see Figure 1 for major roads blocked due to landslide and Figure 3 for an aerial view of typical landslides). Field observations by the Geological Survey of India (GSI) indicated that the geological (i.e. presence of weak, sensitive, unconsolidated and fissured material) and geomorphologic (slope angle, kinematically unstable

Figure 5. Damage due to rockslide and mudslide at Lachung.

Figure 6. ***a***, Pan-caking of the middle two storeys in a 9-storey building at Gangtok. ***b***, Collapse of a building near Balwakhani at Gangtok. ***c***, Complete collapse of a newly constructed 5-storey RC building at Lumshey Basty, Gangtok.

slopes, fluvial and glacial erosion, etc.) features played a significant role in causing these earthquake-induced landslides[9].

Chungthang and Lachung in North Sikkim are two major towns which have suffered maximum damage caused by landslides and poor construction of buildings combined with intense shaking. The aerial photograph in Figure 4 shows the location of Chungthang town surrounded by mountainous terrain and river valley. The maximum intensity of shaking was observed to be VIII. In Lachung, rockslides and mudslides after two days of the main event caused extensive damage, as shown in Figure 5. Intensity of shaking was VI in and around the state capital, Gangtok (e.g. Singtam, Dikchu, Mangan, etc). The general intensity of shaking assigned to a region is based on the observed overall effect of the earthquake on the structures. General damage to buildings was in accordance with the assigned intensity of shaking, except a few, such as the Secretariat building, two multistorey buildings in Balwakhani, and another five-storey building in Lumshey Bastey (Figure 6), all of which suffered either complete collapse or partial collapse due to faulty

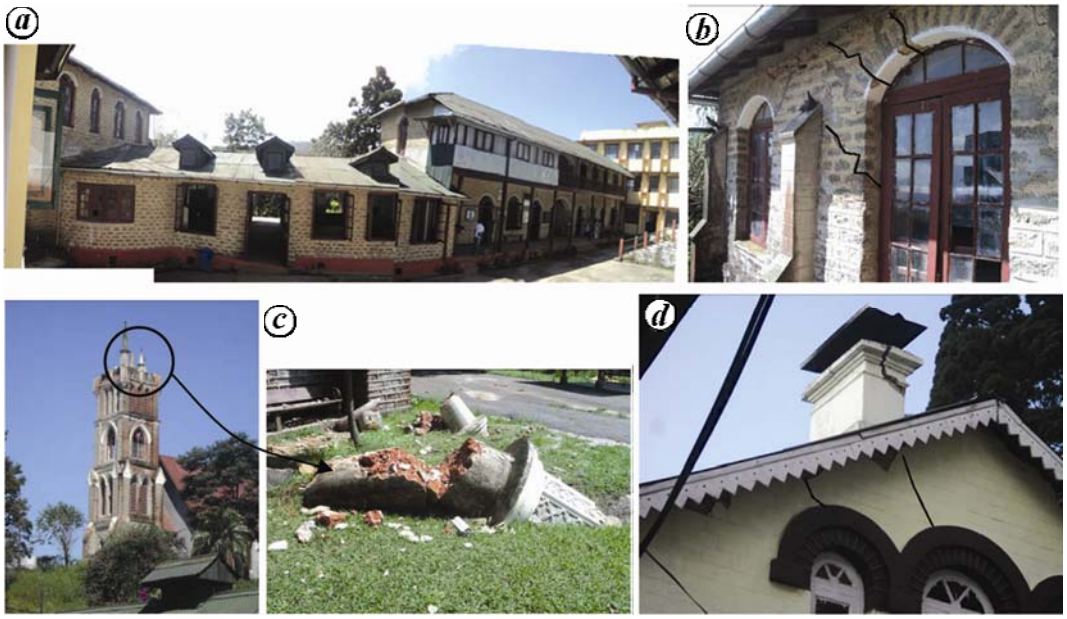

Figure 7. ***a***, Damage reported at Kalimpong Girl's High School. ***b***, Damage to semi-circular arches, diagonal cracks in masonry pier. ***c***, Collapse of brick spires of Mac Farlene Church at Kalimpong. ***d***, Damaged chimney and cracks in the wall above the arched openings at District Magistrate Office in Darjeeling.

Figure 8. ***a***, ***b***, Typical failure at column ends (widely spaced stirrups with 90° hooks, cold junction at the column top, poor concrete quality). ***c***, In-plane failure of weak infill masonry. ***d***, Out-of-plane collapse of concrete block masonry walls.

construction practices and poor workmanship. Kalimpong and Darjeeling in the northern part of West Bengal suffered moderate damages to building stock primarily constructed with stone masonry dating back to the colonial period and maximum intensity of shaking was observed to be V on the MSK scale (Figure 7). Extensive damage to school and hospital buildings was reported in the worst-affected regions of Sikkim and West Bengal.

Many RC buildings in Gangtok and most of them in Chungthang suffered damages of some form or the other: the most common being shear and/or flexure failure at column ends, failure of beam–column joints, in-plane failure of weak infills and out-of-plane failure of slender walls (Figure 8). The traditional houses like Ikra and Shing-Khim (meaning wooden house); Figure 9 *a* and *b* respectively performed significantly better compared to RC-frame buildings and suffered only minor damages at the basement level. Various monasteries all over Sikkim suffered damages to their thick exterior walls constructed with random rubble (R/R) masonry laid in mud mortar. Major civil-engineering projects in the area are hydel power plants, steel and RC bridges. No significant damage was observed or reported to these structures.

There are mainly four type of building construction practices followed in the affected region, namely RC-frame type with infill walls, R/R masonry with stone or wooden post and beam, Shing-Khim-type construction and Ikra houses. These construction practices are distributed according to the economic development and availability of raw materials.

It was a common practice in Sikkim to construct residential buildings using bamboo/wood, until the economic development aided by tourism industry got boost in the early nineties. Such traditional constructions has performed well during the past earthquakes[10]. Presently, RC-frame buildings with masonry-infill are most commonly used in private as well as government construction. These buildings were not in full compliance with the relevant

Figure 9. Satisfactory seismic performance of traditional construction typologies: (***a***) Ikra; (***b***) Shing-Khim house.

Figure 10. Pounding damage in two adjacent buildings at Gangtok.

seismic codes and were not detailed to resist seismic actions. It was evident from the modes of failure of various structural components that the effect of lateral loads was not considered in the design of the structures. Many of the RC buildings in the affected region suffered varying degrees of damage, from moderate to complete collapse during this earthquake.

In RC buildings, burnt clay bricks or solid/hollow concrete block and *in situ*, lightly reinforced concrete walls are commonly used as infills. Modern buildings in RC-frame are mostly planned on rectangular grid of columns at relatively smaller bays, which had significantly helped in earthquake resistance. However, indiscriminate use of partition wall for functional use has resulted in various plan irregularities leading to unacceptably large torsional stresses. Moreover, most buildings have a significant amount of vertical irregularities as the floor levels below the road level are supported on sloped ground. The ground motion input at multiple levels to the building causes complex dynamic response, which is usually not analysed and rarely accounted for in the design of such structures. 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 the buildings (Figure 10).

Beside the discrepancies in general configuration of buildings, other important factors which contributed to severe damages are:

- Poor quality of construction and workmanship, e.g. hand-mixing of concrete, inferior quality of aggregates, no control on water/cement ratio, volume batching, improper consolidation of concrete, etc.
- Inadequate seismic detailing, e.g. no ductile detailing in RC beams and columns (lack of confining reinforcement and stirrups with inadequate hook length not bent at 135°), improper splicing of bars and lapping near the beam–column joint, relatively smaller-sized columns even for buildings as tall as seven stories, cold joints in column below beam, extended floor plans in upper stories over cantilevered beams and columns with corbels, etc. (Figures 8, 11 and 12).

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 the supporting frame element. Most of these infill walls failed in the out-of-plane direction due to their higher slenderness ratio; as thin concrete blocks (80–100 mm), half-brick thick wall and even bricks ‘on edge’ were used (Figure 12).

Traditional construction in Sikkim mostly consists of Shing-Khim and Ikra houses (Figure 9). Such houses were constructed using locally available materials and has performed well during past/recent earthquakes. These practices were observed throughout the affected area and were more in number in the upper reaches like Lachung. Shing-Khim houses are single-storey structures consisting of wooden planks connected by steel flats with bolts and nails. However, Ikra houses are 1–2-storey, timber-framed structures filled with infill panels which are

Figure 11. Complete damage of columns and exterior wall in a building at Chungthang due to poor detailing of column reinforcement, lack of confining reinforcement, improper splicing of rebars and inferior detailing of columns with corbel.

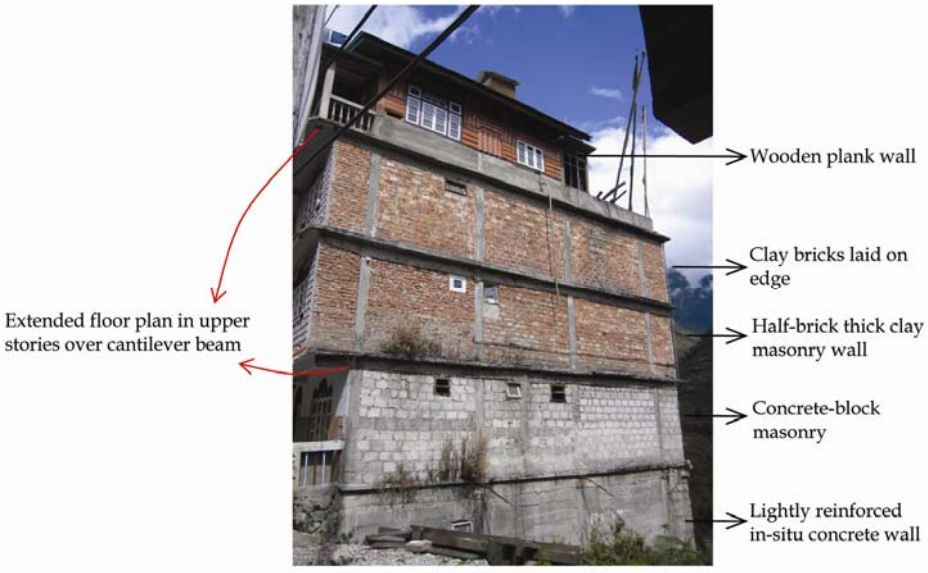

Figure 12. Different infill materials used in different storeys in a building at Lachung.

prepared by bamboo splints woven together with wooden frame and finished with cement/mud mortar plaster on both faces. In Shing-Khim and Ikra construction, the superstructure is supported on a wooden post and an exterior basement wall of R/R masonry is provided for thermal insulation. In the present earthquake no major damage was observed and reported in such houses. Damage was only observed at the foundation level to the R/R masonry in most of these buildings. Presence of wooden frame at close intervals resulted in an excellent earthquake-resistant feature that performed well. Moreover, the closely spaced vertical members prevent the propagation of diagonal shear cracks within any single panel and reduce the possibility of the out-of-plane failure of panels.

The poor seismic performance of cultural heritage structures such as monasteries is a source of concern, as it was found that almost all historic, religious structures suffered varying degrees of damage due to this earthquake. The temples (shrine hall) in monasteries are simple 1–3-tiered structures on a rectangular plan with reduced floor area for the upper stories. The exterior walls are in stone masonry, mostly R/R, while the floors and double-pitched roof are made of timber, using single post and beam system, as seen from a damaged monastery

Figure 13. ***a***, Damaged Buddhist temple at Lachung illustrates typical construction features, with exterior walls in stone masonry and doubled-pitched roof timber construction. ***b***, Partial collapse of exterior masonry walls and timber floors on simple beam-post system holding up for Ringhem Choling Monastic temple at Mangan. ***c***, Damages seen in the historic portion of Samten Choling monastic temple at Lachung (right), while there were no damages to the new addition of RC-framed pavilion at the front entrance (left).

in Lachung (Figure 13 *a*). Heavy damages were observed to the exterior walls at several monasteries, e.g. partial collapse at Ringhem Choling monastery in Mangan, and delamination of walls and cracks in Samten Choling monastery in Lachung (Figure 13 *b* and *c*). King's monastery at Gangtok built in dressed stone masonry suffered no significant damage. Many of the monasteries have recent additions to their structures, such as pavilions, and prayer halls constructed in RC-frame with infills, which performed satisfactorily. In Kalimpong, West Bengal, two brick spires of the historic Mac Farlene Church collapsed and the tall load-bearing walls at the gable end of the building developed numerous cracks (Figure 7 *c*).

Schools and educational buildings also suffered extensive damage, with the partial/complete collapse of around 23 school buildings reported in Sikkim alone. Moderate damages to some schools were observed in Kalimpong District, West Bengal. Schools built during the colonial period, constructed using stone masonry, had damaged to arches, diagonal cracks in walls and separation at roof-wall intersection (Figure 7 *a* and *b*). Some of the structures, including the medical centre and a dormitory of a residential school suffered severe damage, such as in-plane shear cracking and out-of-plane bending of walls, damage to arch abutments and the dislocation of the keystone.

The area has a number of highway and pedestrian bridges over rivers, rivulets and gorges. No serious damage to any of the highway bridges was noticed in the areas visited. However, it has been reported that one of the bridges had some damage at the abutment level mainly due to poor quality and design practice during its construction. Roads in the mountainous region connecting Mangan–Chungthang and Chungthang–Lachung were blocked due to extensive landslides, which resulted in the closure of roads for several days. They remained closed even after two weeks since the earthquake. The road traffic from Mangan to Chungthang, a gateway to both Lachen and Lachung valley was opened through the diversion tunnel of the Teesta hydroelectric project. The transmission and distribution network had also been badly affected. Several 66/11 kV towers and lines were damaged due to falling boulders and debris from landslides. Soon after the earthquake, power outage was reported from the large parts of the state, including Gangtok.

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 and penstocks of several hydroelectric power plants.

The telecommunication network was seriously affected due to uprooting of mobile-phone towers and snapping of communication lines. About 40% of mobile towers were non-functional. In the North District, the communication network was not fully restored even after several days following the earthquake.

Immediately after the earthquake relief workers, including personnel from the Armed Forces, National Disaster Response Forces (NDRF) and the police were deployed to the earthquake affected areas. About 15 choppers from the Indian Army were used for carrying out various rescue and relief operations in the areas which were completely cut-off from the major towns. 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. A ten-member NDRF team carried out relief work across Sikkim in Gangtok, Mangan, Ramam, Lingzya, Dzongu, Chungthang and Lachung. Over 5000 people were provided temporary shelter.

Safe drinking-water sources in the region were affected by the earthquake. Majority of the population in the affected areas relied on the waterfalls and water streams, which had become muddy due to landslides and affected the mainstream water source for the community. Water-purification tablets were made available and a water purification unit was installed in Chungthang. Many social organizations contributed by providing medical, food and emergency supplies. Immediately after the event, the Government of India allocated Rs 500 million for the Sikkim state Government's emergency response. Subsequently, the state Government carried out detailed appraisal of the rebuilding needs.

The earthquake of 18 September 2011 did not come as a surprise to the scientific community, as the Sikkim Himalaya in the north of the MBT has been intensely active in the recent times. The general pattern of damage to structures, landslides, rockfalls, etc. was consistent with the shaking associated with the *M* 6.9 event. However, many dramatic building collapses and damages to structures disproportionate to the observed intensity of shaking were primarily due to faulty construction practices and poor compliance with seismic codes.

Despite the available knowledge base, it is unfortunate that society is not adequately prepared due to lack of implementation, and therefore, seismic risk in the region has risen to unacceptable levels which may lead to a large-scale disaster, if not mitigated through effective intervention in altering the present building construction practices.

This event most prominently highlights the presence of vulnerable building stock in the affected region. It was rather perplexing to discover that a great majority of both government and private buildings seriously lacked earthquake-resistant features, which are essential for a satisfactory seismic performance. Following are the salient lessons that ought to be learnt and acted upon in order to mitigate the seismic risk in the region which is growing at an alarming pace:

- Good construction practice and quality material: Rough terrain, complex topography and remote locations pose serious challenges for sound and quality construction in the hilly areas. Many unique and inherently poor construction features which significantly add to the seismic vulnerability of structures, are: weak and 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, enclosed with slender and inadequately supported masonry walls; columns with corbels; construction on sloped ground; unstable slopes; weak retaining walls, etc. Lack of building materials and expensive transportation cost have led to the usage of various substandard construction materials. It is critical to promote good concrete and masonry construction practice and suitable alternative materials for light and strong partition walls.
- Promotion of earthquake-resistant building typologies: The traditional houses like Shing-Khim and Ikra performed well as expected, as they evenly distribute the deformation which adds to energy dissipation capacity of the system. 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: Sikkim is prone to much greater shaking than caused by the present event; hence compliance to seismic codes cannot be ignored. Strict adherence is mandatory to relevant BIS codes for new constructions and documents like IITK–GSDMA guidelines for seismic evaluation and strengthening for existing buildings.
- Heritage and important buildings: Monasteries which are important historic structures and add to the cultural heritage of the state suffered varying degrees of damage. These structures being old and weak could not resist the seismic loads and thus need to be effectively strengthened to safeguard against future tremors. Important buildings, such as schools and hospitals which are vital in the post-earthquake relief and rescue efforts must be built earthquake-resistant on a high-priority.

- Awareness among all stakeholders: Lack of awareness in the general public about the seismic vulnerability of the area has led to the haphazard planning of towns and construction on sites prone to landslides and sinking (ground settlement). All stakeholders, including builders, contractors, engineers, private owners, government officials and the 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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Recent microtremors near the Idukki Reservoir, Kerala, South India

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The continuing low-level seismicity in the vicinity of the Idukki Reservoir, Kerala, is interesting from the perspective of hydrologically triggered earthquakes. While the frequency of triggered earthquakes in the vicinity of a reservoir usually reduces with time and the largest earthquake usually occurs within a few years on the initial filling, the triggered seismicity in the proximity of the Idukki Reservoir seems to be showing a second, delayed peak, as the 1977 (*M* 3.5) tremor was followed by a slightly larger event in 2011, 24 years after the first burst of activity. Quite unprecedented in the context of reservoir-triggered sequences, we consider this delayed sequence as the hydrologic response of a critically stressed hypocentral region, to monsoonal recharging. The sustained activity several decades after the impoundment and the temporal relation with the monsoon suggest that at least some parts of the reservoir region continue to retain the potential for low-level seismic activity in response to hydrologic cycles.

Keywords: Hydrologic cycles, microtremors, reservoir, triggered earthquakes.

THE Idukki Dam built on the Periyar River in Kerala is one of the highest arch dams in Asia (169 m), which has started generating power since 4 October 1975. With a seismological network in operation since 1971, the Idukki Reservoir is among the few in India that has a pre-impoundment record of the background seismicity. This is particularly important as the reservoir is located in a region of generally low-level seismicity with no regional network to monitor the local seismicity. After the network was established, a large number of mild shocks were recorded, but only a few of these were locally felt and no large earthquakes followed the initial impoundment. The largest event in the vicinity of the reservoir occurred in 1977 (*M* 3.5; ref. 1). Based on the proximity of the microtremor locations to the reservoir, and the temporal correlation with the seasonal filling, the microseismic activity at Idukki was considered as reservoir-triggered[2]. Rastogi *et al.*[3] provide an overview of earthquake frequency subsequent to filling of the reservoir (1974–87), and the data suggest that most earthquakes are located in and around the Idukki Reservoir. Thus, the

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