

Learning from Earthquakes

The M_w 6.9 Sikkim-Nepal Border Earthquake of September 18, 2011

Several teams from India investigated the effects of the Sikkim earthquake between September 25th and November 10th, 2011. This report is based on observations of the following contributors: C.V.R. Murty, S.T.G. Raghukanth, Arun Menon, Rupen Goswami, A.R. Vijayanarayanan, S.R. Gandhi and K.N. Satyanarayana of the Indian Institute of Technology (IIT) Madras; Alpa Sheth of VMS Consultants Pvt. Ltd., Mumbai; Arvind Jaiswal of EON Designers, Secunderabad; Hemant B. Kaushik and Kaustubh Dasgupta of IIT Guwahati; Ajay Chaurasia of CBRI, Roorkee; Colonel Shashi Bhushan of the Indian National Disaster Management Authority (NDMA); Debasis Roy of IIT Kharagpur; and R. Pradeep Kumar of the Indian Institute of Information Technology, Hyderabad. Keya Mitra of Bengal Engineering, Kolkata, and Durgesh C. Rai, Goutam Mondal, Vaibhav Singh, Neha Parool, and Tripti Pradhan of IIT Kanpur also reported on the damaged sites. Eleven of the contributors were supported by the NDMA. VMS Consultants and EON Designers sponsored the visits of their members. The Building Materials and Technology Promotion Council, New Delhi, supported the visit of one contributor from IIT Madras. IIT Guwahati supported the visit of its two faculty members. The IIT Kanpur team received support from the Poonam and Prabhu Goel Foundation at IIT Kanpur. The reconnaissance teams together covered all four districts of Sikkim, with greater focus on the most affected region of North Sikkim and the capital city of Gangtok, and parts of North Bengal.

This report is edited by C.V.R. Murty and Alpa Sheth.

Introduction

An M_w 6.9 earthquake struck near the Nepal-Sikkim border on September 18, 2011, at 18:10 local time. The earthquake triggered a large number of landslides and caused significant damage to buildings and infrastructure. Sikkim was the most affected state of India, followed by West Bengal and Bihar. Neighbouring countries of Nepal, Bhutan, Tibet (China) and Bangladesh sustained damage and losses to varying extent (Figure 1a). The maximum shaking intensity is estimated to be around VI+ on the MSK scale. The earthquake was followed by a series of aftershocks, two of which were M4.5 and M5.0 and hit within 75 minutes of the main shock.

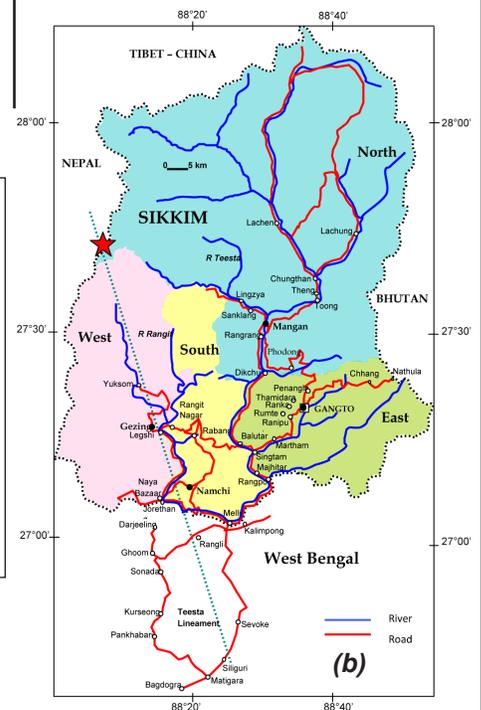
The landslides, rock falls, and mudslides were responsible for most loss of life and damage to infrastructure, as well as associated economic losses. There was also extensive loss of Buddhist monasteries and temples; these heritage structures are built in random rubble masonry with mud mortar. Most multi-story reinforced concrete (RC) buildings were non-engineered and sustained considerable damage due to earthquake

shaking; a small number of these collapsed or suffered irreparable structural damage. Poor performance and widespread damage are of concern in important government buildings, such as the secretariat, police headquarters and legislative assembly, perhaps some of the few engineered buildings in Gangtok. The total loss of life in India is reported to be 78, 60 in Sikkim, and the rest in West Bengal and Bihar. The total loss has been estimated at around US \$500 million.

Sikkim has a total population of about 600,000 people (Figure 1b). Gangtok is the densest region in Sikkim, with a density of about 98,700 persons in an area of 77 sq km (as per 2011 Census of India). This contrasts sharply with the density in North District of Sikkim, which has the smallest, at just about 10 persons per sq. km. In the past decade, Sikkim has recorded an astounding 153% growth in its urban population and a 5% decrease in



Figure 1. ▲ (a) key earthquake-affected areas; and ► (b) areas covered during the reconnaissance, location of epicenter, and the rivers Teesta and Ringit.



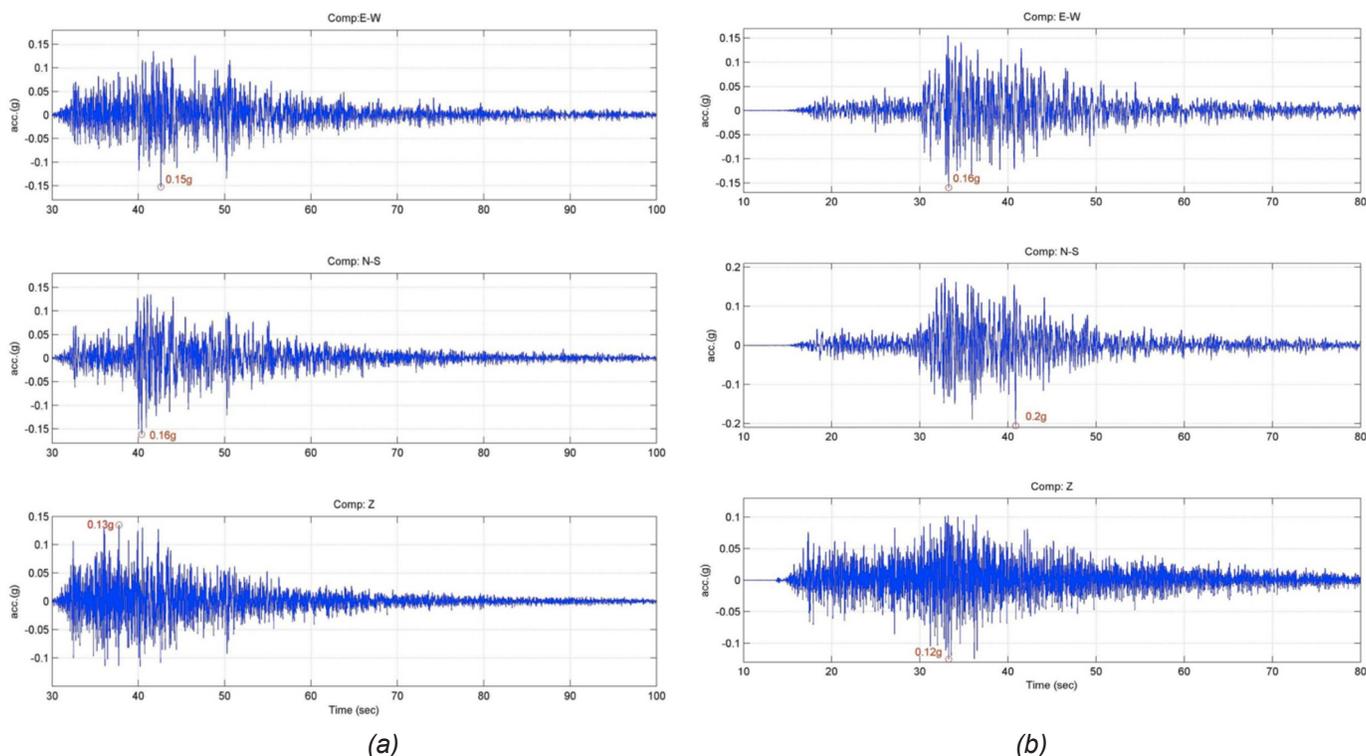


Figure 2. Acceleration time histories for the main shock of 18th September 2011 Sikkim event recorded at (a) Gangtok, and (b) Siliguri (<http://pesmos.in/2011/>).

its rural population. There may be a further push for urban agglomerations in the future, which may make it easier for governance and disaster management in the challenging terrain.

Some parts of North Sikkim (Lachung and Lachen) and the hills of Darjeeling in West Bengal are important international tourism destinations and have seen a growth of multi-story RC buildings. Additionally, North Sikkim shares a border with China and, for strategic reasons, it is expedient for the Indian government to maintain excellent roads and connectivity, even if it may focus on a few key tourism and strategic villages. These villages need to be better equipped for disaster management and as tactical outposts.

Seismological Aspects

The state of Sikkim is spread on the Himalayan mountain range, also known as the “Alpine-Himalayan belt,” with the two main thrust faults

(Main Boundary Thrust [MBT] and Main Central Thrust [MCT]) crossing the state. A great earthquake of M_w 8.1 struck in January of 1934 along the Bihar-Nepal border along the inter-plate boundary; other significant earthquakes in this area in the last 50 years include the September 2009 Bhutan earthquake of M_w 6.1, the February 2006 Sikkim earthquake of M_w 5.3, the August 1988 Bihar-Nepal earthquake of M_w 6.5, and the November 1980 Sikkim earthquake of M_w 6.0.

The Gangtok and Teesta lineaments, transverse to the Himalayas, are responsible for many earthquakes in the region. Other prominent tectonic features in and around Sikkim include the Arun lineament and Dhubri fault in the southeast, and the Kanchenjunga and Purnea-Everest lineament in the north. The focal mechanism solution for this event (as reported by USGS) indicates strike slip faulting and the nodal plane coincides with the Teesta and Kanchenjunga lineaments. The strike, dip, and focal depth of the fault plane have been reported as 313° , 73° , and 35 km, respectively.

The acceleration time history of the main shock was recorded at Gangtok and Siliguri (Figure 2); the PGA was 0.15g at Gangtok. The stochastic seismological projection is presented of the estimated mean peak ground acceleration (PGA) contour in Figure 3a. The axisymmetric contours are attributed to the shallow focal depth of the earthquake. The projected PGA in the meioseismal region is as high as 0.35g; at Lachen, Ravangla, Teesta, Chungthang and Mangan, it is in the range 0.25g-0.29g, and at Gangtok in the range of 0.15-0.20g. Sikkim lies in Seismic Zone IV as per the Indian Standard (IS:1893-Part 1, 2007) Criteria for Earthquake Resistant Design of Structures, in which the design peak ground acceleration is 0.24g for this zone. Pseudo-spectral accelerations of the ground motion recorded at Gangtok are similar to that of the code spectrum for the zone; code design spectral accelerations at lower frequencies are higher than those generated in this event (Figure 3b).

In general, the maximum intensity of ground shaking in the entire affected area was VI+ on the MSK scale, but some pockets had higher shaking owing to site-specific amplification of ground motion on a hillock, e.g., at the ITBP quarters at Pegong in Chungthang (Figure 4). Falling rocks caused significant damage to buildings and hydropower tunnel mouths in the town of Chungthang.

Poor building performance was prevalent in towns sited on soft soil layers of relatively flat river terraces and gradually sloping mountain meadows, probably due to sustained amplification of ground shaking. Mudslides originating from mountain springs led to damage to buildings in Lachung (Figure 5). Even now, large boulders of fragile sedimentary rocks are precariously balanced along hill slopes at many locations.

Geotechnical Impacts

While landslides are frequent in this region during rainy seasons, an estimated 354 new landslides were caused by the event and 48 old ones reactivated (Figure 6). These slides damaged roads and bridges and disrupted relief operations to towns and villages that were completely cut off, some for over three weeks (Figure 7). Subsidence at Ranipool near Gangtok resulted in 180 mm settlement of a part of the National Highway, slowing vehicle movement and causing traffic jams.

Landslide density in Sikkim increased approximately five-fold in

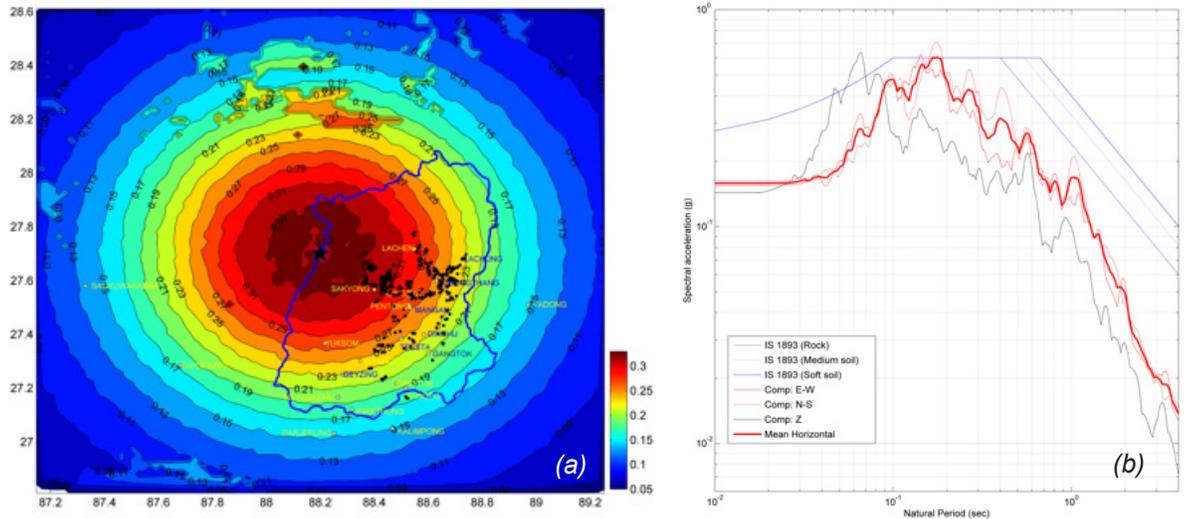


Figure 3. (a) Surface level peak ground acceleration (g) generated from stochastic seismological model. Black dots indicate location of landslides; (b) Comparison of recorded spectral accelerations during the earthquake and Indian Seismic Code design response spectrum at Gangtok.

locations north of Dikchu; this is possibly due to proximity to the epicenter and steeper relief in the mountainous terrain. In the Chaday–Sankalang–Dzongbu area, often these failures were found to have affected the highly weathered mica schists and phyllites. The left bank of Lachung chu in Chungthang was particularly affected by several slope failures.

Some incidents of reactivation of older landslides were reported, for example, the Teendharia (Figure 8) and Balason landslides of the Darjeeling district and the Health Secretariat landslide in Gangtok. The

reactivation in some cases was not co-seismic, but developed over several days after the earthquake because of heavy rainfall in area. On-the-ground inspection revealed signs of continual distress that indicated the post-earthquake landslides were inducements of already ongoing slow mass movements. Enquiry with the locals in Tukdah-Rangolikhola also corroborated the landslide to be episodic, with a large event taking place several decades back.

Site-specific scientific approaches are required for studying relatively



Figure 4. Classic damage in lower stories of RC frame building with large block masonry infill panels at ITBP quarters at Chungthang (photo: Arvind Jaiswal).



Figure 5. Damage to buildings due to rock slide at Lachung (photo: DC Rai).

soft mountain slopes along the Singalila range and in the Teesta Valley, and assessing the landslide potential of in critical areas, for example, near the Leprosy Hospital in Kalimpong (Figure 9). In addition to the above, alternate road network routes should be developed to bring redundancy for rescue and



Figure 7. Landslide at the mouth of the cable-stayed bridge across the Rangit River at Jorethang-Nayabazaar in West Sikkim district (photo: C.V.R. Murty).

relief operations and for keeping all areas connected by roads even in the aftermath of earthquakes.

The Border Roads Organisation (BRO) is responsible for developing most mountain roads in the upper reaches of Sikkim, usually by cutting hill slopes. When cuts are made in mountain slopes to widen or form roads, they are safe when the entire road width is made on the native cut; not so, however, when made on fill



Figure 8. Scouring of the permanent way underneath of the heritage railway line at the Teendharia landslide along NH 55 between Siliguri and Darjeeling (photo: Debasis Roy).

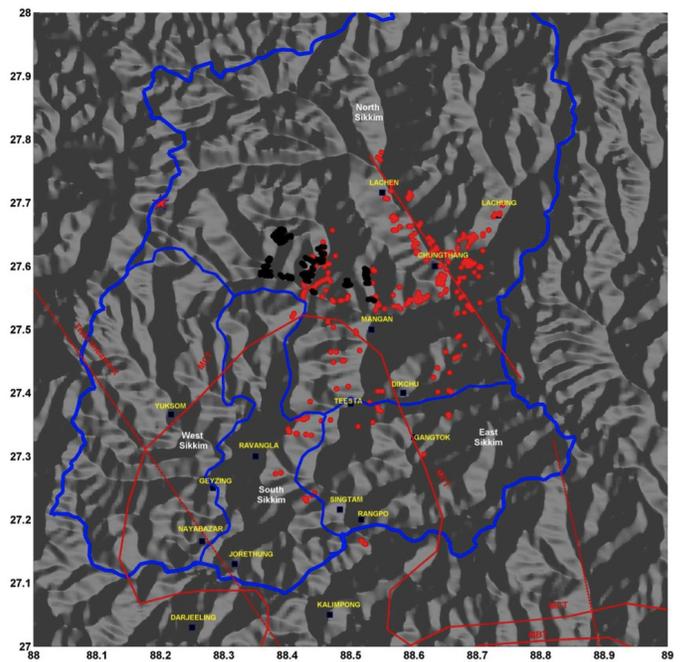


Figure 6. Landslides in Sikkim during the main event; red dots indicate those mapped by National Remote Sensing Centre (India), black dots by NASA satellite image, and star the epicenter (source: STG Raghukanth).

soils with retaining walls, as has been done in Sikkim. In addition, the inner edges of cuts along the mountains are often not provided with seepage/rainwater drains. The construction techniques are not scientific and of good quality; generally, only heuristic and experience-based methods are employed, compromising safety of the construction. A review of the

quality of engineering in hill road construction in the region indicates that, in many cases, local soil data is not being used for assessing the stability of the mountain slopes, and structural geologists are not consulted.

Buildings

Damage. Damage and losses were sustained by houses in the severely shaken areas owing to three main reasons: slides on weak mountain slopes, rolling boulder impacts, and ground



Figure 9. Lateral spreading of the soft soil hillock on which is located the Leprosy Unit of the Sub-Divisional Hospital of Kalimpong (photo: C.V.R. Murty).

shaking-induced damage (Figure 10). In some cases, the latter type of damage may have been exacerbated by the 2006 event (if the structure was not retrofitted). Scientifically based land use zoning should be undertaken to demarcate obviously unsafe sites in the state of Sikkim.

Many instances were observed of soil movement under buildings on hill slopes largely made up of metamorphic and sedimentary rocks covered with soft soil. In areas close to tunneling works for hydropower projects, local people ascribe this creeping to vibrations arising from tunnel blasting, but the earthquake's higher levels of ground shaking initiated a number of landslides.

Building codes. In Gangtok, building permits and town planning are controlled by the Urban Development and Housing Department (UDHD). All buildings are required to follow the Sikkim Building Construction Regulations of 1991 (amended 2000). These regulations define maximum setbacks, ground coverage and height of the buildings. While it is obligatory to submit architectural plans, there is no requirement to submit structural drawings, implicitly promoting non-engineered buildings. There is no requirement for conducting soil investigation either. An engineer from the Department of Mines and Geology of Sikkim inspects the site and determines the number of floors that may be allowed on the plot based on the land-use zonation map of the area (which is not available in the

public domain) prepared by the Department from time to time. The current map divides the city into six categories on the basis of lithology, hill slope, seismicity and other aspects. A maximum of 5½ stories may be built in Zone 1, 4½ stories in Zone 2, and so on, with no construction allowed in Zone 6. UDHD regulations prohibit construction on slopes exceeding 70 degrees (but see Figure 11).

Regulations explicitly assign the responsibility of ensuring structural stability to the owner of the plot, but do not specify how this may be ensured. Booming tourist villages of Lachen and Lachung, and towns such as Chungthang and Jorethang, do not appear to follow any building laws even though the Gangtok Building regulations are applicable across the state. There is no implementation mechanism for these regulations in any town other than Gangtok, and no geological zoning maps for the rest of Sikkim. And the UDHD has no system for punishing defaulters.

In the district of Darjeeling in neighbouring West Bengal, the situation is similar; effectively, there is no techno-legal regime regulating construction. In the three major towns of Darjeeling, Kalimpong, and Kurseong, diploma holders are given the license to design buildings, but designs are not verified at the municipal office.



Figure 10. Damage to houses due to rolling boulder at Lingzya and Chungthang (photos: Arun Menon and Rupen Goswami).

Housing types. The state of Sikkim has been adopting three dominant construction typologies: (1) traditional wood frame construction with ekra/bamboo-matting walling, or wooden plank construction (Shee Khim); (2) reinforced concrete (RC) construction with moment frame type configurations; some



Figure 11. Dense unregulated RC construction on slopes in Gangtok city (photo: C.V.R. Murty).

RC construction mimics traditional wood frame construction type; and (3) unreinforced masonry (URM) construction with masonry units of stone, burnt clay brick or cement blocks, mud or cement mortar, with NO earthquake-resistant features. Of the above three typologies, the third (URM) is less prevalent in recent construction, and the second (RC) most prevalent. However, most of the RC construction in the last two decades is largely nonengineered. Most buildings built in recent times in Gangtok, Chungthang, Pelling, Jorethang, Naya Bazaar and other larger towns in Sikkim are of RC.

Earlier, especially before the 1975 accession of Sikkim to India, buildings were of the traditional ekra and Shee Khim style of up to two stories. However, RC is now the dominant form in response to the boom in tourism and the hydropower industry, and the pressure for more built space in the limited flat areas available for development. Now there are multistory buildings of up to eight stories in Gangtok and up to five stories elsewhere.

Ekra construction consists of a wood frame with cross-woven wood

matting infill wall panels, and a light roof. The matting is plastered on both sides with mud or mud with fine river sand in earlier times, and by cement mortar in recent times. Another variation to this is the use of wood planks in construction by the rich. When made on flat ground, it rests on a relatively shallow and uniform masonry plinth (made of stone and mud mortar), and when made along hill slopes, it rests on a tapered stone plinth. Four varieties of stone masonry plinths are observed in Sikkim and the hills of Darjeeling: random rubble masonry (RRM) with and without mud mortar; dry dressed stone masonry; dressed stone masonry; and dressed stone masonry with pointing. In recent times, the plinth has been constructed with RC. During the earthquake, this type of housing was shaken to varying degrees, but with the exception of distress in some plinths (especially those made of RRM without any mortar), the houses performed exceptionally well. In instances where the cross-woven wood matting was replaced by clay-brick masonry in cement mortar, damage was sustained in the masonry infill walls, including out of plane collapse (Figure 12a and b).

The highly satisfactory performance of this housing validates its appropriateness in the Himalayan region and makes a compelling case for its sustenance. This traditional style (including hybrid varieties with structurally designed basements) should be encouraged in the state of Sikkim and neighbouring states.

Reinforced concrete. As mentioned above, there are about 13,000 RC buildings in Gangtok alone, almost 65-70% of which were built after 1995. Almost all of these buildings are nonengineered (there are only two qualified structural engineers resident in Sikkim). RC residential or hotel buildings are built on steep hill slope sites on tight plots abutting each other. Only a few institutional buildings are engineered, such as government buildings, educational institutions and large hotels. RC construction performed poorly during the earthquake, even though the maximum intensity of ground shaking was only around VI+ scale on the MSK scale in most of the affected areas.

Nonengineered RC buildings across Sikkim typically have a grid of beams and columns in both plan directions. The buildings are 3-8 stories high, except in villages like Lachen and Lachung, where they are dominantly of two stories. Despite a large number of deficiencies in the RC buildings in Gangtok, one feature that may have saved them from more damage is the use of a uniform grid in most buildings. The spans vary from 3m to 4.5m, depending on the site. As these structures are on sloping ground, heights of columns vary, with some of them short columns and some slender columns. Further, because buildings are on hill sides, the width of the building is smallest at the base due to the topography. The roof of the building is partially or wholly in steel roof trusses or joists and metal sheets. The concrete for construction is hand-mixed, with



Figure 12. ▲ (a) Typical ekra house at Gangtok (photo: Alpa Sheth); ► (b) Typical house with wooden planks (Shee Khim) with damaged rubble masonry plinth (photo: AR Vijayanarayanan).

neither control of the water-cement or aggregate-cement ratio, nor any systems for cube testing of concrete or testing of reinforcement. No vibrators were being used for compaction in construction observed during the reconnaissance.

The performance of RC frame buildings with unreinforced masonry (URM) infills would have been better if one-brick-thick URM infills walls were used instead of half-brick-thick URM infill walls, since the half-brick walls either collapsed out-of-plane or were severely damaged in-plane. In cases where infills were absent or poorly built (with too many openings), the damage was significant. In RC frame buildings where URM infill walls were made of large-sized thin cement concrete block units (350mm × 200mm × 75mm) masonry walls, the performance of the building was poor.

Due to a boom in tourism, a lot of residential buildings are now converted into hotels with the owner living on the uppermost floor. With such multiple uses, there is sometimes a change in the layout of the partition walls and some walls are completely removed to make room for a conference hall or restaurant. The Gangtok Building laws have no well-defined land use zoning, and it is possible to have any type of occupancy in any area of the

city. Buildings that had a sudden change in the stiffness pattern of the infill panel walls suffered significant damage or collapse (Figures 13a and 13b). Buildings experienced torsion and collapsed when distribution of stiffness was poor in plan (Figure 13c). Buildings with large appendages (such as Telecom towers) also behaved poorly. A four-story RC building at Dikchu bazaar (Figure 13d) constructed about 10 years ago was constructed on slope over a RC retaining wall and the slope started failing after the main shock. This resulted in severe tilting of the building along the slope, which prompted occupants to vacate the building before it collapsed completely during an aftershock two days later. Another two-story RC building constructed on slope and located near the Dikchu dam site suffered partial collapse; however, it had not been used for residential purposes and therefore losses were minimal. Also, three stories of a residential house pancaked in the town of Naya Bazaar (Figure 13e).

Masonry. Masonry construction is found especially in the British colonial government buildings in Sikkim and Darjeeling. This type has very thick walls made in random rubble stone masonry; dressed stone masonry was used in some government structures. No earthquake-resistant features are found in these structures — no bands, no through stones, and no vertical reinforcements at corners

and around openings. Unreinforced masonry (URM) was used to construct a large number of government schools and primary health centres. This stock sustained dilation of masonry starting from the upper stories (Figure 14).

After it was damaged in the 1988 Bihar Nepal quake, the Archive Building in Gangtok was retrofitted using steel flats all around in the form of bands around window openings. The two-story building performed extremely well during the 2006 earthquake, but significant damage was observed in the lower stories after the recent event (Figure 15a and b).

Heritage structures. Sikkim and the hills of Darjeeling have many Buddhist monasteries, some of which date back to the early 16th century. These historical monasteries are masonry structures, primarily constructed with random rubble masonry (RRM) walls and timber floor slabs and roofs. Some have masonry walls with timber framework. Monasteries constructed in the recent decades are reinforced concrete (RC) structures with infill masonry panels. Structural repairs in recent years — mostly ad hoc and nonengineered — have introduced RC elements (columns, beams and slabs) into the structures. Some monasteries were retrofitted after the 2006 Sikkim earthquake, but were damaged in the



Figure 13. (a) Pancaked nine-story Dzongpo House building in Gangtok; three intermediate stories collapsed owing to sudden change in lateral stiffness (photo: Alpa Sheth); (b) damage to storage facility building in Chungthang (photo: Ajay Chourasia); (c) and (d) collapsed three-story RC frame building at Singtam (photo: Alpa Sheth); (e) pancaking of three stories of RC frame residential building at Naya Bazaar (photo: Alpa Sheth), and (f) collapsed four-story house at Dikchu (photo: Hemant B. Kaushik).

most recent quake. Extensive damage was observed in these monasteries, with partial to near total collapse in several structures. Typical damage included out-of-plane bulging or collapse of random rubble masonry walls; sliding of timber roofs relative to the masonry walls; out-of-plane collapse of orthogonal corners of perimeter RRM masonry walls; and shear failure of interior RC columns (Figures 16a, b, c, d). Almost two months after the earthquake, no initiatives were yet underway to study the genesis of the damage or undertake seismic retrofit.

At least two colonial chapels were severely damaged during the event. The chapel designs had their roots in Scotland and England and no modifications were made on them to reflect the seismicity of the Himalayan region. At the MacFarland Memorial Church in Kalimpong the URM spires atop its bell tower are near collapse (Figure 17), and there is in-plane shear damage to the walls and gothic arches. The chapel on the estate of Dr. Graham's Homes had been damaged during the 2006 event, and was retrofitted locally by tying the arches with a 20mm diameter steel rod with end plates. During the recent quake, there was a much larger in-plane shear failure crack on the front wall and significant damage to the perpendicular wall and internal arches (Figure 18).

Nonstructural damage. This moderate earthquake also highlighted the need to address nonstructural-

Figure 14. Excessive dilation of the upper story of the sandstone stone masonry student cottage built in 1925 in Dr. Graham's Homes estate in Kalimpong (photo: C.V.R. Murty).





Figure 15. (a) Damaged masonry building of the police check post at Lachung (photo: Alpa Sheth); (b) damage to heritage building in Gangtok (photo: Hemant B. Kaushik).

al elements (building contents, systems, facades) formally while designing buildings. Many losses were incurred in hospitals, office buildings, monasteries, and residential buildings. Should the next earthquake be of severe intensity, it may result in much higher loss due to nonstructural elements.

Critical Buildings and Lifelines

Many government buildings were affected, even recently built, engineered RC structures. At the Secretariat Building in Gangtok, made of RC frame with unreinforced masonry infills of cement-block units, there was extensive damage to the infills of lower stories, pounding damage in the false ceiling at construction joints, and delamination of tiles along the corridor in upper stories (Figure 19). The annex portion of the building had damage in two RC columns at the expansion joint. The entire building was abandoned along with the annex portion. The Legislative Assembly Building in Gangtok, a RC frame building with URM infills, was retrofitted in 2010, but it had significant damage to internal and external infill walls, in addition to increased subsidence at the plinth level. Police check-posts and offices made of RC with URM infill walls were damaged to the extent of being rendered unsafe for operations. Also, the Police Headquarters Build-

ing in Gangtok suffered serious damage to its RC elements and URM masonry infills (Figure 20). At the Governor's estate in Darjeeling all dressed stone masonry buildings (1-3 stories tall) had separation at wall junctions and in-plane shear failure.

Schools. Older schools are made of traditional Ekra construction, while the recent ones (including extensions and replacements structures) are URM and RC. Ekra construction performed relatively better than RC buildings, and damage to RC schools deprived the govern-



Figure 16. (a) Collapsed masonry building of the Ringin Monastery at Mangan (photo: Arun Menon); (b) damage to Dubdi Monastery at Yoksum (photo: Alpa Sheth); (c) damage to Chungthang Monastery at Chungthang (photo: C.V.R. Murty); (d) damage to Pemayangtse Monastery in Pelling (photo: Alpa Sheth).



Figure 17. Collapse of unreinforced masonry spires of the bell tower of the MacFarland Memorial Chapel in Kalimpong (photo: C.V.R. Murty).

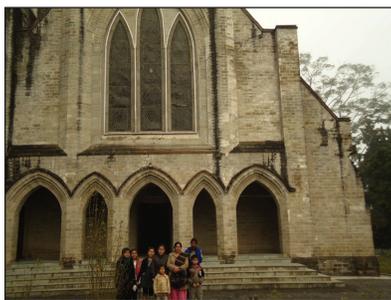


Figure 18. Crack initiating from the central arch and propagating towards the right top through the central glass windows at the chapel in Dr. Graham's Homes estate in Kalimpong (photo: C.V.R. Murty).



Figure 19. Structural damage at expansion joint of Secretariat building in Gangtok (photo: Alpa Sheth).

ment of safe havens for post-earthquake relief camps and emergency services. Over 600 school buildings are said to have suffered extensive damage or collapse. One complete collapse of a school building was observed (Figure 21). A recently constructed school extension with RC frame and roof, without masonry infill walls, had critical damage to RC columns and beams; poor design and quality of construction seem to be the causes. A school in Chungthang had a floor pancake due to movement of the boulder on which a column was founded (Figure 22). Many of these buildings were abandoned and school is now being held in makeshift temporary tents. These will not be adequate in imminent winter.

Some of the school buildings had suffered damage in the 2006 earthquake, but were not retrofitted. For instance, the old building of Government Secondary School at Sichey is a 3-story RC building with brick masonry infill walls constructed in 1969. Minor damage was observed in this building during the 2006 earthquake; however, it suffered extensive damage during the recent quake and the entire school building had to be abandoned. The adjacent new building of similar construction suffered extensive cracking in floors due to ground movement, cracks along the staircases, and separation of brick masonry infill panel along the edges of beam and columns (Figure 23a). RC columns in both buildings were damaged, especially those located near the door openings and in the corridor (Figure 23b). The walls of Ekra rooms in the terrace of the new building also suffered damage in the form of out-of-plane collapse and spalling of cement plaster (Figure 23c).

Medical facilities. Regional government hospitals are located in bigger towns like Gangtok and Gezing, and smaller primary health centers are spread out throughout the state of Sikkim and the Darjeeling hills. These structures range from traditional Ekra-



Figure 20. (a) and (b) Damage to three-story RC frame building with masonry infills of the police headquarters in Gangtok (photos: Alpa Sheth and AR Vijayanarayanan).



Figure 21. Collapse of masonry building of the primary school at Theng (photo: Arvind Jaiswal).



Figure 22. Pancaking of one intermediate story in five-story RC frame building of the Moonlight School at Chungthang (photo: Arun Menon).

type to unreinforced masonry structures, and recently to reinforced concrete. In most of these structures, pounding damage was noticed at construction joints (Figure 24a); frame-infill separation, cracking of plaster and diagonal cracking of infill walls were observed in RC frame buildings (Figure 24b), as was damage due to incorrectly detailed seismic joints.

Some government buildings and hospitals in the state sustained nominal damage and could have been used after the earthquake, but were “declared” unsafe and ordered to be demolished without professional inputs of engineers conversant with safety assessment protocols. This caused severe disruption to medical service, relief operations, and governance continuity. Post-earthquake damage assessment teams that are trained to assess the safety of buildings should be commissioned in the state of Sikkim. This will ensure that critical hospital buildings are examined by personnel with expertise and allowed to stay open if only slightly damaged.

Bridges. Bridges in the region are built with wood, concrete, and steel; similarly, many designs are used: deck slab and girder, arch, truss, suspension and cable-stayed. One dominant concern with most bridges is their exceptionally poor maintenance; corrosion was noticed in RC elements, in particular. In general, no significant loss to bridges was apparent due to earthquake shaking; damage was various: loosening of abutments, pounding of spans, falling of lamp posts on deck, minor distress to anchor blocks of suspension bridges, distress to masonry piers and abutments, pounding (deck-deck and deck-abutment), and residual displacement in deck/abutment (Figure 25). Landslides, rolling boulders, and flash floods caused the most serious damage, with two bridges washed away by landslides and subsequent flash floods.



Figure 23. Damage to government secondary school at Sichey: (a) annex building, (b) RC columns, and (c) Ekra walls on top floor (photos: Hemant B. Kaushik and Kaustabh Dasgupta).



Figure 24. (a) Pounding damage at expansion joints in five-story RC frame building of SMIMS boys’ hostel, Tadong (photo: Alpa Sheth); (b) frame infill separation in Primary Health Centre at Passingdang (photo: Rupen Goswami).

Communications structures.

Communication systems failed in towns like Chungthan, Lachen, and Lachung after the earthquake shaking causing general power failures and/or severe damage to RC buildings with communication towers on their roofs (Figure 26). Telephone connectivity had not been restored even a month after the earthquake in North Sikkim.

Dams and water structures. Water networks were damaged from sources to treatment plants, and from treatment plants to distribution nodes. The city of Gangtok lost its water supply due to landslide damage to the distribution network. In Lachen and Lachung, the water pipes bringing spring waters were damaged due to failure of concrete or rubble masonry pipe supports (Figure 27). The supports of water penstocks from mountain springs at Lachung are made of plain concrete; these penstocks were damaged due to landslides and rock falls.

Along the Teesta River, 32 hydro-power projects are being developed; information is not available on the performance of structures recently completed and in progress. Seventeen employees of Project Teesta III lost their lives due to collapse of access tunnels. The National Hydroelectric Power Corporation (NHPC) has constructed





Figure 25. ▲ (a) Damaged abutment of bridge at Ralom Phamtam [photo: Government of Sikkim] and ► (b) pounding and residual displacement in deck in Jawaharlal Nehru Bridge at Melli (photo: Rupen Goswami).

concrete gravity dams over the Teesta River near Dikchu and over the Rangit River near Rangit Nagar. Though RC buildings in residential colonies for NHPC employees near these project sites suffered minor to moderate damage in the form of cracking in masonry infill walls and minor cracking in RC members, no damage due to earthquake shaking or landslide was observed in the body of any of the dams. Both dams were instrumented to record strong ground motions; however, all five strong-motion accelerographs were reported to have malfunctioned at the time of the earthquake. During the main shaking, a falling boulder destroyed an electrical transformer located on the Teesta V dam site, and severe landslides and ground

deformations were observed near both the dam sites that resulted in accumulation of excessive debris and silt in the reservoir and on the downstream of the dam. The nailed/bolted slopes on the right abutment of Teesta VI hydropower project site near Singtam were affected by mass movements seated deeper than the nailing/bolting.

Electrical power. The meiseoseismal area lost power immediately after the earthquake due to collapse of high tension towers along the distribution network due to landslides (Figure 28). This also resulted in loss of landline and mobile communications in the affected area. High-tension towers and lines were damaged due to falling debris from landslides, and even local distribution poles were dislodged due to ground deformation generated by soft soil slopes. Power was not restored in worst-hit locations even 12 days after the earthquake.



Figure 26. Damage in lower story of RC frame building with telecom tower on its roof at Chungthang (photo: Arun Menon).



Figure 27. Damage to plain concrete pipe supports of penstocks carrying water to town of Lachung (photo: Alpa Sheth).

Post-Earthquake Response

North Sikkim areas of Lachung, Lachen, and Chungthang remained cut off from the rest of the country for over three weeks due to telecommunications damage and

landslide-blocked roads. Food packets were air-dropped from helicopters in these regions during the interim period. Local village heads (Pipons) were appreciative of the immediate response of the Indian Army in providing medical assistance and supplying essential commodities such as food grains, but they were critical of the role played by the local administration (Government of Sikkim) and the National Disaster Response Force (NDRF) deployed by the central government which had come unprepared. NDRF on such deployments needs to be self-contained.

Locals bemoaned the lack of any means of communicating with their families elsewhere in the state or out of it. Some locals lost their lives trying to walk across to other villages or towns to check on children, only to be buried in a landslide. There was a feeling of abandonment as the Chief Minister of the State of Sikkim had not visited the most ravaged sites more than a month after the event.

Damage assessment. Many buildings across the state suffered damage of varying degrees.

One critical question that all government levels in Sikkim faced is how to decide whether a building can be used after an earthquake



Figure 28. Damage to electrical power transmission tower at Lower Payong, South Sikkim (photo: Government of Sikkim).

or not. There was no agency to distinguish between dangerous and benign cracks. Buildings were vacated in panic, and many important government files may have been lost in the process. Some governments constituted formal committees for damage assessment, and placed damaged buildings into three categories: (1) those requiring minor repairs, (2) those requiring major repairs, and (3) those requiring replacement. In general, however, the engineers in the state do not have the background to assess damages. Residents have moved back into many damaged buildings, even though some of these buildings may not be capable of resisting strong aftershocks, and are unfit for occupation.

In the tense moments after the earthquake, many local administrations depended on visiting faculty members and engineers from other states conducting post-earthquake reconnaissance of the affected areas. Some of them managed to contribute a day's effort to identify unsafe buildings, but decisions on a large number of damaged buildings were pending six weeks after the quake. This lack of decisive evaluation led to situations like the state-ordered demolition of the building that serves as the Health and Family Welfare Unit of the main Sir Thutob Namgyal Memorial Hospital in Gangtok. This order stands even when

the six-story RC frame building has no damage (including even fine cracks of frame-infill separation in the URM infill walls) except for some distress in the independently built four-column porch at the entrance.

The Government of West Bengal had deputed the Block

Development Officers (BDOs) to report the number of houses damaged. In the District of Darjeeling, under extreme pressure from the locals to seek government compensation meant for damaged buildings, the BDOs were coerced to post all houses in some areas fully damaged. This resulted in the Government of West Bengal declaring about 37,000 houses damaged, while the field reconnaissance suggests otherwise.

This earthquake is demonstrating that post-earthquake building damage assessment is not just a technical activity, but also an administrative and legal activity, which needs prior rehearsal by all stakeholders (technical, administrative and political leaders), promulgation of appropriate laws to protect persons undertaking damage assessment, and safeguards against misuse by political leaders.



Figure 29. Makeshift school in tents on river terrace at Chungthang (photo: Alpa Sheth).

Intermediate Shelters and Reconstruction

The intensity of ground shaking in the state of Sikkim and hills of Darjeeling during this earthquake was small — only V-VI+ on the MSK scale — so damage to buildings and structures was limited. Persons with severely damaged houses moved to their relatives' houses as an interim measure. Because some schools, primary health centres, and government governance buildings were severely damaged, there is an urgent effort for construction of intermediate facilities (Figure 29). Considering the availability of bamboo in the state, a possible design for intermediate houses, schools, and primary health centers could utilize that as primary construction material; the traditional wood-frame construction could be adapted with bamboo mats as walling; this type of construction is already prevalent in Sikkim.

The Government of Sikkim needs to firm up a comprehensive reconstruction strategy, even though the effort required is smaller than required by other recent large earthquakes. The challenge is made complex due to factors like acute shortage of manpower within the state capable of undertaking earthquake-resistant design and construction, shortage of construction

materials and labor, and the remoteness of affected areas. The state may consider development of designs for earthquake resistant homes in line with the cultural aspirations of the people in the region, and it should establish some form of regulatory framework

and implementation mechanism to ensure conformance to seismic safety construction procedures.

Community Impacts

Villages susceptible to landslides were relocated to safer areas; however, as a result, one saw villagers, especially women, walking between their original and relocated homes over miles of steep terrain in North Sikkim. The harsh living conditions in the cold, steep and poorly accessible terrain, and annual landslides during the rainy seasons, have made inhabitants resourceful and able to deal with lesser disasters. Numerous bamboo bridges made by villagers across streams were testimony to this. The continued presence of the Border Roads Organization in the region is vital. There is an opportunity for engaging the military as they have a permanent presence in the area.

Lessons Learned

This earthquake has brought into relief issues of disaster mitigation and management in the inhospitable region of the Himalayas which is one of the most seismically active regions of the country.

1. The extent and type of damage in newly built RC structures are not commensurate with the intensity of ground shaking. Most damage can be attributed to irregular structural configuration, improper design and detailing, poor construction materials and practice, or complete absence of regulatory framework from the government side to ensure earthquake-resistance in the built environment.
2. No new URM structures should be permitted in Sikkim, and existing ones should be retrofitted, especially the critical, life-line and government structures.

3. Develop a comprehensive plan to retrofit all heritage structures in Sikkim and West Bengal. When even basic earthquake-resistant construction is not known by local architects and engineers, special assistance may be required from outside these states to support this culturally and historically critical work.
 4. There should be an aggressive promotion of traditional Ekra housing by development of a manual of good construction practices and inclusion of this as a formal housing construction typology eligible for bank loans.
 5. Post-earthquake damage assessment teams need to be mobilized from out of state that have sound judgment on usability of damaged structures and no stake in the new construction. As well, technical information needs to be disseminated to professional architects and engineers on accepted methods for assessment and retrofit of damaged structures.
 6. Mandatory review of the safety of all ongoing and completed hydro-power projects should be initiated and the information shared with the community as a confidence-building measure.
 7. Document all losses incurred by nonstructural elements, and disseminate technical know-how to architects and engineers on methods of protecting these elements.
 8. The epicentral area was cut off for more than 12 days after the earthquake. This is not acceptable by any standards in the modern communications era.
 9. There is an urgent need to study the strong ground motions in order to incorporate reasonable expectations in the design codes. There is a network of ground motion instruments in the region operated by various national agencies and institutes, but it must function in the next earthquake.
 10. There is no government engineering and architecture college in the whole state of Sikkim or in Darjeeling to provide regular advice to the governments of Sikkim and West Bengal. There are two structural engineers (with masters degrees) and about 35 architects in the entire state of Sikkim, few trained in the subject of earthquake-resistant construction. The newly opened Sikkim-Manipal Institute of Technology should be encouraged to engage with the state of Sikkim to bring about an environment of earthquake safety in the state. Similarly, an engineering college should be established in the hills of Darjeeling to support the local needs.
 11. Site-specific scientific approaches are required for studying relatively soft mountain slopes along the Singalila range and in the Teesta Valley to assess landslide potential of areas where critical facilities are located (e.g., Leprosy Hospital area in Kalimpong), and to develop measures to mitigate these landslides. The current approach of constructing roads along mountain slopes needs to be reviewed; scientific strategies and structural geologists need to be engaged for constructing roads and determining cuts along mountain slopes. New techniques need to be investigated to make construction of roads along mountain slopes more efficient, scientific, of good quality and durable.
- The lessons learned can have large benefits if they are acted on quickly — unlike the opportunity lost after the 2006 earthquake in the same area. While local residents will remember this earthquake as one that caused landslides and destroyed heritage structures, earthquake professionals see it as a warning before the big one strikes.