2011 Sikkim Earthquake at Eastern Himalayas: Lessons learnt from performance of structures

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A B S T R A C T

On 18 September 2011, all the Indian states and countries surrounding Sikkim witnessed a devastating moderate earthquake of magnitude 6.9 (Mw). Originating in Sikkim–Nepal border with an intensity of VI in MSK scale, this earthquake caused collapse of both unreinforced masonry buildings, heritage structures and framed structures followed by landslides and mud slides at various places of Sikkim. Significant damages have been observed in relatively new framed structures mainly in Government buildings, thick masonry structures, while, the older wooden frame (ekra) non-engineered structures performed well during the earthquake. Further, it is noteworthy that government buildings suffered more than private ones and damages were observed more in newer framed structures than older ones. Analysis of the damages identify lateral spreading of slope, pounding of buildings, out-of-plane rotation, generation of structural cracks, plastic hinge formation at column capitals and damage of infill wall material as predominant damage features. A few remedial measures are also attempted to be mentioned with future need of research and application. It has been felt to create awareness regarding these issues and is the need of the hour.

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1. Introduction

1.1. Regional setting and seismological features

Sikkim is a small state in northeast India at the foothills of the Eastern Himalayas with the main thrust faults (main boundary thrust [MBT] and main central thrust [MCT]) crossing the state (Fig. 1). In the evening of 18 September 2011, it witnessed a moderate earthquake of magnitude 6.9 (Mw), which is referred hereafter as the ‘2011 Sikkim Earthquake’. This particular event, considered as the largest mid-to-deep crustal earthquake of the region recorded by the Himalayan Nepal Tibet Seismic experiment, was followed by a number of aftershocks, three of whose magnitudes were more than 4.2 (Mw) [2]. The earthquake had its origin near the Sikkim–Nepal border. The Gangtok and Teesta lineaments, transverse to the Himalaya’s are responsible for many earthquakes in the region. A strong earthquake of Mw 8.1 struck in January of 1934 along the Bihar–Nepal border along the interplate boundary. Other major earthquakes in this area in the last 50 years include the September 2009 Bhutan earthquake of Mw 6.1, the February 2006 Sikkim Earthquake of Mw 5.3, the August 1988 Bihar–Nepal earthquake of Mw 6.5 and the November 1980 Sikkim Earthquake of Mw 6.0. The hilly terrain of Sikkim, ranging from 27°N to 20°N and 87°59’E to 88°56’E, is wedged between Nepal at its west and Bhutan at its East, flanked by the Indian states of Bihar at its South-West and West Bengal at its south, and surrounded by Tibetan China along its north to north-east boundary. Encircled by the three international boundaries with Bhutan, China and Nepal, this strategically located state is divided into four districts, namely, East Sikkim, North Sikkim, West Sikkim and South Sikkim. Impact of the quake was actively felt by all the Indian states and countries surrounding Sikkim, each of which was witness to human death and building collapse. The acceleration time history of the main shock was recorded at Gangtok and the PGA was 0.15 g. The death toll was beyond 100, the number being highest in Sikkim. It is worthy to mention here that the region falls in Zone IV of the Indian seismic zoning map [3] where a maximum intensity of VIII is expected.

1.2. Account of the disaster

The authors had a technical visit to the areas affected by 2011 Sikkim Earthquake in December 2011. Accordingly, a reconnaissance based damage survey was conducted in December 2011 in
the four districts of Sikkim along with Kalimpong and Siliguri divisions of the Darjeeling district of West Bengal, as these areas were reported to have suffered significantly. Propagation of a large number of aftershocks is a typical feature of the seismic history of this region. However, each of the three aftershocks of the 2011 Sikkim Earthquake is individually capable of causing significant damage to the load-bearing unreinforced masonry structures (URM) of the region which are weak in tensile strength and shear strength. The catastrophic effect of the earthquake is mostly felt in North Sikkim, which is evident from Fig. 2 where one finds only the ruinous remaining of the entirely devastated Mangan Church situated in Mangan town, the district headquarter of North Sikkim.

The impact of the 2011 Sikkim Earthquake seems to be responsible for severe damage of a number of framed structures in addition to the usual damage of URM buildings and infill walls caused by the earlier 2006 Sikkim Earthquake, a moderate quake of magnitude 5.7 (Mw) [4,5]. A number of monasteries, living testimonies of the religio-cultural heritage of the Vajrayana sect of Indian Buddhism, suffered considerable damage.

Among the damaged framed structures, two general trends were noted. Firstly, the government buildings suffered more than their private counterpart. Secondly, damage was observed more in the newer structures than the older ones. These two primary observations point towards any one or combination of three reasons: (a) low-grade quality of material, (b) mediocre workmanship and (c) second-rate technical supervision. It is also to be noted that the magnitude of 2011 quake is relatively higher within last 50 years in comparison to the earthquakes struck in this area. In addition to areas with previous history, landslides further occurred at different places resulting damage of buildings, many portions of the national and state highway sand abutments of bridges as reported elsewhere [6]. However, there was no reported damage of any bridge. Amidst these havoc, it was notable that majority of the non-engineered buildings made with combination of wood and bamboo survived.

2. Damage profile

The buildings of the surveyed area can be broadly divided into three types, namely framed reinforced concrete (RC) structures with brick infill, unreinforced load bearing masonry buildings (URM), and timber-framed buildings with timber board or bamboo-matting (ekra) in between. The URM units are stone ashlars, kiln-burnt clay bricks or
cement blocks laid in cement, cement–lime, lime–mud or mud mortar. The random rubble, locally made brick and bamboo/timber made buildings are categorised as ‘non-engineered’ ones, as their strength properties are not codified. The damage profiles of twenty-five buildings surveyed in Sikkim and Darjeeling, which exhaustively represent various types of damages of engineered as well as non-engineered buildings, are illustrated below. The damage profiles of these buildings are categorised under five general damage features, each followed by suggested remedial measures. Before concluding, the paper further discusses features of the undamaged non-engineered buildings.

2.1. Collapse due to amplification of ground shaking and lateral spreading

In general, the maximum intensity of ground shaking in the entirely effected area was estimated as VI+ MSK scale, but some pockets had higher shaking owing to site specific amplification of ground motion. Significant damage in buildings was reported (e.g., ITBP quarters at Pegong in Chungthang [6]) which were sited on gradually sloping mountain meadows, probably due to sustained amplification of ground shaking. Fig. 3a illustrates one such case where the two private buildings in Gangtok, one six-storied and another ten-storied, on one such hill pocket has resulted in severe damage of the six-storied structure, and complete collapse of the taller heavier one due to amplified ground shaking.

The phyllites and schists of the Precambrian rocks of Sikkim are prone to weathering. This, along with intense rain, causes extensive soil erosion. This constant erosion of the soil causes considerable change in its bearing capacity within short distances, sometimes resulting in lateral movement of slopes during earthquakes. Another three-storied Treasury Building situated in the SDO office compound, Kalimpong in Darjeeling district of West Bengal suffered damages due to differential soil condition induced slope movement. One side of the building has subsided causing wide cracks at the floor and plinth level (Fig. 3b). It is learnt that the rear ground portion of the land, towards hill slope, is actually a filled-up land, which has resulted in subsidence as well as lateral spreading due to earthquake shaking. The 2011 Sikkim Earthquake has further triggered transverse cracks along the shear walls leaving the building abandoned. However, the top floors of the building were relatively less affected. Similar subsidence of floors has also been observed at ground floor of office building within Enchey Monastery Complex (Fig. 3c).

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Fig. 2. Remains of the Mangan Church at Mangan town, North Sikkim entirely devastated by the impact of 2011 Sikkim Earthquake.

Fig. 3. RCC buildings damaged due to deteriorating soil condition during 2011 Sikkim Earthquake; (a) devastated six-storied private building and total collapse of a ten-storied building at Balukholi in Gangtok, East Sikkim; (b) wide floor-cracks due to subsided ground below Treasury Building, Kalimpong, Darjeeling; (c) subsidence of ground below office building within Enchey Monastery Complex, East Sikkim.
2.2. Pounding of buildings

Pounding, a common phenomenon in the hills, was also observed to have damaged many buildings during the 2011 Sikkim Earthquake, including the six-storied private building referred in Fig. 3a, which collided with the one situated to its right. In fact, absence of any effective techno-legal framework regarding the building rules for private construction and ignorance about the ill effects of the phenomenon of pounding, coupled with growing pressure of urbanisation has created this situation. Fig. 4a and b illustrates the issue of pounding of buildings through instances of Gangtok, East Sikkim.

Fig. 4a and b illustrates the issue of pounding of buildings through instances of Gangtok, East Sikkim. Fig. 4c illustrates the issue of pounding of buildings through an example of Siliguri, West Bengal, where two RCC buildings, namely Ganesh Brothers Market Building and Kandu Bhawan were observed to have collided with each other. Apparently no other damage was visually observed from outside. It was further noted that the length of these two buildings, constructed keeping practically no distance between them, is almost six times their width. However, these case studies of Siliguri are considered as an exceptional one which clearly indicates that building rules are not properly followed. In fact, Siliguri is a municipal corporation at the foothills of the Eastern Himalayas with its own building rules framed by the local law enforcing administrative machinery.

2.3. Collapse due to out-of-plane rotation

Out-of-plane collapse of unreinforced masonry walls due to the lateral thrusts of earthquake is a typical failure pattern observed due to the 2011 Sikkim Earthquake. The Mani Lhakhang Prayer Hall at Rongyek near the Sikkim State Jail in East Sikkim illustrates one such case (Fig. 5a). The dominant north–south direction of the ground motion of the 2011 Sikkim Earthquake has resulted in collapse of the 500 mm thick north and south rubble walls of the Hall, while its east and west walls remained almost intact. This phenomenon points towards the issue of absence of proper connection between the north–south oriented walls with the east–west oriented walls. A proper connection between these two sets of walls would have saved the walls collapsing due to out-of-plane rotation as long as the other pair did not fail. Another similar devastating damage is observed in a brick masonry wall of ground floor of Tashling Secretariat building at Gangtok, East Sikkim (Fig. 5b).

The experience regarding masonry walls with circular plan was somewhat similar to those having rectangular plans. One such wall was observed while surveying the Siliguri Special Correctional Home, which has a circular inner security wall of 300 m length. The uppermost portion of the security wall, 2 m high and 0.25 m...
thick, was added above the thicker lower portion in 1997. The lower portion was constructed in 1962. The 2011 Sikkim Earthquake not only caused continuous peripheral crack at the junction of the older and newer portions of the 300 m long wall (Fig. 6a), but also caused out-of-plane failures of the upper thinner portion of the wall at its northern and southern portions which fell in the line of the earthquake ground motion. Fig. 6b shows rebuilt upper portion of the security wall at its southern position. The 114 km distance between Gangtok and Siliguri signifies the devastating impact of the 2011 Sikkim Earthquake, as well as the transitivity of the seismic waves and increases concern about Sikkim and its adjoining areas in case of future seismicity in the region.

2.4. Generation of structural cracks

The structural elements of a building suffering from earthquake undergo tension, compression and resultant shear. The concrete at the bottom portion of RCC beams are generally found to experience cracks during earthquakes because of it being weak in tension. Fig. 7a illustrates one such typical example of RCC beam failure after the 2011 Sikkim Earthquake in the Working Women’s Hostel situated at Deorali in East Sikkim. Again, under impact of main Earthquake and its repeated aftershocks, vertical surfaces of different RCC columns undergone bending, which generated cracks on these surfaces. Severity of the impact of such lateral shocks generated by the 2011 Sikkim Earthquake can be understood from Fig. 7b where one finds deep cracks exposing the reinforcements of a RCC column in the Women’s Polytechnic Siliguri situated at Dabgram Colony, Siliguri of the Darjeeling district of West Bengal. This indicates formation of column hinge at the beam column junction.

2.5. Plastic hinge formation at column capitals in soft ground storey

Formation of plastic hinges at the column capitals in soft ground storey was observed as one of the typical features of any soft storey or partially soft storey building during the 2011 Sikkim Earthquake. Here, the term ‘partially soft storey’ is referred to a building where a portion of its ground floor has columns integrated with walls and the remaining portion has isolated columns. When the forces thus generated at the beam–column junctions become more than the ultimate strength, plastic hinges are formed at the column capitals. Fig. 10a and b illustrate examples in buildings with full soft storey at ground floor, while Fig. 10c–f are examples of partially soft storey ones.

3. Experience of a few undamaged buildings

An important observation during the 2011 Sikkim Earthquake was that some of the surveyed buildings did not suffer any damage though those at their vicinity had suffered much. The examples included both engineered as well as non-engineered ones. In this section, a few such examples are discussed.
It was illustrated through Fig. 3b that how the 2011 Sikkim Earthquake damaged the three-storied RCC building of the Department of Treasury, Government of West Bengal, situated in the SDO office compound of Kalimpong because of considerable subsidence of its rear side, built on filled-up land. However, it was interesting to observe that its neighbouring two-storied RCC building of the Department of Food and Supply, did not suffer any damage (Fig. 11). The probable reason, for this much older government building remaining undamaged, may be attributed to the fact that the land consists of firm stable ground having sound bearing capacity on which it is built and also to the fact that quality of material, workmanship and technical supervision have all worsened over the years, especially for government projects. Another non-engineered single-storied tea shop situated just in front of these two RCC buildings, made of cheap timber, did show no sign of any damage (Fig. 11).

It may be mentioned here that the authors came across many other undamaged structures situated in the vicinity of damaged buildings. Majority of such structures are non-engineered ones made in combination of locally available timber and bamboo (Fig. 12a). However, sometimes RCC structures having traditional timber roofing are also found to have withstood the impact of the 2011 Sikkim Earthquake (Fig. 12b). The reason behind better performance of such structures may be attributed to the ductile nature of bamboo and timber, which has more shock absorbing capacity.

It is learnt that the Enchey Gompa, one of the most important monasteries of the Nyingma order of the Vajrayana Buddhism, after getting severely damaged due to the impact of the 2006 Sikkim Earthquake (Fig. 13a), was retrofitted with FRP sheets. It was observed that the portions thus retrofitted did not suffer any damage after the 2011 Sikkim Earthquake (Fig. 13b). However, those portions which were not retrofitted, like its attic, are damaged (Fig. 13c).

4. Lessons learnt from 2011 Sikkim Earthquake

The damages of the structures in this earthquake exhibited two aspects. Firstly, there are some well-known technical aspects

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Fig. 8. Damaged Buddhist monasteries due to 2011 Sikkim Earthquake: (a) vertical shear cracks in the load bearing stone masonry of Lingtem monastery at Middle Dzongu, North Sikkim; (b) fatal damage of stone masonry walls of Ringhim monastery at Mangan, North Sikkim; (c) vertical shear cracks in a column of Tashiding monastery at Tashiding, West Sikkim; (d) damaged infill walls of Gung monastery at Darjeeling, West Bengal.

Fig. 9. Shear cracks generating at the door–window openings of infill walls due to 2011 Sikkim Earthquake: (a) Siliguri Special Correctional Home, Siliguri, Darjeeling district, West Bengal; (b) Class III Quarters at Jalipool, Gangtok, East Sikkim.
Fig. 10. Hinge formation in column capitals at soft storey during 2011 Sikkim Earthquake: (a) Class-I Govt. Quarter at Nam Nang, E. Sikkim; (b) Fire Station at Jorethang, S. Sikkim; (c) Kunzang Choling monastery at Shipgyer, N. Sikkim; (d) Police Head Quarter building, E. Sikkim; (e) Tashling Secretariat building, E. Sikkim; (f) damaged capital of a column supporting pavilion sheltering Bhanu Bhakta statue at Nepali Research Centre, Gyalshing, W. Sikkim.
which are not being practiced. Engineers, architects, builders and even masons, all those are related to building industry have to come together and make some techno-legal guidelines for implementation. Some of the prominent issues exhibited through damage survey are presented in the following paragraph. On the other hand, there are some issues where research should be carried out to find out economically viable means of strengthening of non-engineered structures which are mostly used by people of lower economic bracket in such hilly areas. Mention of them is also made separately in the following paragraphs.

For reinforced concrete structures, soft or open ground storey is a known source of vulnerability. This has been exhibited in this earthquake. Immediate retrofiting measures through provisions of bracings or strong beams at lintel levels may be adopted for increasing safety of such building. This may arrest the problem of plastic hinging at column ends. Further, bracing lintels may be provided in windows and provisions of lintels may be ensured at the top of the doors to stop crack propagation from door/window corners. Pounding of the buildings can be avoided through provisions of minimum distance worked based on heights of two adjacent buildings. In the hilly region, near the edge of the stepped ground, slope failure has been noticed. These have resulted in subsidence of the part of the building at the edge caused due to landslide of the part of the ground. Thus before constructing building, in such cases, ground improvement aiming to arrive at uniform bearing capacity over the entire area and restricting the slope movement on which the structure is to be build should be made.

However, the speciality of this reconnaissance based damage survey lies in the fact that the damage patterns observed in 2011 Sikkim Earthquake of moderate magnitude and damages observed in developed countries, such as, USA, Japan, China etc. due to earthquake are of different nature. For instance, in 2011 Tohoku earthquake, Japan struck with an earthquake magnitude of 8.1 causing a considerable damage of lifeline facilities and structures. In fact, the reason for most of the damages of structures may be due to high velocity sea water wave force originated by Tsunami, while, the structures designed considering seismic codes performed well in such strong earthquake. A reasonably accurate design properly accounting the earthquake codes is followed in developed countries to design the structures which help to prevent the failures as observed in 2011 Sikkim Earthquake.

In contrary, the damages observed in hilly region of Sikkim mostly for the non-engineered RCC and masonry structures which are used as shelter by the lower economic bracket people in such developing countries. Hence, the comparison of damages may not

Fig. 11. Undamaged engineered and non-engineered buildings in the SDO office compound at Kalimpong in Darjeeling district of West Bengal.

Fig. 12. Few structures remaining undamaged after 2012 Sikkim Earthquake in the vicinity of damaged structures; (a) an undamaged non-engineered single-storied building in the vicinity of the damaged Mani Lhakhang Prayer Hall at Rongyek near Sikkim State Jail, East Sikkim; (b) an undamaged RCC building with traditional timber roofing behind the damaged Tashling Secretariat building at Gangtok, East Sikkim.

Fig. 13. Comparison of performance of Enchey monastery, E. Sikkim, prior to and after seismic retrofitting; (a) cracks in the outer masonry walls after 2006 Sikkim Earthquake; (b) retrofitted masonry walls remain undamaged after 2011 Sikkim Earthquake; (c) non-retrofitted attic damaged after the 2012 Sikkim Earthquake.
be relevant. Therefore, the collation of different types of damages caused due to 2011 Sikkim Earthquake helps to reach a conclusion that what kind of small retrofitting measures may provide adequate resistance for structures to survive during low to moderate range earthquake in such developing countries.

5. Summary and concluding remarks

Masonry structures are found to be a usual victim of earthquake because of out-of-plane collapse of walls. However, such out-of-plane failure can be avoided by strengthening the joints and enforcing the integrated box type behaviour of structures through low cost means as people belonging to middle to low class economic bracket. Present research group is working on this issue by use of L-shaped bar, or binding the masonry by polypropylene packaging bands.

However, wooden and bamboo made structures with light weight roofing have survived the earthquakes. Hence, a mission should be taken to popularise such building with blending of adequate technology, e.g., bolting of two wooden members, their typical foundation with concrete pedestal, adequate trussing of pitched roofs as explained in a recent study [7]. With advent of powerful numerical analysis techniques in structural engineering, reasonably accurate analysis of many structural engineering problems has become possible. However, despite this boast of human civilisation, through such earthquakes nature demonstrates only our limitations. Some of these are the limitations in many aspects including lack of knowledge and understanding of behaviour of masonry and other non-engineered structures demanding more research in this direction. Further, most important deficiency is failure in implementing the already understood principles by the working level because of lack of percolation of knowledge and consciousness in grass root level people like practicing engineers, architects, builders, masons and even common people who are stake holders. Thus, the lessons in the form of remedial measures should be popularised by means of knowledge dissemination through short term course, seminar, symposium etc. This paper is an attempt to explain why damages and casualties occur in developing countries even in low magnitude earthquakes, despite considerable progress in research and development in the realm of earthquake engineering. Thus, this paper may be useful to design engineers, architects, builders and other stake holders in building industry.

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