

# Geotechnical Aspects of Sikkim Earthquake of September 18, 2011

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**Abstract** There was wide spread ground failure and landslide during the recent Sikkim earthquake (Magnitude  $M_L = 6.9$ ) of September 18, 2011. An intensive damage survey was carried out after a week of the earthquake. This paper presents the results of a reconnaissance study in Sikkim. The various geotechnical aspects of the damage caused by earthquake including landslides, failure of retaining walls, foundation failures, damage to roads and creep of soil due to ground shaking have been investigated. The maximum damage was observed in Lachung, North Sikkim district. The paper presents the geotechnical aspects of damages correlating it with level of shaking (intensity on MSK scale) and epicentral distances at different locations. It was found that major damage was due to landslides and failure of retaining walls which in turn are due to movement of soil. In this paper, causes of damages have been investigated and remedial measures, to avoid these in future earthquakes, are suggested.

**Keywords** Earthquake damage · Sikkim earthquake · Landslides · Ground failure · Settlements · Retaining walls · Intensity of shaking

## Introduction

Past earthquakes have caused widespread geotechnical damage in the world [1]. Recent earthquakes affecting India include Killari (1993), Jabalpur (1997), Chamoli (1999), Bhuj (2001), Sumatra (2004), Kashmir (2005) and

Sikkim (2006). India being a densely populated country, effects of these disasters are significant in terms of casualties and economic losses. The country had been visited by a number of historical earthquakes in past and seismic awareness has increased since 2001 Bhuj earthquake. Though it is more than a decade since then, however, the country is not prepared yet to face such major earthquakes. Tsunami generated by 2004 Sumatra earthquake caused widespread damages [2].

A disastrous 6.9 magnitude earthquake [3–5] occurred in India's northern state of Sikkim at 6:11 PM (IST) on September 18, 2011. According to IS: 1893–2002 [6], the region falls in seismic zone IV (second highest in the country). The region is seismically very active and has witnessed a number of major earthquakes in past including Cachar earthquake (1869,  $M = 7.5$ ), Assam earthquake (1897,  $M = 8.7$ ), Bihar–Nepal earthquake (1934,  $M = 8.3$ ) and Assam earthquake (1950,  $M = 8.5$ ).

The Sikkim earthquake left behind a trail of death and devastation, killing 112 people, injuring more than a thousand, and rendering more than twenty thousand people homeless. According to USGS [5], the location of the earthquake was at Latitude  $27.723^\circ\text{N}$  and Longitude  $88.064^\circ\text{E}$  at India-Nepal border region with estimated focal depth of 19.7 km. The earthquake epicenter was located at 68 km NW of Gangtok. However, according to India Metrological Department [7], the magnitude of earthquake was 6.8 and the focal depth of the earthquake has been estimated as 10 km. The event, which comes under the category of “moderate earthquake”, was also reported to be widely felt in Sikkim, West Bengal, Assam, Meghalaya, Bihar, parts of other eastern and northern regions of India. The neighboring countries Nepal, Bhutan, Tibet and Bangladesh also felt intense shaking of the quake. The epicenter lies in a seismically active belt called,

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Alpide-Himalayan seismic belt characterized by two major fault systems main boundary thrust (MBT) and main central thrust (MCT) associated with the collision of the Indian and Eurasian plates, Valdiya [8].

Figure 1 shows the three components of acceleration time history records of main shock as recorded by Pesmos [9]. It can be observed that the peak ground accelerations in EW, NS and vertical directions are 0.15, 0.16 and 0.13 g, respectively. This indicate moderate intensity of earthquake at Gangtok.

### Locations for Damage Survey

Soon after the earthquake, authors visited different parts of Sikkim and carried out the damage survey during September 25–29, 2011. The extensive survey was carried out in the Gangtok City, Capital of the Sikkim state. The team visited all 4 districts of Sikkim i.e. East Sikkim, North

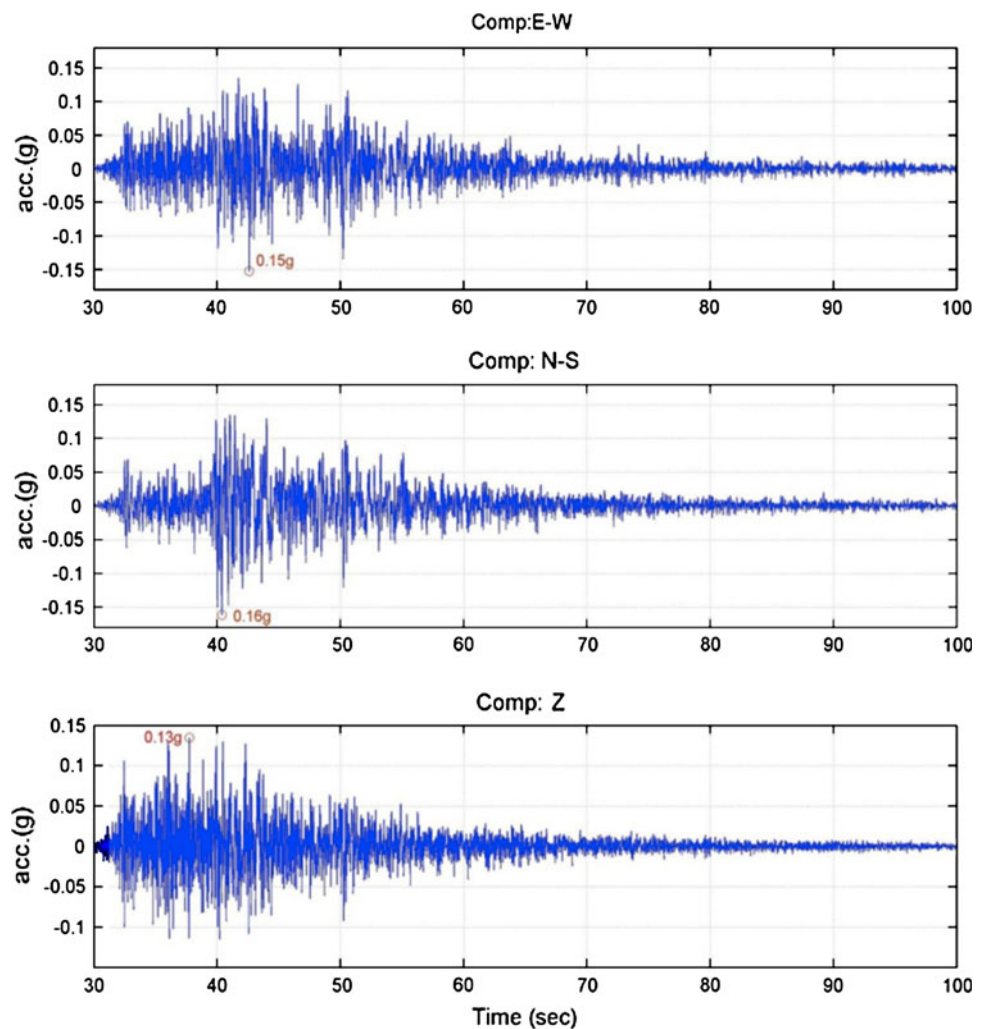
Sikkim, South Sikkim and West Sikkim. Figure 2 shows the major 4 tracts visited by the team i.e.

- (a) Rangpo–Singtam–Ranipol–Gangtok (East Sikkim)
- (b) Singtam–Temi–Legship (South Sikkim)
- (c) Singtam–Temi–Jorhang (West Sikkim)
- (d) Gangtok–Lachung (North Sikkim)

The team need to use the service of helicopters of Indian Army and Indian Air Force between Gangtok and Lachung, as at that time, the north Sikkim was not accessible by road due to massive landslides.

The team members interacted with local government authorities, NGOs and public at large. It was reported that there was heavy rain before and after the earthquake and the region being mountainous, the quake triggered massive landslides. In some regions, the damage to buildings and infrastructure caused by landslides was more severe than damage due to direct ground shaking. Landslides damage the roads and cut-off some areas at higher altitudes in

**Fig. 1** Acceleration time history of main shock recorded at Gangtok on September 18, 2011 (<http://pesmos.in/2011/>)



**Fig. 2** The location of the places visited during the damage survey (shown by filled red circle). (Color figure online)



North Sikkim such as Mangan, Chungthang and Lachung from the Gangtok. Among the places visited, based on damage, the maximum shaking intensity of this earthquake on MSK (1964) scale appeared to be VIII+ in Lachung (North Sikkim District) which is about 68 km from epicenter.

The reconnaissance team surveyed the seismological, geotechnical and structural aspects of damages. The damages include landslides, slope failures, ground failures, settlement of soils, failure of retaining walls, failure of foundations, damage to roads, failures of beams and columns of buildings, monasteries, government buildings, and bridges. This paper investigates the geotechnical aspects of the damage such as landslides, retaining wall failure, ground failure, movement of soil and failure of foundations. This is preceded by a brief review of geology and tectonics of Sikkim.

### Geology, Tectonics and Metrology of Sikkim

The geology of Sikkim is similar to that of the Eastern Himalaya where four distinct geomorphology based transverse zones namely- Sub-Himalaya, Lesser Himalaya, Higher Himalaya and the Tethys Himalaya, are separated by major tectonic dislocations. The geology consist of 4 Precamarian Rocks i.e. Everest Pelitic Formation, Sikkim Group, Chungthang Formation, Kanchenjunga Gneiss Formation [10–12]. The tectonic frame work and the seismicity of the northern Eastern states including Sikkim are considered as a result of collision tectonics in the Himalayan arc and subduction tectonics below the Myanmarese arc. Studies have indicated a very complex tectonic setting of the region due to constant movement of the Indian plate from South to North and Myanmarese from East to West.

The area of Sikkim is about 7,300 km<sup>2</sup> and the elevation in different parts range between 244 and 8,534 m. Thus this indicates that there is large variation in elevation. A number of rivers and tributaries flow through the state, among them Teesta and Rangit are major rivers. Much part of the Sikkim lies in watershed of Teesta River. The intensity of rainfall is very high and variation of precipitation during the year is also high. Average annual precipitation in Gangtok is 3,539 mm, Bhasin et al. [10].

### Landslides and Mudslides

All four districts of Sikkim witnessed massive landslides due to earthquake. It has been reported that earthquake triggered more than 300 landslides. Extremely high occurrence of landslides is attributed to the geology of the region and intense rainfall. High intensity of rainfall contributes to rapid erosion and weathering of rock mass. The increase of water level causes instability in natural slopes. Further, human activities such as excavation work for buildings, roads and embankments add to instability, Mehrotra et al. [12]. Earthquake provides just a triggering action to already unstable or marginally stable slopes. As per landslide hazard zonation map of India, Sikkim lies in second highest zone categorized as “high zone”. This spells the risk, the state inhabits for landslides. Recent earthquake just validated this unpleasant fact. Some of the landslides induced by the earthquake are described. Its effects on build environment are discussed in following sections.

Figure 3 shows a mudslide in Singring, Lachung (North Sikkim), intensity of shaking VIII+. Due to incessant rain followed by earthquake, a water stream changed its path and created a new stream. In this stream, water flown at



**Fig. 3** Massive mudslide in Singring, Lachung (North Sikkim)

such a high velocity that debris of rock also flown with it and created mud mountains at both sides of this stream, this was a strange phenomenon. Perhaps, this is attributed to reduction in strength of rock material due to saturation, Kramer [13] and then it slid due to earthquake force carrying huge boulders and rock pieces with it. This phenomena may be termed as the landslide lake outburst flood where an earlier blocked stream breached due to earthquake shaking. The locals were trying to divert the path of this new stream as it poses threat to the buildings at the downstream. Though size was not measured, however, approximate size of the slide was about 1,000 m in length and about 200 m in width.

A massive landslide occurred near Sorang in West Sikkim (Fig. 4). Sorang (near Jorhang) area is at epicentral distance of about 66 km and intensity of shaking here can be assigned as VIII. It blocked the road and thus movement of vehicles from Jorhang to Sorang. Exposed overburden can be seen in the photograph. Another landslide was spotted in Singtam (East Sikkim) as shown in Fig. 5. Singtam is about 70 km south of Gangtok and is at junction between East Sikkim and West/South Sikkim. Its distance from epicentre was about 70 km with shaking intensity as VII. Approximate area of the slides shown in Figs. 4 and 5 were about 500 × 500 m.

In nutshell, all 4 districts of Sikkim witnessed a number of landslides. There are a number of measures to mitigate the landslides which include installation of anchors and nails on unstable rocky hillside. The reinforcement measures generally consists of introduction of metal elements for increasing the shear strength of the rock. Anchorage can be classified either as active anchorage (subjected to pre-tensioning) or passive anchorage (reinforce of blocks). The other measures include the drainage of water, plantation and geometry modification. The presence of water within a



**Fig. 4** Landslide at about 10 km from Sornag (West Sikkim)



**Fig. 5** Landslide near Singtam (East Sikkim)

rocky hillside is one of the major factors causing instability on the rocky sites therefore drainage will help as mitigation measure.

### Failure of Retaining Walls

In hilly areas, normally toe line of multi-storey buildings are founded on loose soil which is supported by a flexible retaining wall. Due to earthquake, many of these retaining walls damaged which led to failure of supporting foundations. Two such cases are presented below.

Figure 6a indicates collapse of retaining wall (inside boundary drawn) in Lachung and consequently support to columns of a small building is removed. This posed a clear threat to building (Fig. 6b) which could fall at any moment even in a moderate aftershock.

Failure of retaining wall was also observed in Ranipool (intensity VII), which is a small suburban town located near Gangtok at the confluence of tributaries to Teesta and is about 12 km from Gangtok main town. Figure 7a shows retaining wall failure in Ranipool where this failure damaged a building. It was observed that due to earthquake, the

retaining wall on the backside of the building had wide cracks (Fig. 7a) with a gap of more than 15 cm. The cracked portion of retaining wall moved away from the building, creating a wide gap. It was observed that this failure of retaining wall was up to a considerable distance on both sides of the building (Fig. 7a). This in turn separated the stair case from the wall of the building by about 15 cm (Fig. 7b).

To mitigate the damage of retaining walls during shaking, the soil supporting these walls require strengthening treatment and also the seismic design of walls shall be considered before construction. For strengthening of soil, reinforcement or nailing may be used while for seismic design of retaining walls pseudo static method (such as M–O method) may be employed, Kramer [13].

### Ground Failure and Damage to Roads

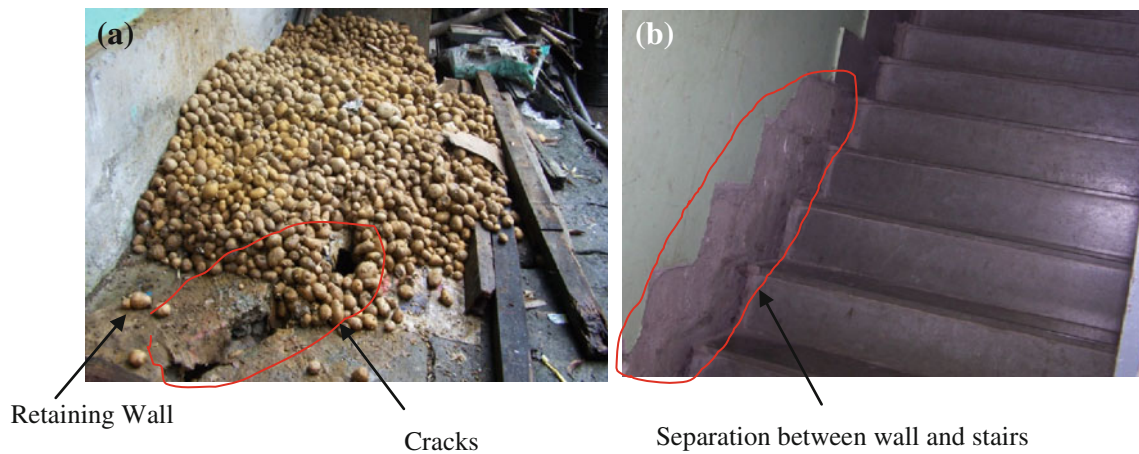
In Lachung, wide cracks with a gap of about 20 cm were observed on the road (Fig. 8a) which can be attributed to the failure of backfill on riverside. The gap created on the road by earthquake shaking is indicating the intensity of shaking. Also the road was damaged due to falling of heavy rock pieces (Fig. 8b). This ground failure in Lachung indicated high intensity of shaking (VIII). The damage to roads can be minimized by providing supports/retaining walls at both uphill and downhill sides. At the same time, the stability of slopes need to be checked for seismic conditions.

### Settlement/Creep of Soil

The problem of creep of soil was prominent in Gangtok, Capital City (epicentral distance 71 km and intensity VII+). There are many multi-storey (5–9 storeys) buildings in the city. In many cases, the adjacent buildings touch



**Fig. 6** Failure of a retaining wall (with red boundary) near Snowlion Mountain Resort, Lachung. (Color figure online)



**Fig. 7** Failure of a retaining wall in Ranipol, Gangtok



**Fig. 8** Ground failure and damage to Roads in Lachung

each other. The areas which are geologically not suitable for multi-storey construction have been used with variety of structural configurations and foundation systems. The toe column line of the buildings, usually ends up on filled up soil, mostly retained by a flexible retaining wall. Many localities in the city are situated on the debris of old landslides and the whole soil mass is creeping under the huge weight of multistorey buildings. The symptoms of this creeping movement are visible along the roadside (Fig. 9). It shall be noted that the foundation used is unsafe, even for normal loads without any earthquake. Since the buildings are resting on filled up soil, strengthening of soil

is required. Further, where the loads are heavy, pile foundations may be used.

According to a senior geologist in Sikkim (personal communication with Mr. Tashi), the geology of Gangtok town can be considered as competent rock with 10'–15' soil cover. Evidence indicated a slow long-term movement of the soil cover which has resulted in cracking and subsidence of ground, floors, and passages. Portions of the buildings which are founded on shallow foundations (partitions, annexes, etc.) have shown gradual and recurring cracking damage in partitions and masonry walls, evident from the past repairs. This damage has been aggravated by



**Fig. 9** Cracks (marked *red*) on the road due to creep of soil in Gangtok. (Color figure online)



**Fig. 10** Tilting of 2 adjacent buildings in “Seesa Gola, Gangtok”

the earthquake to different extents, depending on the local conditions and construction. Particular attention was drawn by the damage in ‘Seesa Gola’, where wide cracks have developed in the ground and a 4 storey building has tilted and leaned to the adjacent building (Fig. 10).

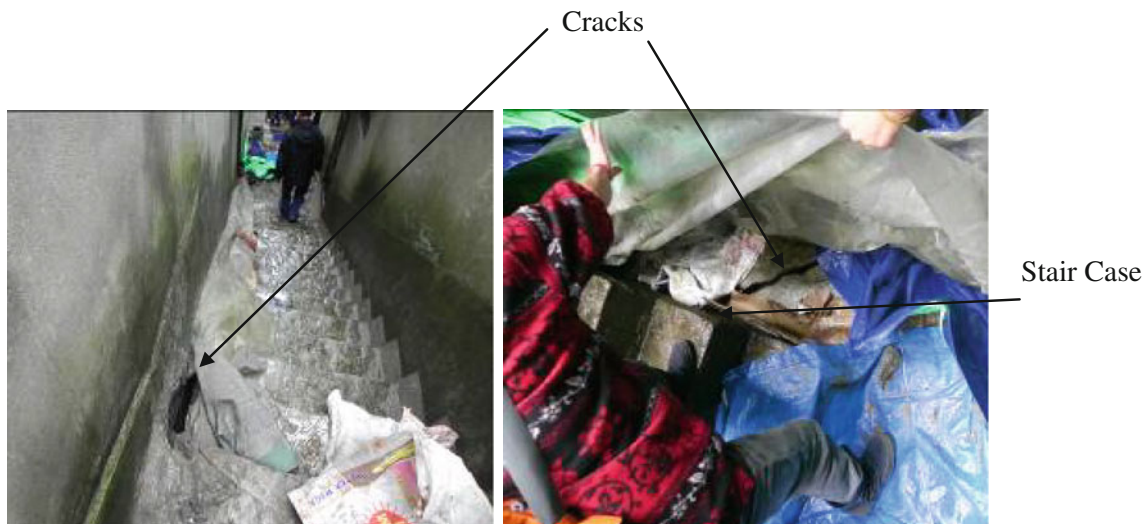
The wide cracks in soil all around the building, as shown in Fig. 11 reveal that the movement is mostly due to rocking at foundation level. It appears that “Seesa Gola” area of Gangtok is located on the debris of a past landslide and the debris mass has undergone some movement during the earthquake. The locality consists of very closely spaced

4–5 storey RC frame buildings with narrow lanes. The 4 storey building (Fig. 10) has tilted and is thrusting the adjacent building at the top. The movement at the top of the 4 storey building is about 0.5 m. However, no structural damage has been observed in the tilted building and all the movement of the building can be attributed to the rocking at foundation. There is possibility of foundation failure, as it was evident that two floors have been added to the building recently and the original foundation may not be adequate for the added floors.

### Foundation Failures

The damage survey was carried out in Jorthang (West Sikkim) which is located on the terrace of Rangit River. Jorthang has epicentral distance about 66 km and intensity assigned is VIII. One of the buildings in Jorthang was totally damaged (Fig. 12) in which 2 of the floors (G + 1) were collapsed. As the ground floor of the building is completely collapsed, perhaps this is due to foundation failure which may be due to excessive settlement caused by shaking. However, the foundation of the building could not be inspected, therefore, the exact order of settlement of soil is not known. However, as the ground floor of the building is completely collapsed, it appeared that soil displaced/settled by about 0.5–1 m in vertical direction. This excessive settlement lead to collapse of soil which in turn lead to failure of foundation and collapse of ground floor.

Sikkim has a traditional construction of low rise light weight timber buildings. A few single storey light weight



**Fig. 11** Wide cracks in soil all around the building in “Seesa Gola, Gangtok”



**Fig. 12** Collapse of ground and first floor of a building in Jorhang (West Sikkim)

timber buildings with GCI sheet roof, and supported on RC columns (stilts) without beams have shown failure of columns and their foundations and retaining walls on downhill side (Fig. 13). However, collapse was avoided due to light weight of timber structure. This suggested that traditional buildings (Ekeras houses) performed well during the earthquake.

**Results and Discussion**

Based on the study of macroseismic effects of the earthquake occurred on September 18, 2011, the Intensity has been assigned to each locality. Interviews of the local public and the administration has helped in this task. For

assigning earthquake intensity Medvedev–Sponheuer–Karnik-1964 (MSK) scale has been adopted which provides comprehensive details for quantifying damage to various buildings.

The intensity was assigned at a specific locality keeping in view the type of structure, the grade of damage to each structure (e.g., Grade I to Grade V) and the number of structures suffered specific grade of damage (e.g., single/few, many or most). Earthquake intensity being a subjective quantity, it is difficult to apply a uniform criteria and considerable element of judgment is involved in its assignment. At several visited localities, the intensity was assigned after careful examination of the extent of

**Table 1** List of places visited and assigned intensities

SN	Station	Lat	Long	Approximate distance in Km from epicenter	Intensity
1	Bagdogra	26.6993	88.3168	117	V
2	Silliguri	26.7098	88.3582	118	V
3	Savoke	26.8902	8847.31	102	V+
4	Rangpo	27.1746	88.5313	77	VI–
5	Mamring	27.1750	88.5168	76	VII
6	Majitar	27.1876	88.4997	74	VII
7	Singtam	27.2317	88.4974	70	VII
8	Ranipool	27.2909	88.5914	71	VII
9	Gangtok	27.33195	88.6135	71	VII+
10	Temi	27.2391	88.4252	65	VII–
11	Namchi	27.1565	88.3263	68	VII+
12	Jorhang	27.1417	88.1805	66	VIII
13	GPU 44	27.14573	88.1476	78	VII
14	Legship	27.2795	88.2749	54	VII+
15	Lachung	27.6890	88.7429	68	VIII+





**Fig. 13** Traditional light weight construction performed well except failure of foundation and supporting structure, Singring, Lachung (North Sikkim)

structural damage, type of materials used for construction, pre-earthquake conditions and workmanship of buildings, and in-depth discussions among the fellow team members. The Intensities thus assigned to various places are given in Table 1.

From Table 1, it can be observed that the maximum intensity (VIII+) is assigned to Lachung while minimum intensity (V) to Bagdogra/Silliguri area. Mahajan et al. [14] also reported similar values of intensities. Intensity of shaking indicated in Table 1 is correlating well with the geotechnical damages reported in this paper.

## Summary and Conclusions

In this paper, the effects of geotechnical aspects of Sikkim earthquake (of September 18, 2011) e.g. landslides, failures of ground and foundations, failure of retaining walls and damage to roads were discussed. From the damage survey presented, following conclusions may be drawn.

1. Landslides occurred mostly in North Sikkim and West Sikkim. Practical mitigation measures for landslides need to be devised.
2. It was observed that most of the damage in Gangtok was due to creep and settlement of soil. This movement of soil need to be checked for effective seismic hazard mitigation [15].
3. Traditional light-weight construction performed extremely well and shall be encouraged with new techniques developed so that it can withstand higher level of shaking.

4. In order to mitigate the seismic effects, long term monitoring of soil movement, pore water pressure and seismic activity is required.

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