Forensic investigation of earthquake induced failures during Sikkim 2011 earthquake, India

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ABSTRACT

This paper presents forensic investigations of earthquake induced failures during Sikkim 2011 Earthquake, India. Detailed field geotechnical observations and geophysical investigations have been carried out at selected locations affected by 2011 Sikkim earthquake. Field observation, drilling of boreholes with sample collection (DBS), surface wave testing by Multichannel Analysis of Surface Wave (MASW) method and Ground Penetrating Radar (GPR) survey have been carried out at sites having slope failures, settlement and structural failures. Three different failure cases: distressed pavement over a natural slope, a school building, and secretariat building failures are discussed with reference to the field tests carried out. GPR radargram showed the cracked portion of pavement and the depth of the cracks. DBS and MASW at school building show the presence of loose cohesionless soil layer below the top dense layer, which might have undergone cyclic mobility and hence resulted in a settlement and cracks in the floor slab. GPR investigation at Sikkim secretariat building showed that the building is constructed on a sloped ground, where one side is filled with soil (damaged side) and the other side is directly resting on the rock. The study highlights the possible reasons for local seismic wave amplification and the associated damage with the help of field investigation carried out.

Keywords: Seismic hazard, Investigation, Soil testing, GPR, MASW

1. INTRODUCTION

Overburden soil above the hard stratum/bedrock play a very important role in the modification of seismic waves and failure of structures. Several examples of earthquake induced failures due to subsurface soil layers are reported. However, very limited studies are available on forensic investigation of earthquake induced failures. Though, India experienced many devastating earthquakes and related geotechnical failures in the past, very limited geotechnical forensic investigation studies were carried out.

This paper presents first forensic investigations of earthquake induced failures during Sikkim 2011 Earthquake, India. Detailed field geotechnical observations and geophysical investigations have been carried out at selected locations affected by 2011 Sikkim earthquake. Field observation, drilling of boreholes with sample collection (DBS), surface wave testing by Multichannel Analysis of Surface Wave (MASW) method and Ground Penetrating Radar (GPR) survey have been carried out at sites having slope failures, settlement and structural failures.

2. ABOUT SIKKIM AND 2011 SIKKM EARTHQUAKE

Sikkim is a small Himalayan state in North-East India and is very popular with its tourist attractive cities like Gangtok, Tsongmo Lake or Changu Lake, Kachupuri Lake and many hydropower projects along the Teesta river. As per the Indian seismic code (IS: 1893: part 1: 2002), the entire region of Sikkim lies in zone IV with a zone factor of 0.24. On the basis of Modified Mercalli Intensity (MMI), the seismic zone IV is associated with seismic intensity VII.

Sikkim state is surrounded by various seismic features and faults: well known Main Frontal Thrust (MFT), Main Boundary Thrust (MBT) and Main Central Thrust (MCT) oriented in the E–W and N–S direction (Gahalaut, 2011, Rai et al. 2012, Kumar et al. 2012, Hazarika and Kumar, 2012). Other significant geological/tectonic features in and around Sikkim include: Tista lineament, Kanchenjunga lineament, Purnea-Everest lineament, Arun lineament and Dhubri fault in the southeast as shown in Figure 1 (Gahalaut, 2011, Mahajan et al. 2012). Alignment of these tectonic features and their size affects the seismicity of the location. Several high and moderate intensity earthquakes have already been occurred in the state of Sikkim and adjoining area. Some noticeable earthquakes that have affected the region (Nandy, 2001 and Thakur et al. 2012) are listed in Table. 1.

2011 Sikkim Earthquake

An earthquake of moment magnitude (*Mw*) 6.9 struck near the Nepal-Sikkim border on September 18, 2011, at 18:10 local time. The US Geological survey (USGS) reported that the epicentre of this event was located at 27.72°N and 88.08°E near India–Nepal border region, about 68 km NW of Mangan (Gangtok) at a focal depth of 19.7 km resultant of strike–slip faulting and the nodal plane coincides with the Teesta and Kanchenjunga lineaments whereas Seismic Monitoring Network of India Meteorological Department (IMD) reported that epicentre location at 27.7°N and 88.2°E, with focal depth of 10 km resultant of the reverse–faulting mechanism at thrust interface (Rai et al. 2012, Gahalaut, 2011).

Table.1 Previous significant earthquakes near Sikkim

Year	Earthquake	Magnitude
1869	Cachar earthquake	M_w: 7.5
1897	Shillong plateau earthquake	M_w: 8.7
1923	Meghalaya–India earthquake	Ms: 7.1
1930	Dhubri earthquake	Mw: 7.1
1934	Bihar-Nepal Border earthquake	Mw: 8.3
1941	Assam earthquake Near Tezpur	Ms: 6.5
1943	Assam earthquake Near Hojai	Ms: 7.2
1947	Arunachal Pradesh earthquake	Ms: 7.7
1950	Great Assam earthquake	Mw: 8.5
1954	Arunachal Pradesh earthquake	Ms: 7.7
1957	Arunachal Pradesh earthquake	Ms: 7
1984	Silchar earthquake	Mw: 6.0
1988	Nepal-India Border earthquake	Mw: 6.4
2006	Sikkim earthquake	Mw: 5.7
2009	Bhutan earthquake	Mw: 6.2

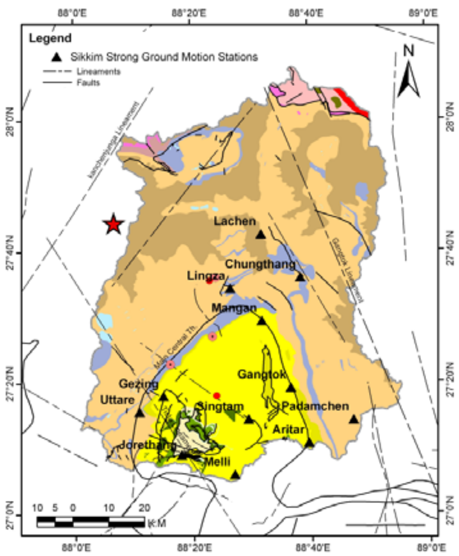

Fig. 1 Tectonic setup of Sikkim and USGS Shake Map of the magnitude 6.9 Sikkim earthquake, Sept. 2011. (Source: Sikkim Strong Ground Motion Stations – Geology, IIT Kharagpur)

The strike, dip, and a focal depth of the fault plane have been also reported as 313°, 73°, and 35 km, respectively (EERI, 2012). The other source parameters seismic moment, source radius, corner frequency and stress drop estimated by Hazarika and Kumar (2012) for moderate size of this earthquakes (range 4–5.1) are 7.9×1021 – 6.31×1023 dyne-cm, 0.225 – 0.781 km, 1.8 – 6.5 Hz and 47.59 – 389.1 bar. The epicentre of this Sikkim earthquake lies in Alpide–Himalayan seismic belt which is seismically active Himalayan belt. The main shock was followed by a few significant aftershocks (as shown in Table 2) of magnitude 5.0, 4.5 and 4.2 which were also felt in many parts of the country Assam, West Bengal, Bihar, Orissa, Uttar Pradesh, Delhi. Aftershocks were also felt around the Sikkim 30 minutes after the earthquake.

The maximum damage and claimed at least 100 lives were observed due to this moderate earthquake event in Northern Sikkim and Western Sikkim because of a landslide, failure of a retaining wall, foundation failure, and road damage (Thakur et al. 2012, Maheshwari et al. 2011, Kumar et al. 2012, Rajendran et al. 2011, Rai et al. 2012, and Chakraborty et al. 2011).

A team of 10, 8 from IISc, Bangalore and 2 from IIT Guwahati was visited Sikkim on February 18, 2012. For a week, the team conducted MASW and GPR surveys, auguring for soil samples, road damage surveys, interview with populace and interaction with geologists and engineers. The team travelled through serenely beautiful and at the same time extremely dangerous terrains of Sikkim. Roads connecting Gangtok with Dzongu and Mangan with Chungthang and Lachung further were especially dangerous.

Several major transport routes were damaged due to landslides in already rain affected slopes. The highways connecting Gangtok-Mangan, Mangan- Chungthang and Chungthang-Lachung suffered major damage severely hampering relief efforts. Main road routes were restored by September, however, other routes connecting upper and lower Dzongu were still in a fragile state, i.e., in February 2012 when the team visited the site. Upper Dzongu is the nearest Indian habitat near the epicentre.

Table. 2 Epicentral location of main shock and aftershocks by IMD and USGS (Rajendran et al. 2011)

Date	Time	Lat. (˚N)	Lon. (˚E)	Depth (km)	Mw
18/09/2011	12:40:52	27.72	88.14	50	6.9
18/09/2011	18:11	27.70	88.20	10	6.8
18/09/2011	13:11:59	27.48	88.50	35	4.8
18/09/2011	13:11:59	27.60	88.50	-	5.0
18/09/2011	13:54:20	27.28	88.30	35	4.7
18/09/2011	13:54:17	27.50	88.40	-	4.5
18/09/2011	21:51:52	27.60	88.40	-	4.2
22/09/2011	16:44:43	27.60	88.40	-	3.9

Field observation, drilling of boreholes with sample collection (DBS), surface wave testing by Multichannel Analysis of Surface Wave (MASW) method and Ground Penetrating Radar (GPR) survey have been carried out at sites having slope failures, settlement and structural failures. Places inspected were at or around Gangtok, Rangpo, Jorthung, Singtam, lower Dzongu, upper Dzongu, Mangan, Dikchu, Tung, Chungthang, Lachung and Pangong. MASW and GPR surveys were carried out where a decent stretch of at least 25 m was available. GPR was carried out along the MASW survey lines and soil samples were collected using hand augur up to a depth of around 1.4 m. This paper presents the forensic investigations of three different failure cases: distressed pavement over, a natural slope, a school building, and secretariat building failures, with reference to the field tests carried out.

3 FIELD TESING

In order to understand the subsurface soil character and soil properties, field testing MASW, GPR and DBS has been carried out at selected locations and typical results are presented here.

Soil samples were obtained through hand augering by 100 mm auger up to about 1.4 m. Classification tests were conducted on the samples obtained at road site and the school site. It was found from the tests that the soils were of predominantly sand with some traces of silt raging about 7-12 %. At both the locations the soils were of poorly graded sand with symbols SP.

MASW system consisting of 24 channels Geode seismograph with 24 geophones of 4.5 Hz capacity is used in this investigation. The seismic waves were created by impulsive source of 15 pounds (sledgehammer) with 300 mm x 300 mm size hammer plate with ten shots. These waves are captured by the vertical geophones/receivers and further analyzed by inversion. Twenty-four geophones are arranged linearly and the sources are kept on one side of the MASW line. Geophone spacing of 1 m and source distance of 4 m, 8 m and 12 m are being used. In order to enhance the signal to noise ratio, vehicle movements on the roads was completely stopped during MASW recording period. Surface wave records are used to extract dispersion curve and to estimate the shear wave velocity. Location of MASW survey lines is shown in respective Figures. Figure 2 shows the shear wave velocity of the subsurface in three selected sites. In general, it is observed that soil found in the shallow depth of the investigated sites is loose to medium dense and followed by rock or very dense layer. More discussion of the shear wave velocity (SWV) is presented in the respective section.

GPR study has been carried out to image the variation in the subsurface soil layers and bedrock depth. GPR survey parameters are frozen based on initial trial survey for the clear waveform signature with a penetration depth of 2.5 m for 500 MHz and up to 15 m for 25 MHz antenna. GPR survey has been carried out parallel and across distressed locations. Two antennas are used in the same locations to get a good picture of the subsurface. Recorded GPR waveform data are processed and used to get radargram. The raw data were processed using data processing steps. The aim of this processing is to enhance signal-noise ratio and highlight interfaces and radargram textures. The processing includes a band pass filtering, DC removal, subtract mean trace and gain control. Only very fundamental filters are applied to the raw data to avoid introducing artificial textures into the radargram. Wave character/ radargram image quality depends mainly upon the dielectric properties of the materials and which is a function of density, moisture content and porosity. Typical GPR radargram obtained from GPR and result interpretation subsurface is given in the respective section.

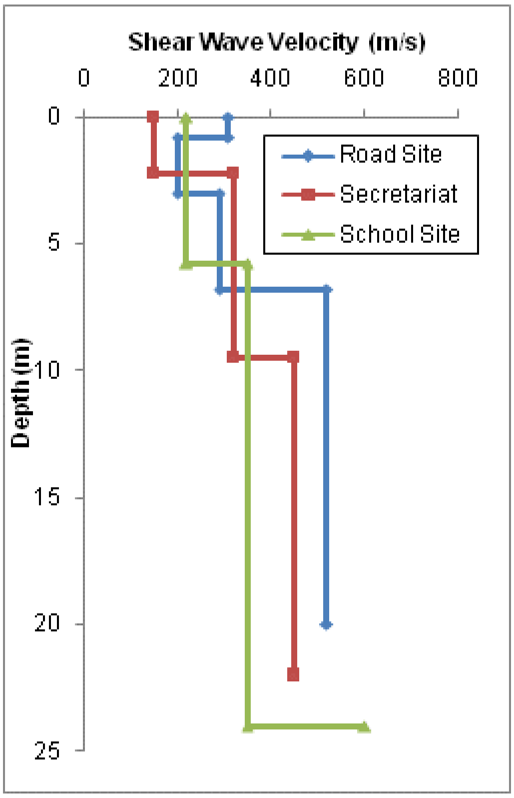

Fig. 2 Shear wave velocity with depth obtained from MASW survey

4 DISTRESSED PAVEMENT OVER A NATURAL SLOPE

This particular site was located at the Western bay pass, Bulbulay Road, Gangtok (1 km away from Tashi view point towards Ganeshtok). Circular slide inducing cracks, settlement on the road and lateral movement of slope were observed. Incipient landslide condition. Field Photo is shown in Figure 3 and MASW and GPR survey lines are shown in Figure 4. MASW study shows that about 0.5 to 1.0 dense layer with SWV of about 350 m/s found due to pavement section and followed by loose material with SWV of less than 200 m/s and the SWV increase with depth. Soft material below the pavement layer and above rock/hard layer might experienced reduction in strength due to saturation and cyclic loading which might cause partial slope failure in this site. Typical radargram from GPR is shown in Figure 5. GPR radargram shows layers of dense and loose layers similar to MASW data. GPR also shows the movement of layers due to slip formation. Presence of heterogeneous layers below pavement might cased cyclic mobility and resulted slip movement.

Fig. 3 Road damage due to landslide at Bulbulay road, Gangtok

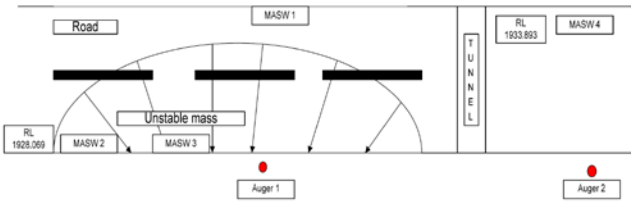

Fig. 4 Investigations location at Bulbulay road, Gangtok

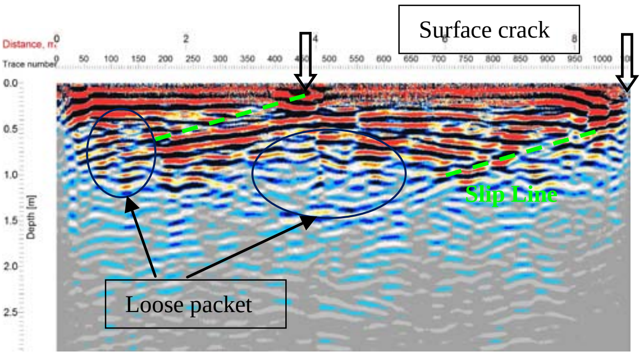

Fig 5. A typical GPR profile of the cross section of the road using a 500MHz GPR antenna

5 SCHOOL BUILDING

The school building located at Upper Dzongu, North Sikkim subjected to severe damage during the earthquake. Settlement of the building and tilting because of the uneven settlement has been observed as shown in Fig. 6 The single storied building under study was constructed on a filled up soil. According to local people there was a lake before and the land was reclaimed for constructing the house. The adjacent school building remains intact with some minor cracks but the building under study has suffered extensive damage. MASW and GPR tests were conducted. Soil samples were also collected at the location. It can be observed from MASW SWV (Fig 2) that presence of loose soil on the surface up to a depth of 5 m, where the foundation of the building was housed. Borehole samples also reveal the soil found in that poorly graded sand (SP) with more of sand fraction material. Figure 7 shows GPR radargram from inside School. Non uniform subsurface layers oberserved, which might have resulted due to filling of existing lake. The findings of this study confirm the presence of loose soil below the floor and foundation, which have caused loss of shear strength due amplified dynamic load. It is suspected the settlement of the filled up soil due initial liquefaction and local site effect.

Fig. 6 Distressed School Building at Upper Dzongu

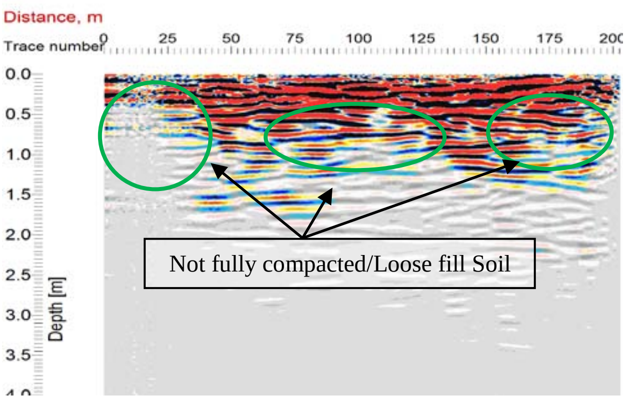

Fig 7. A typical GPR profile radargram below distressed school buildings using a 500MHz GPR antenna

6 SECRETARIAT BUILDING

Old Secretariat building, Gangtok, Sikkim is located at 27.32463ºN , 88.61430º E, 1701 m elevation. Extensive structural damage of the 5 storied framed structure with masonry infill was observed. The earthquake resulted in a severe damage in the [part of the Secretariat building resulting in cracking of the structural members. It can be highlighted that one part i.e back side of the building damaged more when compared front side building (Fig 8). This building is structurally sound and designed according to seismic code. A GPR survey carried out from front side back side to get subsurface soil layer and rock depth. MASW survey carried out close to back side as shown in Fig 9.

Fig. 8 Photos of damaged secretariat building

Fig. 9 GPR and MASW survey close to secretariat building

SWV velocity profile close to secretariat building is shown in Figure 2. Very loose material having shear wave velocity less than 180 m/s found up to 3 m and followed by medium dense soil with SWV of 320 m/s up to 10 m and followed by hard/rock layer. GPR radargram using a low frequency antenna of 25 MHz is shown in Fig 10.

It can be observed from Fig.10 that the front side of secretariat building having a hard layer (more refection) close to surface and depth of the rock / hard layer keep increasing toward backside.

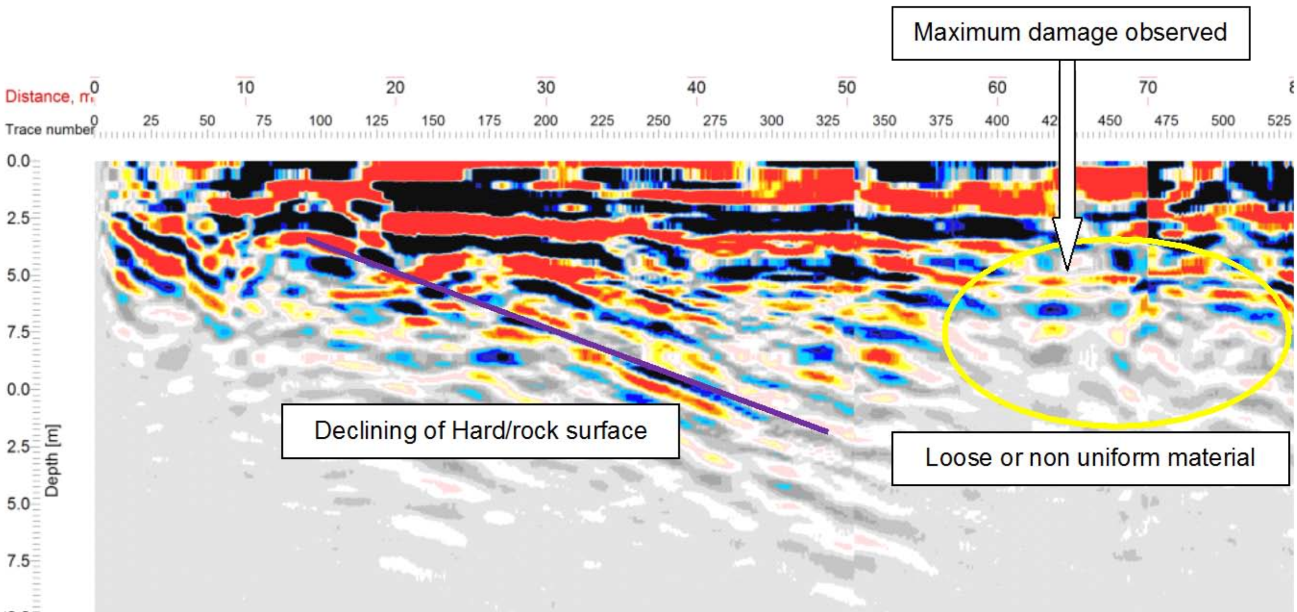

Fig. 10 GPR radargram shown variation of soil thickness at secretariat building

Depth of rock/hard layer is about 7 m to 10 m close to damage location, which is matched well with MASW SWV observations. The presence of loose soil also observed at the back side of the building. Overall site subsurface profiling shows that depth of soil at the front side (no damage) is less or nil and more at the back side of the building. Non uniform thickness might cause non uniform site effects. Ground motion at front side is less and there may not be any site amplification due to absence of soil. Site effects and amplification might have occurred due to loose soil filled close to back side of the building resulted more ground motion when compared to the front side of building caused extensive damage at only back side. As the building was constructed by similar design and construction and non uniform amplification cause damages at one side of the building. More detailed numerical analysis is required to prove our interpretation. Even though there significant advancement made in earthquake Geotechnical engineering, still we need a more forensic study to understand these kind of peculiar seismic failures.

7 CONCLUSIONS

This paper presented some of the field test results and observations from three different locations of Sikim earthquake affected areas. MASW and GPR tests were conducted along with a collection of samples at few locations. Most of the locations the top few meters of of the ground consists of sandy soils with some silt traces. GPR radargram showed the cracked portion of pavement and the depth of the cracks. DBS and MASW at school building show the presence of loose cohesionless soil layer up to 5 m, which might have undergone cyclic mobility and hence resulted in a settlement and cracks in the floor slab. GPR investigation at Sikkim secretariat building showed that the building is constructed on a sloped ground, where one side is filled with soil (damaged side) and the other side is directly resting on the rock. The study highlights the possible reasons for local seismic wave amplification and the associated damage with the help of field investigation carried out. Further detailed studies are essential like ground response analyses and dynamic soil tests to complete the investigations.

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