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ORIGINAL PAPER

Reconnaissance report on geotechnical effects and structural damage caused by the 3 January 2017 Tripura earthquake, India

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Abstract

An earthquake of moment magnitude M_w 5.7 shook the northeastern region of India on 3 January 2017 at 14 h:39 min:0.5 s local time. The duration of the tremor lasted for about 5–6 s and had its epicenter in Dhalai District, Tripura, India. Even though the earthquake was of moderate magnitude, it caused damage to several masonry dwellings in Tripura and triggered soil liquefaction, lateral spreading, and landslides near the epicentral area. The sand boils containing appreciable amount of silts were ejected to the ground surface at the Kanchanbari and Kumarghat area due to the liquefaction-induced upward ground water flow. This is possibly the first liquefaction evidence in India induced due to a moderate earthquake magnitude of M_w 5.7. This paper reports the field reconnaissance observations of geotechnical effects and damage to buildings following a shallow, strike-slip earthquake in northeast India on 3 January 2017. In addition, the distribution of surface peak ground acceleration of the earthquake estimated from the empirical equations based on the available data is evaluated and discussed.

Keywords Tripura earthquake · Geotechnical effects · Structural damage · Liquefaction · Peak ground acceleration

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1 Introduction

On 3 January 2017 at 09:09:0.5 UTC time, a moderate magnitude earthquake of M_w 5.7 rocked the northeastern part of India. The tremors were also felt in the neighboring countries of Bangladesh and Myanmar. Large-scale damages due to the earthquake were observed in the Indian state of Tripura. Following the main event, aftershocks were observed on 4 and 6 January 2017 in Dhalai District of magnitude less than four. Modified Mercalli Intensity (MMI) of IV was reported in Kamalpur, Ranirbazar, Agartala, Ambasa, Kailashahar (towns in Tripura) while MMI of III was reported in surrounding areas, viz. Aizawl (Mizoram), Imphal (Manipur), Dhaka, Barisal and Chittagong (Bangladesh). The Geological Survey of India (GSI) located the epicenter of the main event near the Tripura–Mizoram border area along an unnamed lineament, trending in the NE–SW direction crossing through the Tripura Fold Belt axis. The focal depth was estimated to be 17.1 km at co-ordinates 23.791°N, 92.269°E, respectively. This observation was made using the four Seismo-Geodetic Observatories of GSI located at Agartala, Itanagar, Nagpur and Jammu (GSI 2017). The epicenter location of the event specified by USGS (US Geological Survey) and damage locations reported by Indian agencies (GSI, IMD) are shown in Fig. 1. Table 1 presents the earthquake parameter of the event given by Global Centroid Moment Tensor (GCMT) project and USGS. The locations of the reconnaissance survey conducted by the post-earthquake reconnaissance team in the affected area are also shown in Fig. 1.

This was evidently, the first earthquake reported in the region for the year 2017 and was only the fourth earthquake of moderate magnitude reported after 1950 in Tripura to

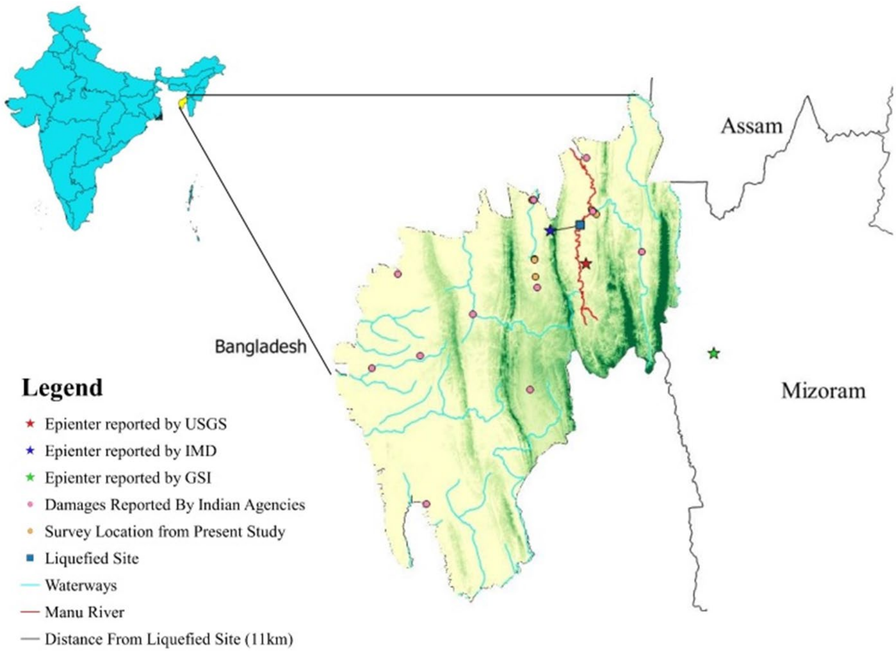

Fig. 1 Epicenter locations reported by IMD (Indian Meteorological Department), USGS (US Geological Survey) and GSI (Geological Survey of India) for 3 January 2017 earthquake

Table 1 Earthquake parameters reported by GCMT and USGS for 3 January 2017 Tripura earthquake

Parameter	Global CMT			USGS		
Date	03-01-2017			03-01-2017		
Centroid time	09:09:04 GMT			09:09:02 GMT		
Latitude	23.98°			24.015°		
Longitude	92.03°			92.018°		
Depth (km)	24.5			35.5		
Half duration (s)	1.5 s			1.63 s		
M_w	5.6			5.7		
mb	–			5.5		
Ms	5.7			5.3		
Scalar moment (N m)	3.15E+17			4.10E+17		
Nodal plane 1	Strike = 64°	Dip = 86°	Slip = – 2°	Strike = 57°	Dip = 88°	Slip = – 12°
Nodal plane 2	Strike = 154°	Dip = 88°	Slip = – 176°	Strike = 147	Dip = 78°	Slip = – 178°

Table 2 District-wise damages caused by 3 January 2017 earthquake in Tripura

District	Damages to houses			Human fatalities	
	Fully	Severely	Partly	Death	Injured
West Tripura	0	0	6	0	1
Unakoti	31	1040	3326	0	6
North Tripura	0	0	123	0	0
Dhalai	11	427	1716	1	0
South Tripura	0	0	1	0	0
Sepahijala	0	0	43	0	0
Khowai	0	0	4	0	0
Gomati	0	0	0	0	0
Grand total	42	1467	5218	1	7

have the epicenter located within the federal state boundary. The earthquake also triggered landslides in several places in a radius of 5 km along the Chhamanu Govindabari road, Tripura. It is to be noted here, in the year 2016 at the same day, i.e., on 3 Jan. 2016, the region had also experienced a 6.7 magnitude Manipur earthquake of maximum Modified Mercalli Intensity VII (USGS 2016). The epicentral distance between the two earthquakes was measured to be approximately 188 km. It was reported by the State Disaster Management Authority of Tripura that a total of 5218 houses were partial damaged, 1467 severely damaged and 42 houses fully damaged causing 1 death and 7 injured in the state. Table 2 shows district-wise damages occurred due to the event in Tripura. The location of the damage areas can be accessed from the electronic supplement material (ESM1) provided along with the paper. The earthquake also caused surficial slope failure, lateral spreading and liquefaction in Kumarghat area. The continuous ground cracks of about 20–50 m long near the epicentral area were also observed.

The strong motion record for the earthquake was obtained from the North East Institute of Science and Technology (NEIST), Jorhat, Assam, India. The NEIST station is placed at

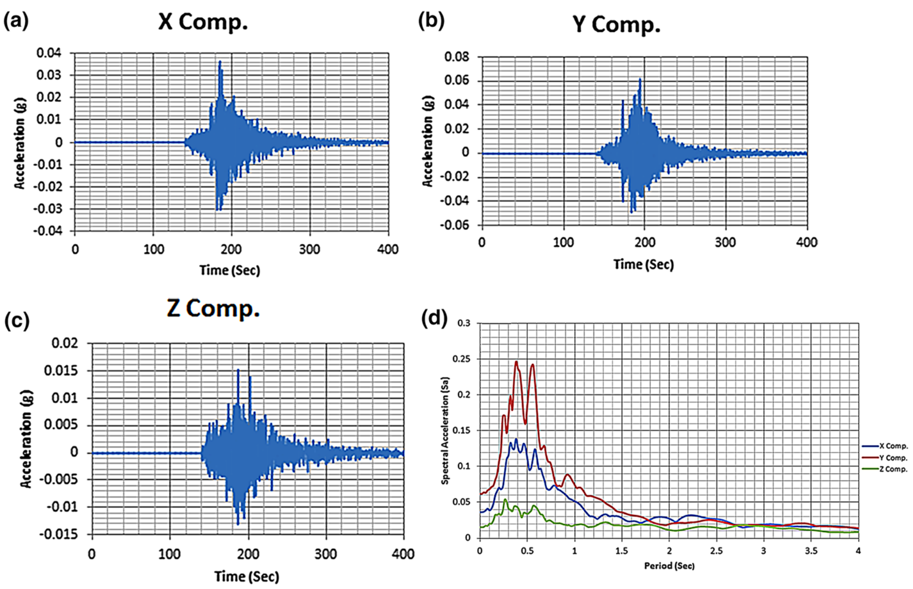

Fig. 2 **a**–**c** Acceleration time history of 3 January 2017 Manu earthquake, Tripura, for component X, Y, Z, respectively. **d** Spectral acceleration for all the three components corresponding to 5% damping

Onguri Hills, Tezpur, India (Lat.: 26.61781°N and Long.: 92.77936°E) on a bedrock site at an elevation of 112 m above mean sea level and is about 297 km from the epicenter. Figure 2 shows the acceleration time history plot of X, Y and Z components of the event and also the spectral plot. It can be noted here that Fig. 2b shows the maximum peak ground acceleration of 6.4% g, i.e., 0.064 g at 297 km from the epicenter. Hence, this necessitates the need for region specific studies for effective infrastructure design and disaster management. The maximum spectral acceleration is estimated to be 0.25 g in the horizontal Y component for this earthquake. This report summarizes the field reconnaissance survey of the geotechnical and structural damage, which was observed by the team from 8 January 2017–19 January 2017.

2 Seismicity of Tripura

Tripura is situated in the northeastern part of India, adjacent to the Himalayan belt that is seismically very active due to the convergent boundary of the Indian plate with the Eurasian plate. The Indian plate is currently moving toward northeast at 5 cm per year (Kumar et al. 2007; NDMA 2010) while the Eurasian plate is moving relatively slow. The fault line along both directions is the reverse fault due to which subduction and over-thrust occur. In this region, earthquakes of small to moderate magnitude occur quite often.

The entire state of Tripura falls in seismic zone V as per Indian Standard Code (IS 1893 2002) with a zone factor of 0.36, which clearly signifies the severity of earthquake hazards in the region. The current Indian Seismic Zonation map was prepared based on past Seismicity and Seismo-Tectonic information. However, this zonation map does not reflect the possible future seismic hazard and associated geotechnical hazards of site effects, liquefaction and landslide in the region (Anbazhagan et al. 2014). The state experienced

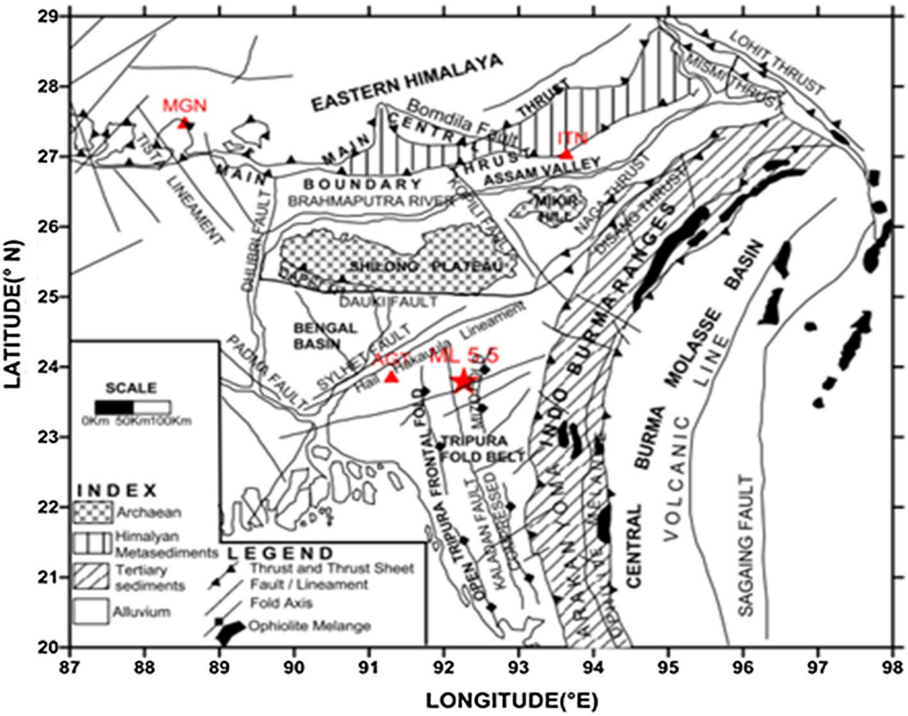

Fig. 3 Tectonic setting of northeast India and surroundings (after GSI 2017). The epicenter of Tripura earthquake is shown as a star symbol. The triangles indicate the location of the Seismo-Geodetic Observatories of GSI (*AGT* Agartala, *ITN* Itanagar, *MGN* Mangan) in NE India

several earthquakes in the past; most significant being 1897 Shillong earthquake of M_w 8.7, 1918 Srimangal earthquake of M_w 7.1, 1950 Upper Assam earthquake of M_w 8.6 and 1997 Bandarban earthquake of M_w 6.1. In addition to the plate boundaries, the unceasing seismic threat for the state are from the Madhupur fault located in Bangladesh, the Dauki fault passing through Meghalaya and the northern segment of Tripura that follows the International Border between India and Bangladesh (Rahman et al. 2015). At present, the southernmost thrust in the Himalaya-Shillong Plateau region is believed to be taking place along the southern fringe of the plateau co-inciding with the Dauki fault (Gupta 2010). Fault map of Tripura and adjoining area presented by GSI is shown in Fig. 3.

Tripura is located between the co-ordinates 22.933°N to 24.333°N latitude and 91.15°E15°E to 92.333°E longitude. A very large number of moderate to strong magnitude earthquakes took place within the state boundary and its 100 km radius around it. Figure 4 shows the epicenter locations of the past earthquakes in Tripura including the present earthquake event under discussion. In December 1950, Tripura had witnessed another earthquake of moderate magnitude 5.9. The epicenter of this event was 9.1 km from Ambassa in southern direction. Then, 33 years later in 1984, another earthquake of magnitude 5.3 occurred and epicentral distance was approximately 34 km from Ambassa. Since 1950, there are four earthquakes of moderate magnitude in the state of Tripura and all the epicenters were located very close to the Ambassa. Prior to 1950, a significant number of past earthquakes of strong magnitude can also be traced in the seismic history of the

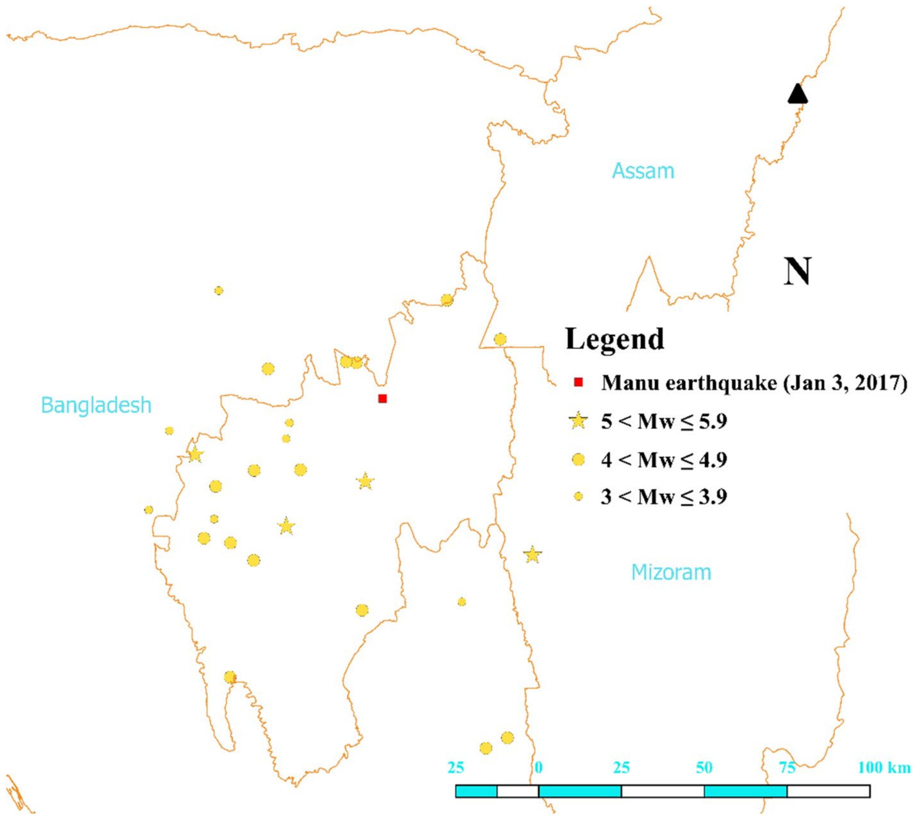

Fig. 4 Epicenter locations of past earthquakes in Tripura and surroundings after 1950 based on USGS data. The square symbol represents the epicenter of 3 January 2017 Tripura earthquake

Tripura or surrounding region which are not included in Fig. 4. Most of the researchers (Khattri 1987; Bilham et al. 1995; Pandey et al. 1995) working on the seismicity of the Himalayan region believe that the Tripura or northeast region still possess a high potential for the next major earthquake.

3 Geotechnical effects

Generally, a larger earthquake causes several surface failures and permanent deformations on the ground surface. Limited field evidence is available on surface failures and permanent deformations on the ground surface due to moderate earthquake, i.e., magnitude less than 6. However, field visits to several possible locations show that considerable ground failure and liquefaction were caused by this earthquake. The survey location is given in Electronic Supplement Material (ESM1). An unprecedented liquefaction had been identified for this moderate earthquake in an agricultural land at Kanchanbari, Kumarghat, Tripura, which was approximately 10 km in distance from the epicenter. Because of liquefaction, lateral spreading and landslide near the epicenter area had also been observed. A summary of the geotechnical impacts is discussed below:

3.1 Soil liquefaction

The liquefaction-induced phenomenon such as sand boils is identified at Kanchanbari, Unakoti District, Tripura at latitude 24.118°N and longitude 91.991°E. Figure 5 shows the location of liquefaction site in Google map. The liquefaction features observed were in the linear alignment of sand boils pattern trailed in a curvilinear path (see Fig. 9). The length of the linear sand boils varies from 20 to 51 m in length. Though the extent of liquefaction was not very large, the liquefied area was measured to be 290 m × 210 m. The sand boils were observed in the potato-farming field located just next to River Manu. The photographs of liquefaction after the earthquake are shown in Figs. 6 and 7, which were taken immediately after the earthquake (photographs collected from local people) and 5 days after the earthquake. There was no rainfall in the region between the time of the earthquake and the IISc team visit. Gray color of very fine sand and silt had ejected during liquefaction.

Local people working in the farmland had witnessed the surface sand boiling phenomenon very closely, which occurred immediately after the earthquake shaking in the liquefied site. The sand gushing with water had continued for about 15–20 min after the earthquake. Apart from these locations, liquefaction had also been observed in an open excavation (i.e., elliptical sand boils) and on the river bed. Most of the liquefaction signatures were noticed on river deposit or close to the river. Further, there was no liquefaction observed in the capital city of Agartala and surrounding area, which was far away from the epicenter location. The authors could not find any previously reported liquefaction induced by moderate earthquake magnitude in Tripura, and this is probably the first of such incident reported.

Figure 5 shows the satellite image of the liquefied area with location coordinates, where the Manu River can be seen. According to the inhabitants of that location,

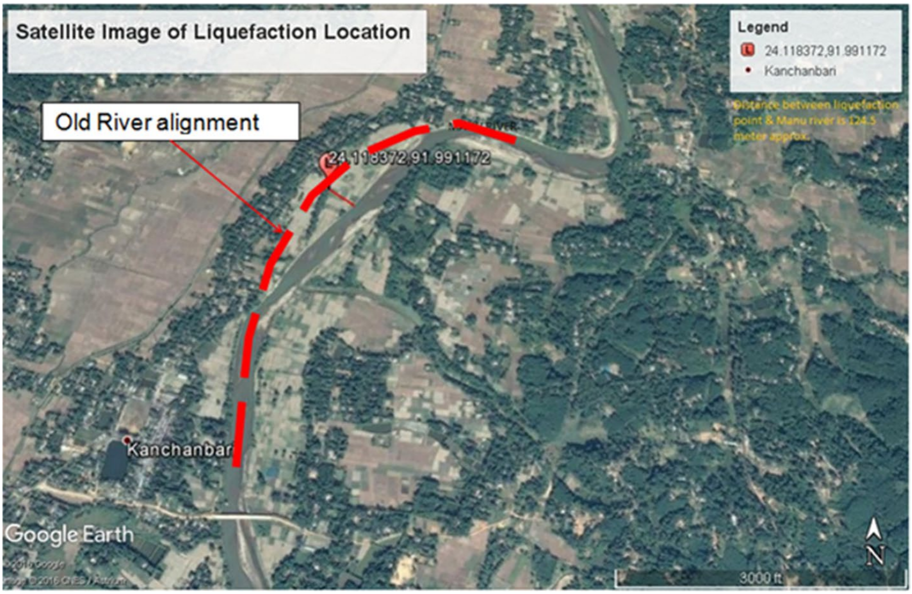

Fig. 5 Satellite image of the liquefaction area located at Kanchanbari, Kumarghat in Unakoti District, Tripura, India. *Source*: Google earth

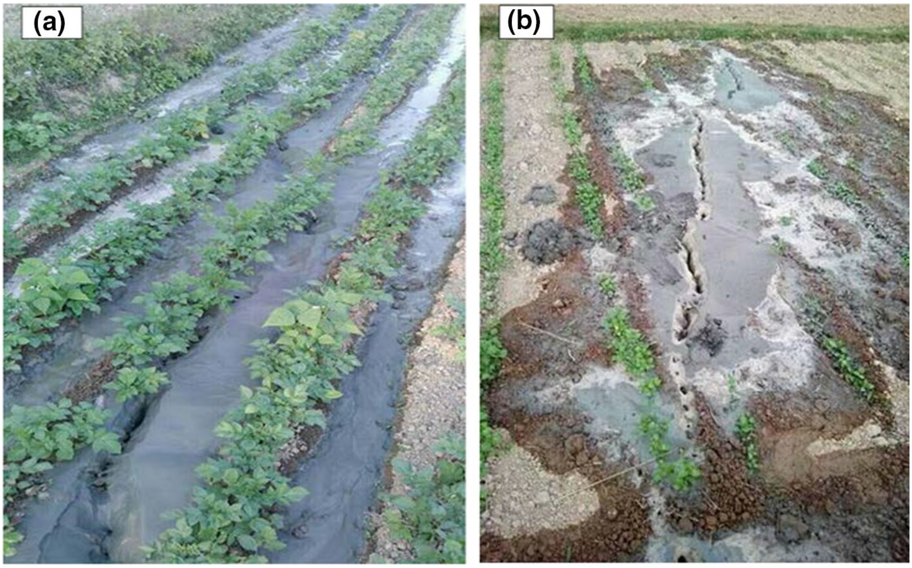

Fig. 6 **a**, **b** Liquefaction manifestations at surfaces as sand boils, immediately after the earthquake in an agricultural farm at Kanchanbari, Kumarghat, Tripura (photograph taken on 3 January 2017 collected from the local people)

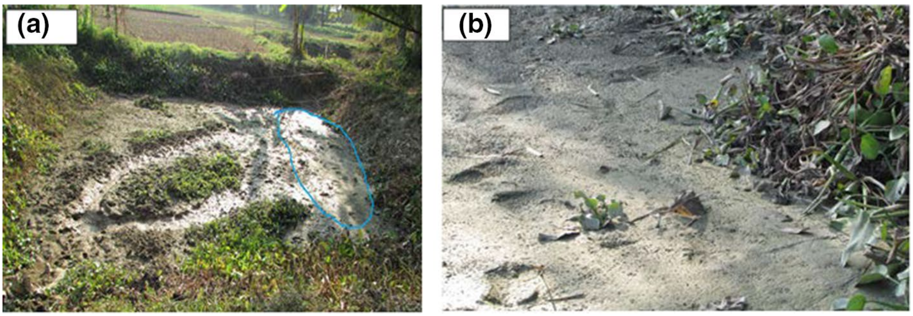

Fig. 7 **a** Observed liquefaction in one of the open excavations next to the agricultural farm land. The close-up view of the circled portion has been shown in (**b**)

50–60 years ago the river was flowing through the area that is presently being used as agricultural land (see Fig. 5). Thus, loose, river deposited soil has been converted into agricultural land, which was liquefied during the earthquake. The present meandering of the river in the figure may evidently support that statement. The presence of loose, saturated sandy and silty soil with very little clay (which is highly susceptible to liquefaction) and existence of water table at a depth of 1.5–2.5 m depth may have suitably led to liquefaction for this moderate magnitude event in the area.

3.2 Detailed schematic representation of the liquefied site

In the last 16 years in India, evidence of widespread liquefaction phenomenon was observed in Kutch region and other parts of Gujarat during Bhuj earthquake 2001 (EERI 2001), near Baramulla area in Jammu and Kashmir during 2005 Kashmir earthquake (Sahoo et al. 2007; EERI 2005) liquefaction in Bihar due to 2015 Nepal Gorkha earthquake (Lizundia et al. 2015) and liquefaction at Kanchanbari, Tripura, due to this moderate earthquake (Fig. 8).

IISc team measured surface feature of liquefaction from the liquefied site (see Figs. 5 and 6), and it is shown in Fig. 9. Mapping of the ground feature of liquefaction as shown in Fig. 9 represents that, an array of linear sand boils was observed as depicted in the schematic diagram in Fig. 9. Lines A, B, C, D, E are the linear sand boils, and line F is the linear crack developed due to the earthquake. The thicknesses of sand deposits due to sand boil were measured to be about 120–150 mm above the existing soil. This indicates that duration of shaking was considerably high at the liquefied site to eject a significant amount of sand with water. On the line A, shown in Fig. 9, first 20 m (ab) had been liquefied following that the next 43 m (bc) is un-liquefied, but again sand boiling had started from c point and extended up to 51 m in length until d. The length of the lines B, C, D, E and F was 25.5, 32.3, 33.6, 31 and 17 m, respectively. One point can be noted here that lines A, B, C, D were nearly parallel to each other except the lines E and F. The line F is a linear crack of width about 100 mm. From the schematic diagram, it can be clearly observed that liquefaction occurred in a curvilinear trend that extended up to the bank of the River Manu. Three to four numbers of elliptical sand boils were seen on the river bank, which was just next to the line F, and one sand boil was observed in an open excavation shown just above the line C. The distance between the liquefaction starting point (from point a) and the river was about 125.5 m.

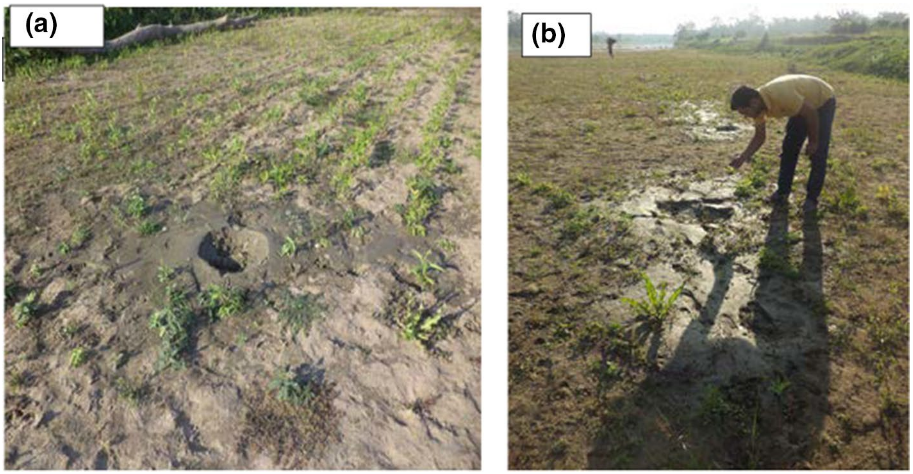

Fig. 8 **a**, **b** Elliptical shape sand deposits due to sand boils during liquefaction at the Manu river bank (photography by Rajesh Debnath)

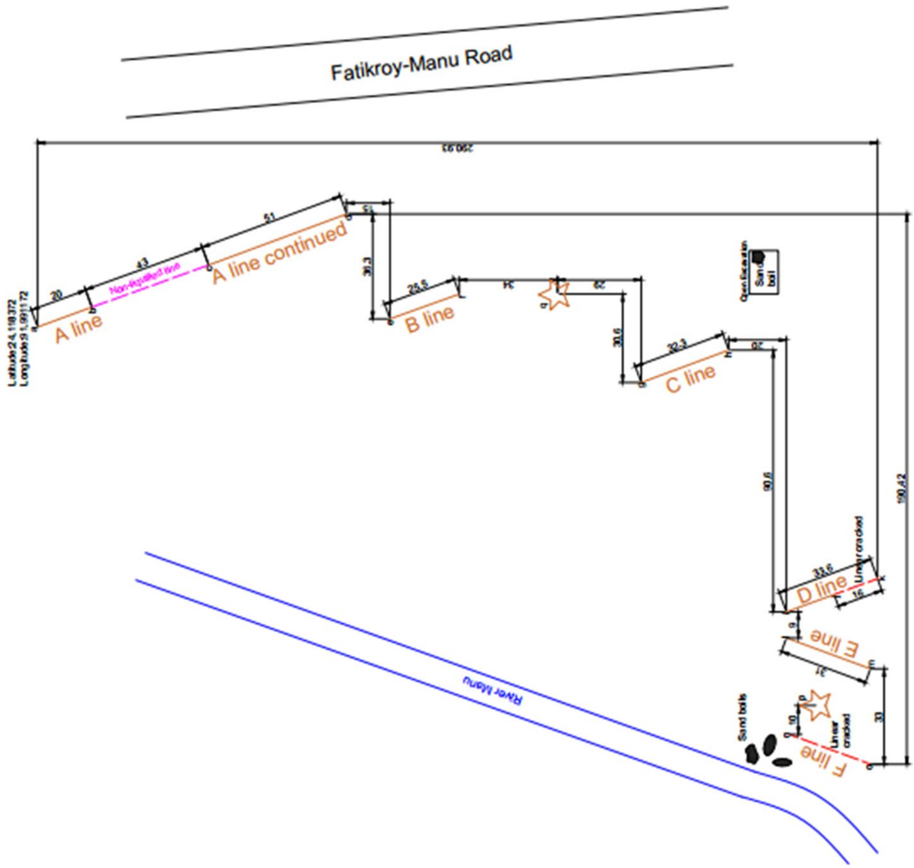

Fig. 9 Schematic representation of the liquefied area at Kanchanbari, Kumarghat, Tripura, India (24.118°N and longitude 91.991°E)

3.3 Lateral spreading and slope failure

Liquefaction-related phenomenon such as ground deformations or lateral spreading and slope failures instances could be seen in several past earthquakes of magnitude more than 6.0. Often, it causes significant effects on different structures, especially on pile foundations. However, a very few incidents are reported where a moderate earthquake magnitude causes lateral spreading and slope failures (Twayana et al. 2014; Valkaniotis et al. 2014). The permanent ground deformations, often, occur because of both liquefaction and faulting, though it can also be the results of earthquake shaking itself rather than the liquefaction (Aydan et al. 2008). The 3 January 2017 Manu Earthquake caused lateral spreading at two locations, near the liquefied area at the bank of the river Manu which is shown in Fig. 10. The ground cracks were parallel to the river that extended up to 3–5 m in length. The lateral displacement of 50–80 mm was observed, in which top layers were moved toward the river. The earthquake also caused surficial slope failure at regions close to ponds in Kumarghat, Tripura, and is shown in Fig. 11. The horizontal length and height of the slope were measured to be 2.56 m and 1.53 m, respectively.

Fig. 10 Lateral movement of the ground toward the river Manu is observed at Kanchanbari, Tripura

Fig. 11 Surficial slope failure at one of the ponds in Kumarghat, Tripura

However, since no rainfall occurred prior to this earthquake, there was no massive landslide being observed in the state. Yet, a tree was uprooted and toppled across the road in the Longtharai subdivision, Dhalai District, Tripura, which may be expected from a magnitude of 5.7 earthquake. Because of this, a 5-km road got blocked along the Chhamanu Govindabari road, Tripura, for more than 3 days. This failure was essentially due to the dynamic instability, i.e., overturning moment as the soil fails by slipping and looses its shear strength during the earthquake. The area was about 16 km distance from the epicenter. While analyzing the large-scale slope failures considering some of the major recent earthquakes worldwide, as reported by Aydan (2015a, b), it was revealed that the effects of the earthquakes on hanging wall or mobile side of the earthquake are greater than those on footwall or stationary side of the earthquake fault. The study of effect of fault movement due to this on the 3rd January 2017 Manu earthquake is not under the scope of this report as the quality of the data corresponds to a field reconnaissance survey where the focus is more to present field data without in-depth analysis.

4 Performance of the buildings and damage to structures

The common dwellings in Tripura comprise of clay mud houses (Kutcha), Masonry or Pucca brick walls and Assam-type houses. In some of the hilly regions and villages, bamboo houses can also be seen with a thatched roof. Most of the government buildings are either unreinforced load-bearing masonry or RC framed structures. More than 40% dwellings are mud houses with a gable roof or tin sheets roof which are vulnerable even for a moderate intensity earthquake. Most of the effected mud wall houses were 10–15 years old. However, no provisions for earthquake resistance were incorporated while constructing such houses. Hence, there is an urgent need to incorporate the earthquake-resistant provision in those buildings to prevent future risk.

The state of Tripura is well known for its tradition; hence, old traditional mud houses and modern reinforced cement concrete (RCC) buildings with and without engineering design are widespread in the state. According to the state disaster management report, a total of 6727 houses were affected of which 5218 houses partially damaged, 42 houses fully damaged and 1467 houses severely damaged (TDMA 2017). The maximum number of house damages was reported in Unakoti District and followed by Dhalai District. The IISc team visited selected possible locations, and details of observed damages are presented here.

4.1 Damage to unreinforced masonry buildings

Figure 12a, b shows damage caused to a masonry building with light GI (galvanized iron) sheet roofing. The building serves as a school. Horizontal cracks are developed in the masonry long wall in between the window openings at the sill and lintel levels. The cracks have extended up to the corner, and similar cracks have been found in the orthogonal wall as well. The cracking can be attributed to out-of-plane flexure, indicating poor flexure bond strength of masonry. The building is in seismic zone V as per Bureau of Indian Standard (BIS 1893 2002). It is a non-engineered building lacking in basic earthquake-resisting features like lintel band.

The damages suffered by a two-storied load-bearing masonry building are shown in Fig. 13a, b. The damages were in two dwelling units of the building located on the ground floor. The building served as housing for the police personnel. In one of the dwelling units in the orthogonal wall (Fig. 13a), horizontal crack at the lintel level was observed. There is a vertical crack observed in one of the walls (Fig. 13b) adjacent to the corner.

The damages caused to the other dwelling unit in the same police station are shown in Fig. 14a, b. The cracks initiated from the floor level (Fig. 14a) and propagated in an inclined direction and reached the lintel level of the adjacent orthogonal wall (Fig. 14b). The cracking can be attributed to combined effect of shear and flexure. Even though the building is engineered, it has suffered damage possibly due to poor construction practices.

At certain places, the horizontal cracks were observed at the junction of the roof slab and masonry wall which can be classified as sliding shear mode of failure. Similar such kind of failure was observed in several one- and two-storied load-bearing masonry buildings in Dhalai District, Tripura.

Fig. 12 **a**, **b** Damage caused to a masonry building with light GI (galvanized iron) sheet roofing which lacks lintel band

4.2 Damage to unreinforced mud houses

This earthquake caused damages to several non-engineered mud houses in varying degree as may be expected from a 5.7 magnitude earthquake. Typical damages suffered by mud houses are presented in this section. The building shown in Fig. 15a has suffered damage due to the formation of vertical crack at the corner where two walls meet. Due to this kind of cracking, the integral behavior of building can be jeopardized resulting in an independent response of various walls and may cause the out-of-plane collapse of wall/s leading to collapse of the building. Figure 15b shows another mud house at Samrucherra village in Unakoti District, Tripura, where one of the walls has suffered out-of-plane collapse due to corner failure. Improper or lack of bonding element at the junction is the cause for such a failure. The damage of another mud house as shown in Fig. 16 can be attributed to out-of-plane flexure, leading to collapse of the wall due to both horizontal and vertical cracks. In Fig. 17, it can be observed that the building is non-engineered and lacks lintel band located in Lalchai, Dhalai District, Tripura. The building has a vertical crack adjacent to the window and close to the corner. Several

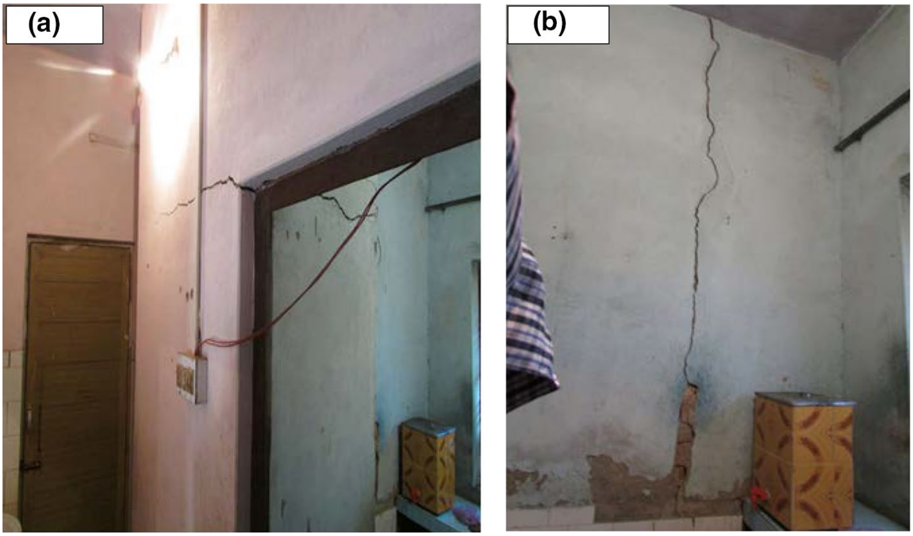

Fig. 13 **a**, **b** Damages suffered by a two-storied load-bearing masonry building

such cracks were observed in the entire Dhalai District which is likely to have high potential to collapse in the next event if necessary measures are not taken immediately.

4.3 Damage to reinforced concrete frame buildings with masonry infill

The failure patterns observed in a two-storied RC frame with masonry infill building are shown in Fig. 18a, b. It can be observed that cracks are essentially in masonry infill in the horizontal direction indicating sliding shear failure. The buildings served as Kamalpur Sub-Divisional Magistrate office in Dhalai District, Tripura, India.

The damages observed in another two-storied RC frame with masonry infill building are shown in Fig. 19a–c. The building is served as Kamalpur BM hospital which has suffered structural damage in several locations in this earthquake. Two of the rooms, namely the ultrasonography and X-ray, suffered severe damage. The medicine storage racks were not properly anchored; as a result, medicine bottles toppled and fell to the ground. The cracking is essentially in the masonry infill in the horizontal direction. The cracks were initiated in the masonry wall just above the lintel level and have propagated to the junction of roof slab with the wall and extended to the corners. At the corner, the crack (Fig. 19b) was in the vertical direction separating the two masonry walls. Figure 19c shows horizontal crack just above the plinth level in the masonry wall. The cracks were observed on both faces of the wall at the same level. The damages can be attributed to combined flexure and shear.

Figure 20a shows damages in the form of vertical cracks in the masonry infill's adjacent to RC column in shop building located at Kumarghat, Tripura. The enlarged view of the circle portion is shown in Fig. 20b.

In Dhalai and Unakoti districts of Tripura, about seven school buildings were inspected for damage by the IISc team. Two of the schools suffered severe cracks, which required immediate retrofitting and rehabilitation. There was extensive damage to one of the school buildings (Bamancherra Class XII School), and it is preferable to demolish

Fig. 14 **a**, **b** Damages caused to the dwelling unit in the police station due to poor construction practices

the building and reconstruct from the safety point of view for future earthquakes. It is reported by one of the teachers that students were terrified, and they stopped attending classes for more than 5 days after the earthquake. It is imperative to study all school buildings and take necessary steps for retrofitting and reconstruction for future projected seismic hazard in the region. Additionally, as the people of the state are not well acquainted with the general insurance policies for housing, the provisions for insurances for dwelling houses are encouraged to be established in Tripura. It can be understood from this reconnaissance study that the important buildings (schools, government offices and police station), and engineered and non-engineered houses suffered wide spread damages due to this moderate earthquake apart from the geotechnical failures. It clearly indicates that most buildings in the state are prone to earthquake damages. This moderate earthquake damages can be taken as warning and detailed vulnerability and risk studies should be carried out for the future-predicted seismic hazard in the region, which could help to retrofit vulnerable buildings and reduce losses.

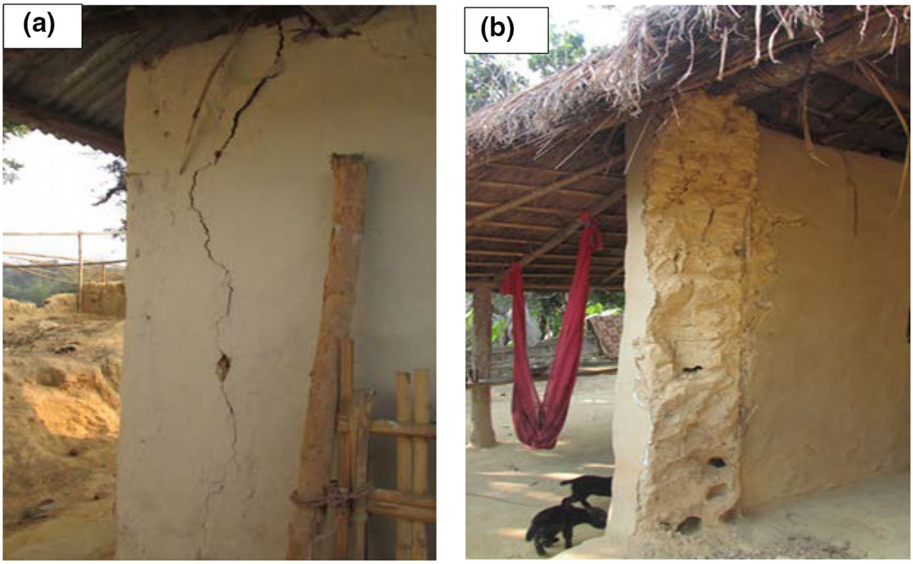

Fig. 15 **a**, **b** Damages of the two mud houses due to the formation of vertical crack at the corner and out-of-plane collapse failure

Fig. 16 Out-of-plane failure at one of the mud houses in Tripura

5 Description of the epicentral location

The epicentral area was visited following the coordinates of USGS (24.016°N, 92.006°E) and IMD (24.1°N, 91.9°E). The GPS tracker was used for this purpose. The first visit was completed for the USGS coordinates, and no sign of ground failure was observed in the area. Hence, next visit was made to the IMD coordinates. Numerous ground surface cracks were found in the IMD-provided location and thus may be considered as the location of the epicenter which differs by only 14 km distance with USGS coordinates. It was located at one of the peak points of Longtarai hill in Dhalai district, which was approximately 20 km (map length) distance from Ambassa. The area consists of hillocks and valleys that covered by trees, rubber garden, banana, areca, bamboo tress and other deciduous plants.

A very old water body (lake) with deep water depth was found in the area along the valley that was created by introducing local earthen bund on the other side of the

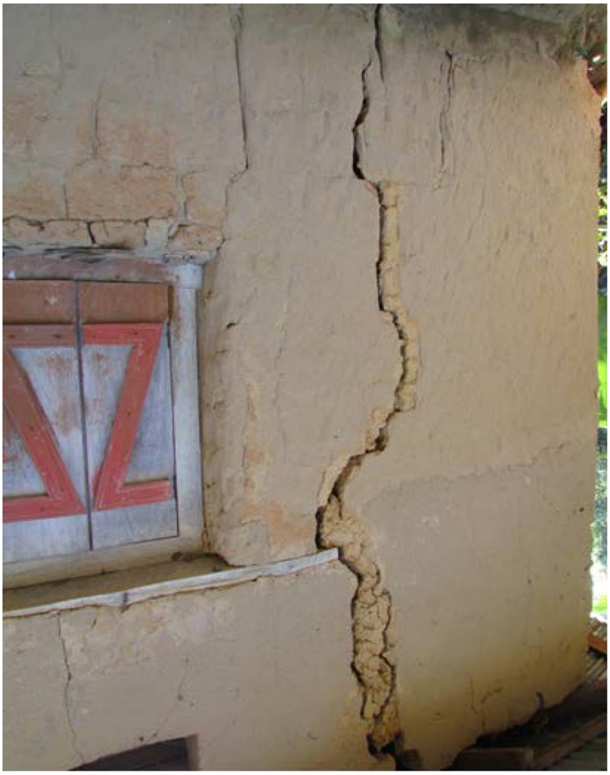

Fig. 17 Lack of lintel band at mud house

valley, maybe 60–70 years ago. At one side of the lake, an impression of wet watermark was noticed, at more than 1 m above the static water level. The existing wet watermark even 5 days after the earthquake clearly indicates the strong shaking, during the earthquake in that area. In the epicentral location, the continuous ground cracks of 20–50 m long were measured. Figure 21 shows the crack patterns of a tree, developed due to ground shaking in the location. The cracks were propagated in all direction where the tree roots were elongated. All the trees effectively carry the similar crack patterns in the area. People near the epicentral area expressed that they felt like a floating body during the shaking, and suddenly, few of them fall to the ground from their upright standing position. Fortunately, none of them got hurt.

The soil at the top surface appeared to be loamy soil. This soil possesses a high cementations property. Because of this property, the soil becomes very hard in the winter season and very soft during the rainy season. This may be the possible reason that even after the strong ground shaking, the trees in the area were not uprooted. One point to be emphasized is that the bamboo clumps at the epicenter location resisted the shaking so well that virtually no ground cracks were observed, wherein the trees at 5–10 m apart showed considerable ground fissures all around. This goes on to show that study of soil–tree interaction can be explored for dynamic loads, which may provide a new dimensional approach towards solving the civil engineering foundation problems in future.

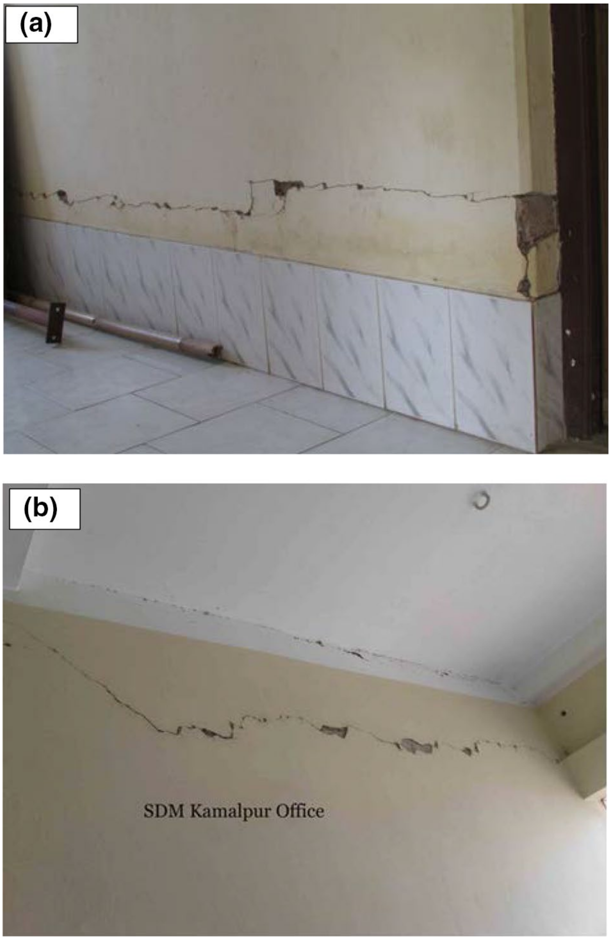

Fig. 18 **a**, **b** Sliding shear failure at two-storied reinforced concrete frame buildings

6 Inference of site effects from intensity of the earthquake

A part of this study is to understand the reason behind liquefaction and heavy damage, the level of shaking is estimated qualitatively and quantitatively using the intensity scale as well as by the peak ground acceleration (PGA). Although intensity scale gives a preliminary idea regarding damage distribution, it only captures the damages occurred to the structures or human experiences and responses. On the other hand, PGA reflects the source parameters of an earthquake and response of the overlying soil column.

The PGA value could be obtained from recorded instrumental data from various seismic stations in and around Tripura. However, not much seismic stations are available to capture the PGA distribution for the whole area. In such instances, felt intensity reports published by various agencies and literatures could be used to estimate the PGA from various empirical equations available both at bedrock level and at the surface. For this purpose, intensity reported by USGS and Debbarma et al. (2017) close to the liquefied site for the 3 January 2017 Manu earthquake is utilized. Also, the intensity derived from

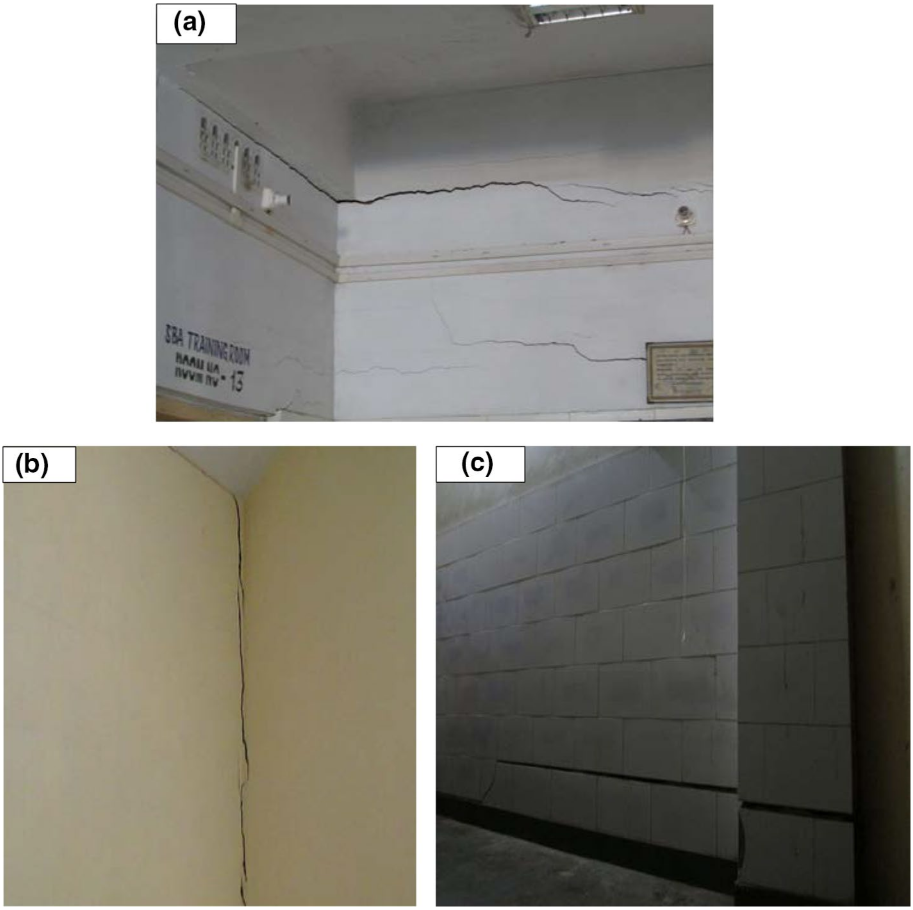

Fig. 19 **a–c** Damages observed in two-storied RC frame hospital building with masonry infill

observation made during the field visit is considered. Surface level PGA is estimated at selected locations using the equations relating intensity and PGA. Many of the relations developed are such that MMI is a linear function of PGA (Wald et al. 1999; Arioglu et al. 2001; Atkinson and Kaka 2007; Tselentis and Danciu 2008; Faenza and Michelini 2010; Worden et al. 2012; Bilal and Askan 2014; Caprio et al. 2015; Anbazhagan et al. 2016). Some of the relationship that considers MMI as a function of PGA is hypocentral distance and magnitude (Tselentis and Danciu 2008; Worden et al. 2012; Bilal and Askan 2014; Anbazhagan et al. 2016). However, since intensity is a function of site effect, the relationship should contain an independent variable which characterizes the site. Anbazhagan et al. (2016) suggested that average shear wave velocity in the top 30 m (VS30) could be that potential independent variable for estimating the macroseismic intensity of any site. They have derived an equation considering VS30 as one of the variables and further refined it and proposed the relation which is a function of PGA, hypocentral distance (R), moment magnitude (M_w) and it inherently considers the site effect without the Vs30 as variable. This equation is valid for Himalayan region. Since seismicity of Tripura is influenced by the Himalayan region, this equation by

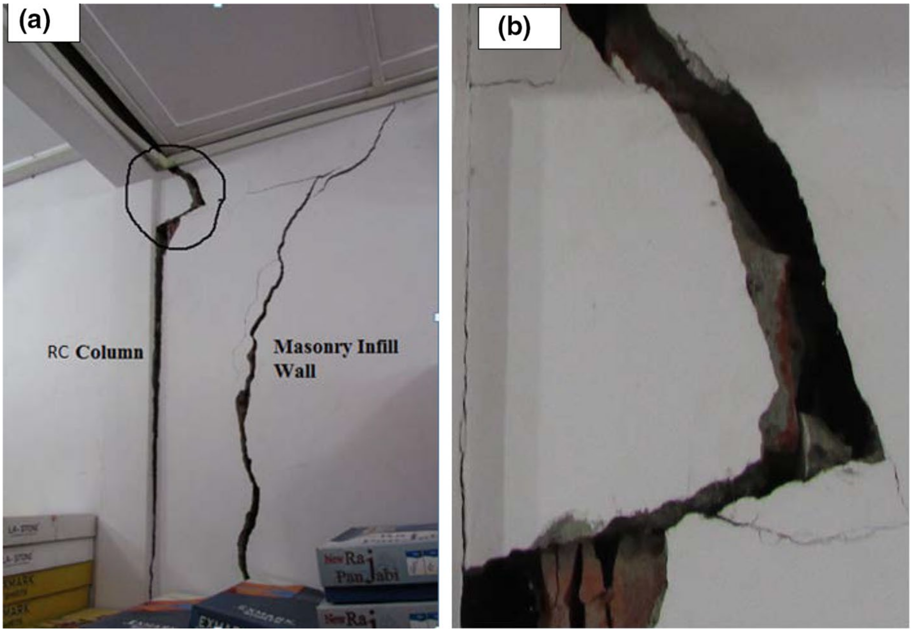

Fig. 20 **a** Formation of vertical cracks in the masonry infill reinforced concrete wall and **b** cracks in RC column–masonry wall joints

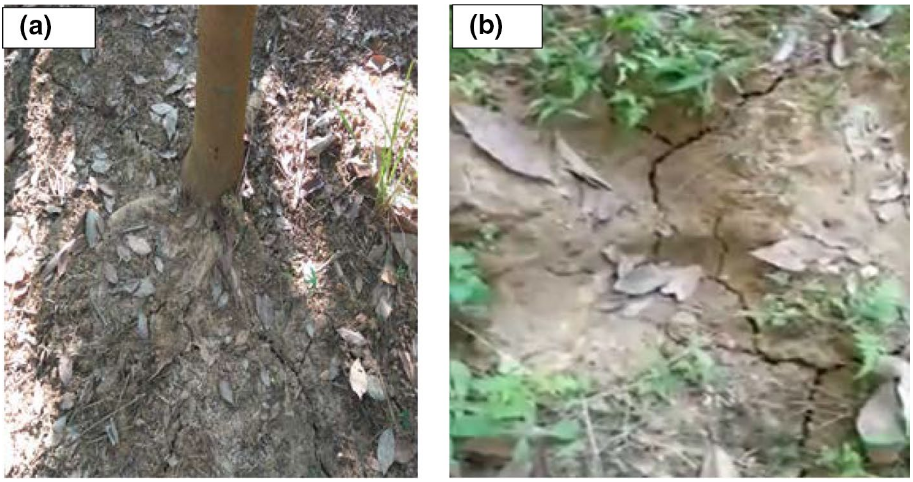

Fig. 21 **a**, **b** Surface cracks at the epicentral area located at the top hill of Longtharai, Dhalai, Tripura

Anbazhagan et al. (2016) is used to calculate the surface PGA from reported intensity values. Table 4 shows surface PGA estimated from intensity at selected locations.

Fair comparison of bedrock and surface PGA can give qualitative and quantitative information about amplification. Since there is no bedrock motion recorded close to liquefied/highly damaged sites, bedrock-level PGA is calculated using regional ground motion

Table 3 GMPEs applicable for Tripura region used in the present study

Authors	Applicable magnitude	Applicable distance (km)	Standard form of equation	Coefficients value for zero-period acceleration
Nath et al. (2012)	4.6–8.1	≤100	$\ln Y = c_1 + c_2M + c_3(10 - M)^3 + c_4) \ln\left(r_{\mathrm{rup}} + c_5 \exp\left(c_6M\right)\right)$ where Y is ground motion parameter in g M is the moment magnitude r_{rup} is the fault rupture distance in km	$c_1 = 9.143$ $c_2 = 0.2470$ $c_3 = -0.0140$ $c_4 = -2.67$ $c_5 = 32.9458$ $c_6 = 0.0663$
Singh et al. (2016)	4–8.5	1–300	$\ln Y = c_1 + c_2(M - 6) + c_3(M - 6)^2 - \ln R - c_4R$ where Y is ground motion parameter in g M is the moment magnitude R is the hypocentral distance in km	$c_1 = 2.0282$ $c_2 = 0.8569$ $c_3 = -0.0472$ $c_4 = 0.0091$

prediction equation (GMPE). Nath et al. (2012) developed one such attenuation relation for Shillong region using synthetic ground motion database. Singh et al. (2016) proposed a predictive relation for northeastern Indian region for crustal events using region parameters. Table 3 gives the applicability and functional form of the two GMPE. These GMPEs are used together by assigning them with equal weights.

Table 4 summarizes the PGA estimated at both bedrock level and surface level using the procedure mentioned above. It can be observed from the table that the surface PGA is much higher than of the bedrock-level PGA values for most of the sites. In some cases, the surface acceleration has been estimated to be up to 0.5 g at locations close to the epicenter. However, the absence of recording stations near these locations makes it difficult to verify these higher values. The first row in the table, i.e., 24.118°N and 91.991°E, is the liquefied site being investigated in this study. It can be seen that at this point the PGA increased from 0.152 g at the bedrock to 0.281 g at the surface which is sufficient to cause liquefaction. This is confirming to the observation made at the investigated site. First-level amplification based on ratio of surface PGA to bedrock PGA is estimated and presented in the last column of Table 4. It can be seen in many of the places, amplification values are more than 1, and in few places, it even reached 5.4. So, it clearly indicates that subsurface soil present in Tripura plays a significant role in amplifying bedrock motion which led to liquefaction failures.

7 Distribution of surface peak ground acceleration (PGA) and intensity

Figure 22 shows the surface PGA distribution near the epicenter of the event estimated using the expression suggested by Anbazhagan et al. (2016) as discussed in the previous section. The estimated PGA value varies from 0.05 g to a maximum of about 0.57 g and at the liquefied site (Kanchanbari, Kumarghat, Tripura), it goes up to 0.28 g which is sufficient to cause liquefaction for loosely deposited sandy soil sites. It can be seen from Fig. 22 that northern part of the state bordering Bangladesh has a higher value of PGA as opposed to the central Tripura where it is in the range of 0.05–0.1 g. Though the observed value is based on some assumptions or obtained through the regional GMPE's, it can be used as preliminary risk assessments (Aydan 2015a, b). However, as the attenuation relations, with

Table 4 Estimated PGA value at bedrock level and surface level nearby liquefied sites and at various places in Tripura for 3 January 2017 Manu earthquake India

Latitude	Longitude	Damage intensity from IISc team survey	Distance from epicenter (km)	$PGA_{bedrock}$ (g)	$PGA_{surface}$ (g)	Amplification = $PGA_{surface}$/$PGA_{bedrock}$
24.110	91.986	VI	11	0.154	0.275	1.78
24.190	92.096	VI	21	0.127	0.397	3.12
24.277	91.957	VI	30	0.105	0.569	5.42
24.000	92.151	VI	15	0.145	0.310	2.14
24.197	91.828	VI	29	0.107	0.554	5.20
24.118	91.991	VI	12	0.152	0.281	1.84
24.300	91.723	V	46	0.072	0.040	0.56
24.427	91.884	V	48	0.068	0.044	0.65
24.479	91.771	V	58	0.054	0.064	1.17
24.526	91.850	V	60	0.053	0.066	1.26
23.831	91.628	V	48	0.069	0.044	0.64
24.449	92.342	V	60	0.052	0.067	1.29
23.623	91.821	V	49	0.067	0.045	0.67
24.159	92.037	V	16	0.141	0.012	0.09
24.011	91.837	V	20	0.131	0.014	0.11
24.166	92.031	IV	17	0.140	0.000	0.00
24.153	92.046	IV	16	0.143	0.000	0.00
24.196	91.833	IV	29	0.108	0.001	0.01
24.197	91.834	IV	29	0.108	0.001	0.01
24.169	91.851	IV	25	0.117	0.001	0.01
23.958	91.840	IV	21	0.129	0.001	0.00

proper emphasis on the sense of the earthquake are of potential importance, there is a need to confirm the validity of the proposed value.

Figure 23 presents the intensity map in Modified Mercalli Intensity (MMI) scale, which is generated using the data collected by the IISc team during the reconnaissance survey in the earthquake affected area. An intensity of V is reported near the epicenter of the earthquake which is sufficient to cause structural damage. It can be observed from Fig. 23 that the intensity keeps on increasing toward the north east of the state reaching a maximum of VI, whereas in the central part of the state it is seen to have intensity values ranging from IV to V. This preliminary estimation of surface PGA and intensity map for the 3 January 2017 Manu earthquake highlights the need for site-specific amplification and liquefaction estimation in Tripura to account them for the design of new buildings, infrastructure, etc. and also to retrofit the old structures to minimize catastrophic losses in case of any future event.

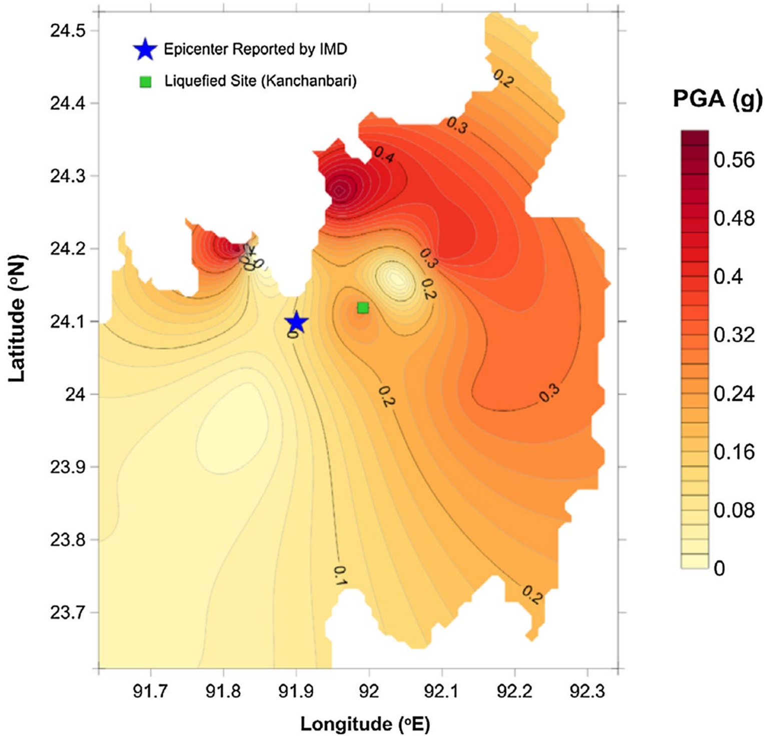

Fig. 22 Surface PGA near epicentral area and liquefaction site for 3 January 2017 Manu earthquake, Tripura

8 Summary and conclusions

On January 3, 2017, the state of Tripura, India, experienced a moderate earthquake of moment magnitude (M_w) 5.7. The epicenter of the earthquake and focal depth is reported to be 19 km northeast of Ambassa and 28 km from the ground surface. Even though the earthquake was of moderate magnitude, it caused damages to buildings in the districts of Dhalai, Unakoti, and Sepahijala. Liquefaction was observed at the place of Kanchanbari in Unakoti district in agricultural fields adjacent to Manu River bank. The earthquake resulted in landslides and lateral spreading of the ground in many places.

The damages were mainly seen in unreinforced masonry (URM) buildings, mud houses and low-rise RC-framed buildings. It is reported that the damages were partial in about 5200 houses, severe in about 1450 houses and about 42 houses collapsed. Damages were also observed in public buildings and hospitals. The earthquake is reported to have not caused severe disruption to the general public as lifelines and transportation services were not affected significantly.

Essentially, the damages to URM buildings and mud houses can be attributed to lack of earthquake-resistant features like horizontal bands (RC or timber) and poor.

The soil in Tripura is mostly soft and medium dense in nature with water table less than 15 m as per the existing geotechnical report which is a favorable condition for

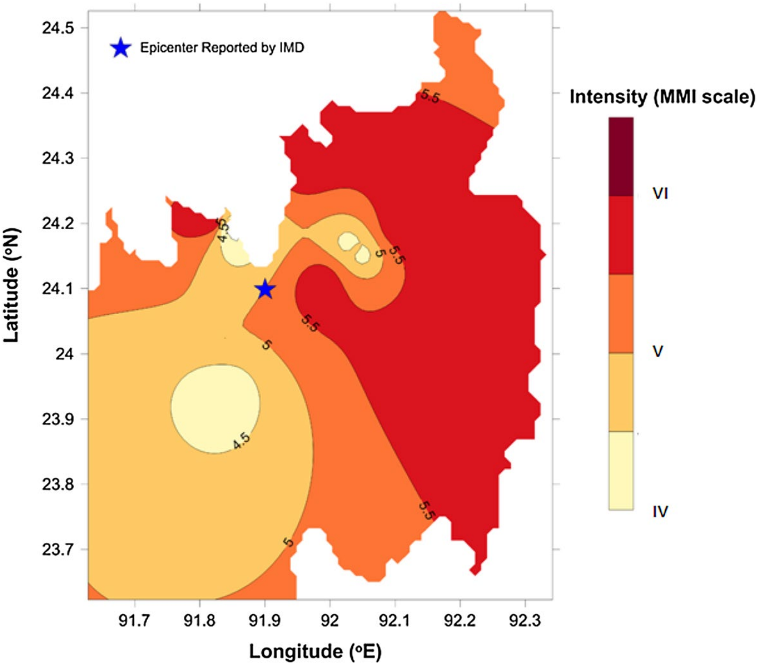

Fig. 23 Modified Mercalli Intensity (MMI) map created by damages reported in this study

liquefaction. Hence, incorporation of liquefaction analysis may be suggested as a prerequisite to the new important structures planned in the region.

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