



# On mitigation of earthquake and landslide hazards in the eastern Himalayan region

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## Abstract

Mitigation of geological hazards through science and engineering applications is one of the most effective ways to reduce their impact on human life and local infrastructure. It involves precise mapping of hazards, assessment of their potential, monitoring, early warning, geotechnical treatment, design of vital infrastructural facilities and creating awareness at local levels. Several such initiatives have been taken at government level to deal with the earthquakes and landslides in the eastern Himalayan region. These efforts facilitated identification of potential areas and sites, susceptible to future events and helped in improving our understanding of crustal structure, geodynamics, tectonics, seismogenesis, and soil properties, etc. The paper highlights details of the major initiatives, significant achievements, and priorities to help in better mitigation of earthquake and landslide hazards in the eastern Himalayan region.

**Keywords** Eastern Himalaya · Geological hazards · Mitigation · Risk reduction · Earthquakes · Landslides

## 1 Introduction

The Eastern Himalaya (EH) is about a 1200 km long segment of the Himalayan collision zone, extending from the Arunachal Himalaya in the east to eastern Nepal in the west and the frontal foredeep of Assam in the south to the Tibet hinterland in the north. It comprises Sikkim, Bhutan, Arunachal, and the Eastern Himalayan Syntaxis (Fig. 1) and forms part of the 2500 km east–west trending Himalayan arc, which is considered one of the most seismically active zones in the world, due to the underthrusting of the Indian continent beneath the Eurasian continent. The stresses generated due to continued convergence, at a rate of ~3.5–6 cm/yr, since ~50 Ma (Gansser 1964) resulted in accumulation and strain energy release, manifested in the form of earthquakes of varied types and magnitudes. The Eastern Himalayan Syntaxis

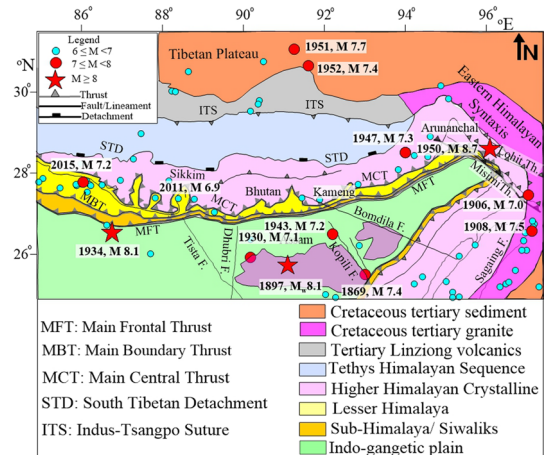
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**Fig. 1** Map showing tectonic features with broader geological formations in the eastern Himalaya (modified after Yin 2006)



(EHS) lies in the easternmost Himalaya and forms a hairpin like bend in the rocks, resulting in the generation of the great Assam-Tibet earthquake of 1950 (Mw 8.7), the largest in India. This zone is characterised by several NW–SE trending regional thrust faults, e.g. Lohit and Mishmi thrusts, and the region is marked by high seismicity, rapid erosion, and high uplift and exhumation rates. Owing to the complex geodynamic setting, the plate motion and other geodynamic processes in this part are largely unknown.

The region is generally characterised by steep slopes, lofty hills and complex geological and tectonic settings. Also, the intense rainfall in this part of the Himalaya not only contributes to rapid erosion and weathering of the rock mass, but also increases the groundwater level, which leads to reduction in the stability of natural slopes. These geo-environmental conditions lead to two prominent geological hazards in the EH region, namely, earthquakes and landslides.

In recent times, many towns in the Eastern Himalayan region have grown considerably in terms of infrastructure, transportation, population, etc., ultimately altering the socio-economic conditions. Moreover, the fast expansion and unplanned growth of infrastructure have increased the vulnerability levels due to geological hazards. The government of India has taken several scientific and technology-based initiatives towards monitoring and assessment of geohazards, especially earthquakes and landslides, early warning of landslides and specific research for acquiring new data to understand the crustal structure, geodynamics, tectonics, seismogenesis, geotechnical properties, etc. with the ultimate goal of human safety and risk reduction due to future geohazards in the region. Several organisations and academic institutions in the country, including the National Centre for Seismology (NCS), Geological Survey of India (GSI), North Eastern Institute of Science and Technology (NEIST), North East Council (NEC), North East Space Application Centre (NESAC), National Geophysical Research Institute (NGRI), etc., are engaged in various research activities to achieve these goals. In this study, we summarise these efforts as well as important findings and future perspectives.

## 2 Seismicity, landslides and tectonic setup

The region, excluding Sikkim, falls in the highest seismic hazard class of zone V in the seismic zonation map of India (BIS 2002). The earlier studies show that the region has the potential for large-to-great earthquakes (e.g. Srivastava et al. 2013). The EH region has been the site of several large earthquakes (Table 1) including the 1950 Great Assam earthquake ( $M_w$  8.7), which occurred along the Mishmi thrust, and the 1934 Bihar–Nepal border earthquake ( $M_w$  8.1). The 1934 Bihar–Nepal border earthquake was felt over a wide region in India, Nepal and Tibet (Dunn et al. 1939). The 1906 ( $M_w$  7.0) and 1908 ( $M_w$  7.5) earthquakes were located along the northern end of the right-lateral Shan–Sagaing Fault (Xiong et al. 2017). Another prominent earthquake that occurred on October 23rd 1943 ( $M_w$  7.2) is related to the Kopili Fault zone (Nandy and Dasgupta 1991). Moreover, not much is known about the 1947 Lang earthquake in Tibet that occurred in eastern Arunachal Pradesh, close to the surface trace of the Main Central Thrust (MCT); Chen and Molnar (1977) assumed a shallow angle thrust faulting to the north. The earthquakes of 1951 ( $M$  7.7) and 1952 ( $M$  7.4) were located along the Yadong–Gulu rift in southern Tibet (<https://www.volcanodiscovery.com/earthquakes>). The earthquake, which occurred in the westernmost part, is the largest aftershock ( $M_w$  7.2) of the 2015 Gorkha earthquake ( $M_w$  7.8) that struck in the eastern Nepal Himalaya (Arora et al. 2016). In addition, many moderate and small earthquakes have occurred in this region.

Another prominent geohazard that prevails in the EH region is landslides. The entire EH mobile belt is highly prone to landslide activity for reasons such as: (1) high relief and highly rugged topography, (2) fragile and dissected rock formations, (3) higher intensity of precipitation, and iv) high seismicity rate. A study in the Sikkim and West Bengal parts of the belt, occupying an area of about ~7960 sq km, has shown that landslides of different types and magnitudes occur several times every year (Fig. 2). Most of these landslides are triggered by incessant and heavy monsoon rainfall; the terrain is also prone to earthquake-induced landslides. Several such events were triggered in the region, mainly during the Bihar–Nepal Earthquake of 1988 ( $M_w$  6.8) and the Sikkim Earthquake of 2011 ( $M_w$  6.9)

**Table 1** List of large earthquakes occurred in Eastern Himalayan region

Sl. no.	Date and origin time (UTC)	Latitude (°N)	Longitude (°E)	Depth (km)	Magnitude
1	1869-01-10	25.5	93.0	–	7.4 M
2	1897-06-12	26	91.0	–	8.7 $M_s$
3	1906-08-31	27.46	97.04	–	7.0 $M_w$
4	1908-12-12	26.56	97.13	–	7.5 $M_w$
5	1930-07-02 21:03:43	25.93	90.18	15	7.1 M
6	1934-01-15 08:43:25	26.86	86.59	15	8.1 $M_w$
7	1943-10-23 17:23:21	26.63	93.85	15	7.2 M
8	1947-07-29 13:43:24	28.50	94.00	60	7.3 $M_w$
9	1950-08-15 14:09:34	28.36	96.45	15	8.7 $M_w$
10	1951-11-18 09:35:54	31.05	91.26	30	7.7 M
11	1952-08-17 16:02:14	30.64	91.60	25.0	7.4 M
12	2011-09-18 12:40:51	27.72	88.06	19.7	6.9 $M_w$
13	2015-05-12 07:05:19	27.78	86.12	15	7.2 $M_w$

*M* Magnitude (Not defined),  $M_s$  Surface-wave Magnitude,  $M_w$  Moment Magnitude

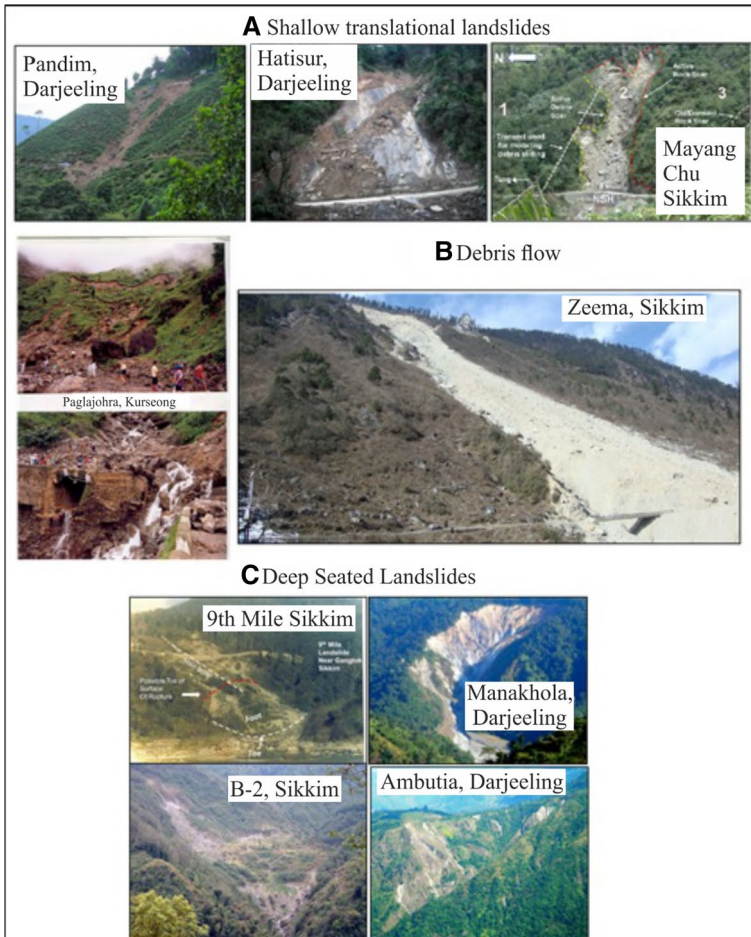
(Ghosh et al. 2012; Martha et al. 2014). Table 2 lists some of the major and deadly landslides since historical times, of which the event of 1968 has been the most devastating. The national highways in the Sikkim–Darjeeling Himalaya were badly damaged and it took nearly one and a half years for their restoration (Sinha et al. 1975). Apart from the 1968 event, several other prominent landslides have occurred in the region, in 1950, 1980, 1991, 1993, 1998, 2003, 2007, 2011 and 2015 (Paul and Ghoshal 2009; Ghosh et al. 2016).

Tectonically, EH is mainly traversed by the South Tibetan Detachment System (STDS), Indus-Tsangpo Suture (ITS), Main Central Thrust (MCT), Main Boundary Thrust (MBT) and Himalayan Frontal Thrust (HFT) (Fig. 1). It represents the collision boundary between the Indian Plate and the Lhasa terrain (southernmost block of the Eurasian Plate) in southern Tibet and consists of Ophiolite along with an imbricate melange of flysch sediments, which represent the remnants of the Tethyan Sea that separated India from Asia (Chan et al. 2015). To the south, lies the geological unit named as Tethyan Himalaya (TH), comprised of Neo-Proterozoic-Palaeozoic to Palaeogene sediments and bounded to the south by the STDS. This is interpreted as a system of normal faults which separated Tethyan sediments from the Greater Himalayan basement (Kellest et al. 2018). The next southern developed fault system is the MCT, which is a northeast dipping plane separating the Higher Himalaya from the Lesser Himalaya and is characterised by a thick zone of intense shearing. The MBT is a steeply north dipping fault at the surface that flattens with depth (Valdiya 1980). To the south of the MBT, lie the deformed Siwalik foothills, characterised by back thrusts (Dasgupta et al. 2000), intense folding and thrusting, etc. The southern end of this sub-Himalayan fold belt is marked by a boundary between the deformed Siwalik rocks and recent alluvium of the Brahmaputra plains and is designated as the Main Frontal Thrust (MFT) or Himalayan Frontal Thrust (HFT).

Besides the major thrusts, which lie parallel to the strike of the Himalayan arc, various transverse strike-slip faults cutting across the Himalayan orogenic belt from the Tibetan hinterland through the Siwalik foreland have also been mapped in the region. These have been delineated from the Assam-Arunachal foredeep, like the Kopili Fault,

**Table 2** List of major landslides in Darjeeling–Sikkim Himalaya

Date/time of event	Loss/Damage
12th June 1897	1542 people died with catastrophic damage to infrastructure
24th September, 1899	72 people died with huge loss of property
10–12 June, 1950	127 people died
2–5 October, 1968	677 deaths as per official record and profuse damage to infrastructure
3–4 September, 1980	215 people lost their life
15–16 September, 1991	2 people died and huge land and property got damaged
11–13 July, 1993	15 people died
5–8 July, 1998	Several deaths and road blockades
10–11 July 2003	24 people died at Gayabari landslide
15–17 July 2007	Damage of properties in Darjeeling and adjoining areas
7–9 September, 2007	12 lives were lost and damage to several properties in Darjeeling region
26–27 May, 2009	25 lives were lost and profuse damage to properties in Darjeeling area
18th September, 2011	Triggering of many landslides induced by earthquake in Sikkim
14th September, 2012	Extensive damage in six tea gardens in Darjeeling district
1st July, 2015	19 people died and land/property of Limbudhura village washed away



**Fig. 2** Images showing landslides of varied types and magnitudes in the Eastern Himalaya

the Bomdila Fault, the Dhubri Fault and the Tista lineament (Fig. 1) (Mukhopadhyay 1984; Nandy and Dasgupta 1991). These transverse faults cut across the orogen parallel thrusts, including the basement thrust (MHT), thus limiting the possible rupture lengths along with the MBT, MFT, etc. for future earthquakes (Godin and Harris 2014; Mugnier et al. 2017; Godin et al. 2018).

Apart from these structure and tectonic features, the Indo-Burmese megathrust located east of the EH region can also influence its hazard scenario. The Indo-Burmese megathrust is associated with the Indo-Burma Subduction beneath the Indo-Burma range. The recent studies by Steckler et al. (2016) and Vorobieva et al. (2021) suggest that this mega thrust is locked and may produce a great earthquake ( $M > 8.0$ ), which may affect the adjoining regions, including the study area (EH).

### 3 Significant initiatives, studies and results

Science and technology interventions are the essential tools to monitor and deal with natural hazards. Several steps have been taken in the EH region in the form of monitoring, seismic zonation, assessment of earthquake hazard, landslide zonation, experiments on early warning of landslides, etc. Bansal and Verma (2012, 2013) presented details of Science and Technology (S & T) interventions and earthquake awareness in the Indian context. A few important activities that are taken up with the support of the Government of India in the region are summarised below.

#### 3.1 Seismic monitoring

The precise earthquake location, which is primarily dependent upon the quality of the seismic network, serves as the basic inputs for any exercise related to earthquake hazard. India has a history of about 120 years of seismic monitoring, with Alipore (Kolkata) being the first observatory, established in 1898 after the occurrence of the Great 1897 ( $M_w$  8.1) Shillong earthquake in the NE region. Presently, the National Seismological Network (NSN), operated and maintained by the NCS, has 115 stations, spread across the country and equipped with state-of-the-art broadband seismographs and accelerographs. The NSN includes 21 stations in the NE region of India: with 14 stations in the eastern Himalaya (Sikkim-1, Assam-7, Arunachal Pradesh-4, and Nagaland-2). Like in any other country, the density of the network has increased in different phases in India. Digital seismometry started in India mainly after the Latur earthquake of 1993, and the present network of 115 has been fully operational since 2018. Details of station locations, date of installation, type of instrumentations, and site geology, etc. are available in the paper by Bansal et al. (2021).

In addition, several broadband seismographs and strong motion accelerographs were established in project mode from time to time for specific studies. For example, the Indian Institute of Technology, Kharagpur (IITKH) has been operating 23 seismic stations to study the seismic structure, lithospheric deformation, and seismicity of the Indian plate in the Sikkim Himalaya. Also, a strong motion network consisting of 10 stations in Darjeeling–Sikkim has been maintained by IITKH since 1998. These project-based networks have generated earthquake data for about 300 events with magnitude  $\geq 2.5$  and  $< 7.0$ . Similarly, NEIST, Jorhat is also operating a few broadband seismographs and strong motion accelerographs in the Assam area.

Further, NCS plans to strengthen the national network in the next few years, with deployment and operations to focus on the least explored areas like, EH and the seismically active contiguous tectonic domains of the Brahmaputra River Valley, Eastern Himalaya Syntaxis, the Bengal basin, and Indo-Burmese Wedge (NCS 2021). An inter-spacing of 60–80 km has been suggested to achieve the objective of detection of an  $M_{2.5}$  earthquake at 5–6 stations as well as ensure robust estimation of the epicentre and focal mechanism solutions.

#### 3.2 Seismic hazard and microzonation

Accurate seismic hazard assessment of a region is the key to prepare an effective strategy for its mitigation. Seismic hazard zonation at the micro-level, i.e. microzonation, has emerged as a viable process that embraces a more enhanced study of earthquake-prone regions by subdividing them into smaller zones of equal hazards, thus, allowing more

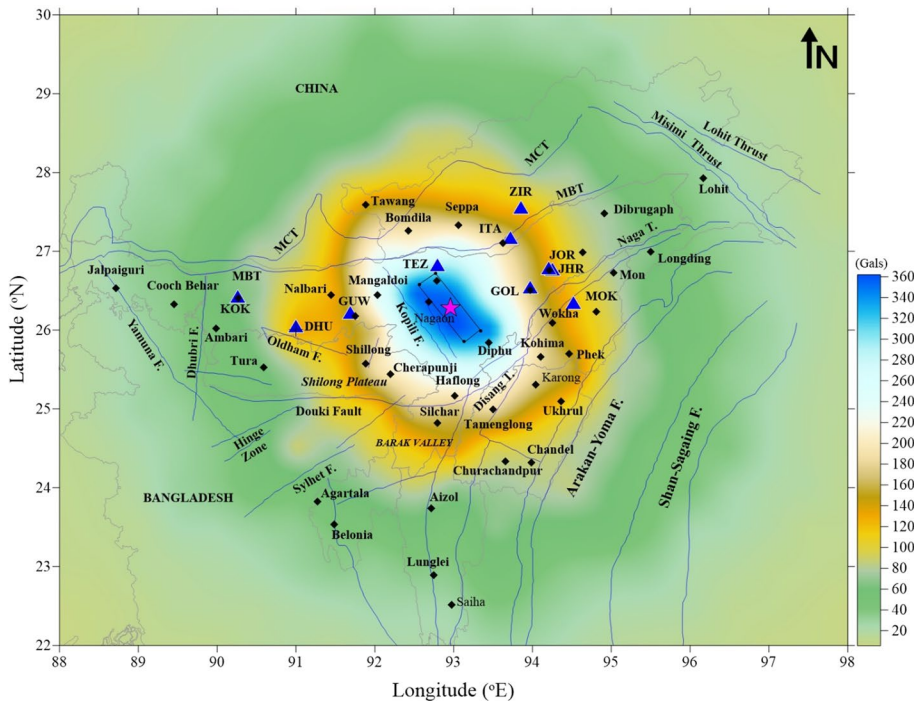


efficient urban planning. As an initial step in risk mitigation studies, seismic microzonation requires a multidisciplinary approach with active interactions between geological, seismological, geophysical, and geotechnical parameters. Thus, seismic microzonation provides a more realistic and reliable representation of the ground-motion characteristics in a given area. In particular, since predicting earthquakes is almost impossible, studying specific subsurface soil dynamics can aid our efforts to reduce the impact of natural hazards like earthquakes on human life and livelihood.

Recognising the importance of microzonation, a concerted effort was initiated at national level more than two decades ago (Verma and Bansal 2013). As a part of this initiative, microzonation studies of Sikkim and Guwahati, in the eastern region, were taken up with the help of IITKH, initially under the overall umbrella of the Department of Science and Technology and later with the support of the Ministry of Earth Sciences. For the Sikkim region, the seismic hazard microzonation was carried out by synthesising the different thematic layers, namely, Geology, Soil Site Class, Slope, Landslide, Rock Outcrop, Frequency, simulated Peak Ground Acceleration, Predominant Frequency, and Site Response at predominant frequencies. The final microzonation map depicts high hazard values in south Sikkim (Singtam and adjoining regions), where the Seismic Hazard Index (SHI) is  $> 0.65$ , with peak ground acceleration (PGA) ranging between 0.79 g and 0.83 g. While north Sikkim is associated with low hazard (PGA  $\sim 0.2$  g), the western portion is found to have a moderate hazard with PGA values of the order of 0.4 g (Pal et al. 2008; Nath and Thingbaijam 2009). This study was extended further to Darjeeling–Sikkim by Adhikari and Nath (2016). Corresponding to the spatial distribution of PGA and PSA at 0.2 s, 0.3 s, and 1.0 s for 10% probability of exceedance in 50 years with a return period of 475 years at the surface, the PGA variation is found to vary from 0.260 g to 0.861 g. The major areas of Gangtok, Mangan, Uttare and Siliguri exhibit higher hazard levels, while Ghum, Sonada and Lingza fall into the moderate category. The northern parts were found to have low hazard (PGA 0.260 g). Also, the next generation prediction models for Darjeeling–Sikkim were developed for different environments, i.e. normal, strike-slip, and reverse faulting earthquake nucleation (Adhikari and Nath 2016). A new model for the surface consistent probabilistic seismic hazard of Darjeeling–Sikkim was developed by considering, both the layered polygonal and active tectonic sources, seismicity parameters, and 42 new ground-motion prediction equations (GMPEs).

Similarly, microzonation of Guwahati was taken up and completed with different thematic maps (Nath et al. 2008a, b). The study is based on the M8.7 scenario earthquake and utilises strong motion data from the local network. The microzonation map depicts five hazard zones with a maximum hazard index of 0.55 and a minimum of 0.16 in the western and eastern areas of Guwahati, respectively. These studies have direct applications in earthquake engineering, like site-specific design response spectra.

In a recent study, Sutar et al. (2017, 2020) estimated the maximum earthquake potential of the Kopili Fault, a notable structural feature in the area, associated with the occurrence of several large and many moderate earthquakes. They used different approaches, dependent on fault geometry, slip rate, geodetic moment rate, convergence rate, etc. to estimate the maximum earthquake potential of the Kopili fault and found it to be  $M_w$  7.3. Such a large earthquake, upon its occurrence, may generate significant ground shaking and cause widespread damage. They predicted the peak ground accelerations based on empirical Greens Functions and stochastic finite fault modelling techniques. It is inferred that the sites within 250 km of the source zone, e.g. Dhekiajuli, Tezpur, Nagaon, Hajoi, Seppa, Bomdila, Rupa, Udalguri, and Shillong, may experience PGA of the order of 160 to 360 gals (Fig. 3).



**Fig. 3** Simulated peak ground acceleration map of northeast region (NER) of India for a Mw 7.3 potential event in the Kopili source zone. Pink star indicates the location of the potential event. The hypothetical rupture plane of this event is depicted by a rectangle. The important cities of the study region are shown in black diamonds; the blue triangles represent the location of the SMA stations. The abbreviations used are MBT (Main Boundary Thrust), MCT (Main Central Thrust), F (Fault) and T (Thrust), KOK (Kokrajhar), DHU (Dhubri), GUW (Guwahati), TEZ (Tezpur), ITA (Itanagar), ZIR (Ziro), GOL (Golaghat), JHR/JOR (Jorhat) and MOK (Mokokchung). The unit of the legend shown adjacent to the figure is in Gals (after Sutar et al. 2020)

The probabilistic seismic hazard assessment (PSHA) is a traditional and effective method used to estimate the level of ground motion with a specified probability of exceedance. Such studies have been carried out by several researchers for the North East region of India. A study by Khattri et al. (1984) and Bhatia et al. (1999) suggested higher hazard in and around the Arakan-Yoma Subduction (AYS) region. Das et al. (2006) have also reported a high hazard scenario for its northern parts, i.e. the EH region. Similarly, based on the extreme value theory, Yadav et al. (2011) reported earthquake hazard parameters and probabilities of occurrence of medium and large earthquakes (Mw 4.0–7.0) with their return periods for different zones in the northeast region. Their analysis shows that the AYS zone has low mean return periods and high probability of occurrence of moderate and large earthquakes (M6.0–M7.0) in comparison with the other three zones, namely, the Shillong Plateau Zone, the Eastern Syntaxis Zone, and the Himalayan Thrusts zone. They also estimated the mean return period for the earthquake of magnitude Mw 6.5 to be about 9–10 years, 59–78 years, 72–115 years and 88–127 years in the AYS zone, Himalayan Thrusts Zone, the Shillong Plateau Zone and the Eastern Syntaxis Zone, respectively. Chetia et al. (2019) have analysed the probability of occurrence of earthquakes (Mw  $\geq$  5.0) in northeast India using 100 years of data. The study, which is based



on Kolmogorov–Smirnov statistics, reports the mean occurrence period for  $M_w \geq 5.0$  to be  $\sim 74$  days with a 50% probability and the probability of recurrence of such an earthquake within 140 days to be 80%.

### 3.3 Crustal deformation studies

A national GNSS programme was launched more than two decades ago in India for monitoring the crustal deformation to facilitate constraining the Indian plate movement, estimation of strain accumulation and convergence rates in the regions of high seismic activity (Verma and Bansal 2012a). Under the program, about a dozen permanent GPS receivers were established in the EH region at identified locations. Over the period, these permanent and those deployed in campaign mode, from time to time, across some well-known faults in the region have generated a good amount of datasets. The datasets have helped in taking up specific R & D problems related to constraining the Indian plate movement and crustal deformations in different parts of the region. Some of them are discussed in this section:

- Jade et al. (2007) estimated the inter-seismic deformation based on permanent and campaign mode GPS observations. The Euler pole of rotation of the Indian tectonic plate determined in ITRF2000 was located at  $51.7 \pm 0.5^\circ\text{N}$ ,  $-15.1 \pm 1.5^\circ\text{E}$  with angular velocity of  $0.469 \pm 0.01\text{Myr}^{-1}$ . The results also highlight statistically insignificant present-day active deformation within the Shillong Plateau and in the foreland spur, north of the plateau in the Brahmaputra valley.
- The estimates of Euler Pole rotation were later refined (Mahesh et al. 2012) using data from 26 permanent and campaign GPS sites, located on the Indian plate and along with its boundary, and suggested that the Euler pole is located at  $51.44 \pm 0.07^\circ\text{N}$ ,  $8.9 \pm 0.8^\circ\text{E}$ , and rotating with an angular velocity of  $0.539 \pm 0.002^\circ/\text{Myr}$ . They also inferred that the internal deformation of the Indian plate is very low, and the entire plate mainly behaves as a rigid plate. Further, the predominantly northward motion of about 36 mm/yr of the Indian plate with respect to the Sunda plate along its eastern boundary in the northeast India is accommodated through dextral motion along the Sagaing fault in the east and in the Indo-Burmese wedge in the west. The 1906 M7.0 and 1908 M7.5 events occurred on the northern end of the Sagaing fault. The plate boundary in the Indo-Burmese wedge appears to be located between Aizwal and Imphal, accommodating about  $16 \pm 2$  mm/yr of dextral motion. The GPS derived differential motion on the northwest–southeast trending Kopili fault was found to be  $3.0 \pm 1.5$  mm/year with dextral motion, consistent with the earthquake focal mechanisms in the region.
- The limited GPS observations and knowledge about crustal deformation in EHS pose a gap in a comprehensive understanding of its geodynamics. Focusing on the geodynamic setup of EHS in relation to the Tibetan Plateau and Burmese, Singh and Kumar (2013) analysed the data of four permanent GPS sites located in the Mishmi Complex of EHS. Considering the EHS as a stable block, they estimated the crustal velocity of the Tibetan Block and the North and East China Blocks. The study highlights that the Mishmi Block is moving with a very slow rate of  $\sim 2.36$  mm/yr, compared to the eastern Tibetan block and the Burmese arc, and it accommodates the maximum strain (after the 1950 Great Assam earthquake of  $M_w 8.7$ ).
- In another study, Barman et al. (2016) estimated the current inter-seismic deformation of the Kopili fault zone in northeast India and slip rate of the fault. The study reveals that the sites in the Assam region move with an average velocity of 9–10 mm/

yr towards the south of southeast in India-fixed reference frame (Fig. 4). The rate of change in the baseline length of observation sites across the Kopili fault shows E-W convergence of  $\sim 2.0$  mm/yr across the fault. The study further shows an average right-lateral slip of  $2.62 \pm 0.79$  mm/yr and a shallow locking depth ( $3 \pm 2$  km) for the Kopili Fault. It is also hypothesised that the slip of the Kopili fault is contributing to seismic moment accumulation of  $\sim 70.74 \times 10^{15}$  Nm/yr, which is good enough to produce large earthquakes ( $M_w \geq 5.17$ ) in future (Barman et al. 2016).

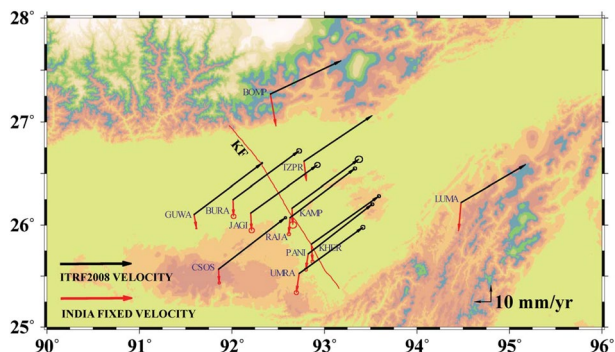
- Bisht et al. (2020) computed GPS velocity with respect to the 2008 International Terrestrial Reference Frame (ITRF 08) using data from six permanent sites in the EH region. The study shows that the Indian plate is moving towards the NE with an average velocity of  $46.95 \pm 0.23$  mm/yr. They also report the higher movement of India towards the eastward direction ( $36.11 \pm 0.17$  mm/yr), compared to the northward direction ( $29.02 \pm 0.16$  mm/yr).

### 3.4 Crustal conductivity imaging

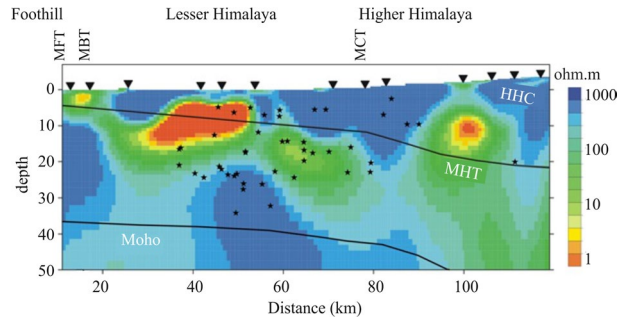
Magnetotellurics (MT) is an effective tool to penetrate deeper depths and investigate the lithospheric structure and inhomogeneity. Such studies have been taken up in different corridors of the EH. In the Sikkim Himalaya, Patro and Harinarayana (2009) and Kumar et al. (2014) carried out MT studies to derive the conductivity distribution within the collision regime. MT soundings were undertaken at 18 sites along a 120 km long traverse (Siliguri to Yumthang), in the Sikkim region. Data analysis and modelling reveal the presence of a conductive zone representing Siwalik sediments beneath MFT and MBT, which extends down to crustal depths of  $\sim 10$  km. The crustal column on the Indian side is reported to be modelled as a resistive segment (Fig. 5). The study also highlights the presence of a conductive zone in the higher Himalaya, i.e. north of the MCT, which is interpreted to be the electrical signature of the MHT (Patro and Harinarayana 2009). The conductive nature of the MHT in higher Himalaya is suggested to be due to the presence of metamorphic fluids. Further, it is reported that the region north of MCT is characterised by a highly complex structure with a mix of conductive and resistive layers (Kumar et al. 2014).

A similar study conducted in the Manabhum area of Arunachal Pradesh by Harinarayana et al. (2005) reported varying electrical resistivity throughout the region. It shows electrical resistivity of 50–300  $\Omega$  m for the top alluvium, moderate resistive layer with varying thickness (few metres to 4 km), followed by more conductive formations (10–20  $\Omega$  m). These high conductive formations are followed by more resistive layer, probably

**Fig. 4** ITRF2008 and India-fixed velocities drawn from campaign and permanent GPS sites (after Barman et al. 2016)



**Fig. 5** 2-D electrical images in the Sikkim Himalaya across the MCT (after Patro and Harinarayana 2009). Filled black stars represent the earthquake locations



the basement, with  $65\text{--}700\ \Omega\ \text{m}$ . In the Shillong plateau and Brahmaputra valley, Gokarn et al. (2008) carried out MT imaging using twenty-six broadband MT stations for over 200 km profile. Their study has delineated the Dauki fault as a NE-SW striking thrust with a low dip angle; similarly, another thrust zone sub-parallel to the Dauki fault zone has been observed in the Brahmaputra valley. Further, the study suggests that the Shillong plateau acts as a supracrustal block and not participating in the subduction process.

### 3.5 Paleoseismological investigations

Paleoseismological investigations have proved to be very helpful in studying historical and pre-historical earthquakes and their return periods. The eastern region has experienced a few historical earthquakes, and some recent paleoseismological studies have highlighted interesting results. For example, the study carried out by Rao et al. (2017), based on trenches at Pasighat, Arunachal region has provided chronological constraint on the paleo-earthquake surface rupture and suggested that the 1950 (Mw 8.7) Assam earthquake did break the eastern Himalayan front and produced a co-seismic slip of  $5.5 \pm 0.7\ \text{m}$ . Another recent study from Pasighat (Coudurier-Curveur et al. 2020) inferred uplift and abandonment of terraces of elevations between  $2.6 \pm 0.1\ \text{m}$  to  $7.3 \pm 0.1\ \text{m}$  and  $11.5 \pm 0.1\ \text{m}$ . Similarly, another episode of surface rupture was reported from the trench studies (across a scarp in Himebasti Village) on the eastern bank of the Subansiri River along the MFT (Pandey et al. 2021). The causative earthquake was believed to have occurred in the age ranging between 1655 and 1826 CE and it is further argued that the most recent rupture at Himebasti occurred after 1450–1650 A.D. The scarp shows  $\sim 6.8\ \text{m}$  of vertical separation and a dip-slip displacement of 11.2 m. It was further suggested that the scarp was formed by the historically reported 1697 CE Sadiya earthquake. The study also suggests rupture of adjoining segments due to two major events that occurred within a time interval of about 250 years.

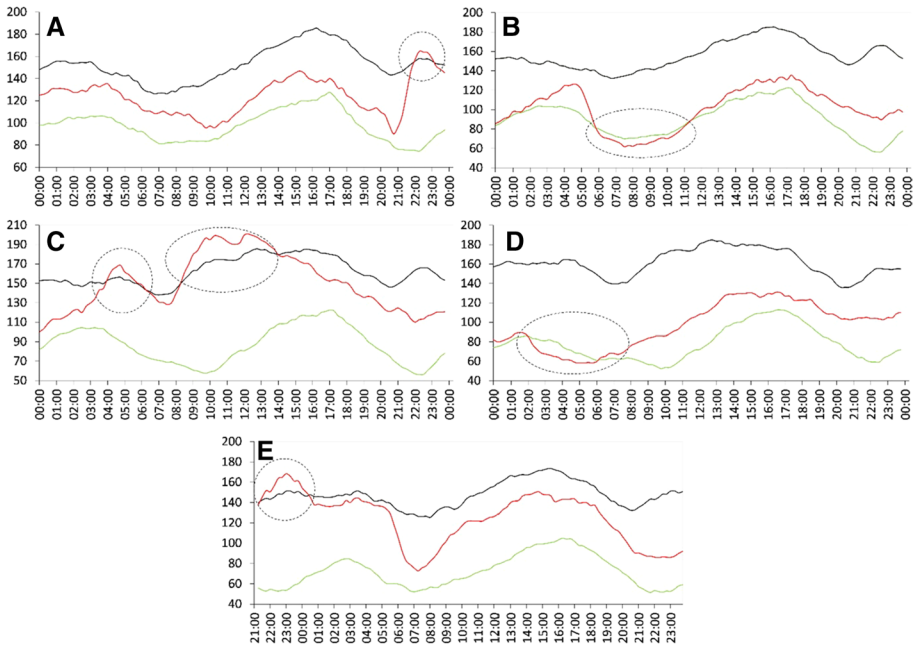
### 3.6 Earthquake precursory studies

Prediction of earthquakes on a scientific basis about their location, magnitude, and time is still not possible anywhere in the world. There have been consistent efforts to predict earthquakes by countries like the USA, Japan, China, and Russia for more than 60 years. However, by and large, the anticipated success rate could not be achieved. Of late, the study of earthquake precursors has been recognised as a promising area of research. A precursor is defined as a quantitatively measurable change in an environmental

parameter that occurs before a main event and is assumed to be linked to the preparation of the mainshock (Wyss and Booth 1997). Several precursors associated with geophysical, geochemical, hydrological, seismological, atmospheric, and geodetic anomalies have been reported during moderate and large earthquakes in the past. Details of earthquake precursors and the progression of earthquake precursory studies in India have been discussed by Bansal and Verma (2018). Quite a few new land and space-based techniques, including GPS-based geodesy, radar interferometry, and microgravity, are now being used for identifying possible earthquake precursors (Verma and Bansal 2012b). The earthquake precursory studies in India though initiated long back, the systematic studies started with the launch of a dedicated national programme by the Ministry of Earth Sciences to take this initiative forward systematically (Verma and Bansal 2012b). This program is aimed at acquiring long-term datasets on multi-parametric geophysical observations in selected regions, considered seismically active, to study the precursory behaviour in relation to earthquake occurrence and prepare a predictive model. To achieve the goal, a few multi-parametric geophysical observatories (MPGO) were set up at selected locations. The first MPGO in the country was setup at Ghuttu, Uttarkhand State of northern India through Wadia Institute of Himalayan Geology, Dehradun. Later, a few more MPGOs were established in different parts of the country (e.g. Shillong, Manipur and Gujarat). One such observatory has been established in the Mikir hills (Assam), eastern Himalaya. The observatory is equipped with Seismograph, Accelerograph, GPS, MT system, Magnetometer, Radon and Helium monitoring systems, etc.

Simultaneous continuous measurements of multidisciplinary parameters have been useful in characterising the time variability of each parameter. The parameters related to Total Electron Content (TEC), magnetic field variations in Ultra Low Frequency (ULF) range and other magnetic and resistivity observations have shown anomalous behaviour or changes at the time of occurrence of a few moderate size earthquakes at local epicentral distance, particularly, within 100 km. Chetia et al. (2020a) investigated soil radon (Rn-222) emanation, geomagnetic total field intensity (Btotal) and TEC prior to the September 2018, Kokrajhar (Assam) earthquake of magnitude  $M_w$  5.5. It is reported that the anomaly in soil Rn-222 continued for about 50 days (Fig. 6) and 26 days in Btotal (Fig. 7) before the occurrence of this event. The TEC anomaly was also reported to have persisted for about two weeks prior to the earthquake. In another related study, apparent resistivity imaging has been carried out for a fixed interval time of 3 days to examine the precursory signature before the earthquake event (Chetia et al. 2020b).

The above studies clearly demonstrate that there are substantial positive field-based examples (ground observation data like He, Ra, gravity, magnetic field, TEC, resistivity, surface temperature, etc.) which evidently show precursory signals prior to the earthquake occurrence. However, all these studies are being done in hindsight. Since the earthquake phenomenon is nonlinear and even two earthquakes at the same location may have different characteristics, it makes it difficult to use these precursory signals in real-time forecast. Therefore, understanding and quantification of the complexities involved in establishing a correlation between different precursory signals and earthquake occurrences is a priori requirement. We believe that a focused approach to analyse the past data with the latest tools like, Artificial Intelligence (AI), Machine Learning (ML), and the Internet of Things (IoT) will help in achieving the goal. Further, strengthening of MPGO observations with in-situ measurements of magneto-telluric recordings, besides monitoring other geophysical parameters, will be useful in drawing meaningful inferences. Also, we envisage that these measurements with add-on facilities will further

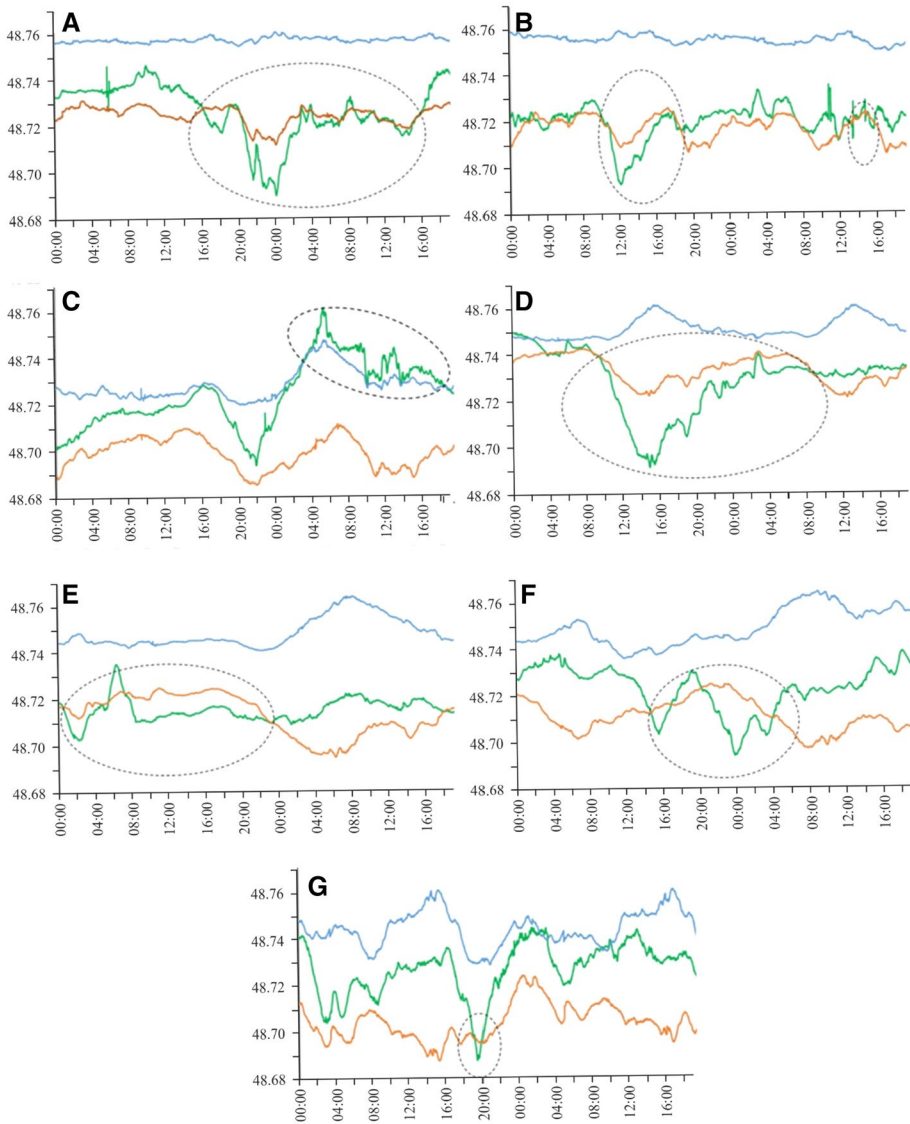


**Fig. 6** The plot depicts anomalies in soil Rn-222 emanation at different time period—(A) 24-July-18, (B) 28-July 2018, (C) 29-July-2018, (D) 4-August-18 and (E) 29-August-18 to 30-August-18 (after Chetia et al. 2020a, b). The horizontal axis (x-axis) represents time on the respective date and the vertical axis (y-axis) represents soil Rn-222 emanation in  $\text{KBq/m}^3$ . The Black, Red and Green line represents Upper Boundary (UB), soil Rn-222 and Lower Boundary (LB), respectively. The anomalies in the soil Rn- emanation during the time period is represented by the dotted sphere

help in validating interlinked parameters and standardising the role model configuration of MPMO, which could be replicated in other parts of the country.

### 3.7 Landslide susceptibility mapping

The landslide investigations in the EH region have been carried out since 1899, when Thomas Oldham of the Geological Survey of India (GSI) studied the landslide-affected area of Darjeeling town after a devastating landslide event on September 24th, 1899. Since 1950, GSI has been engaged in landslide and slope stability studies in the Darjeeling-Sikkim Himalaya and has generated a rich spatial landslide geo-database (Ghosh 1950; Dutta 1966; Sinha et al. 1975). Soon after the 2013 Uttarakhand disaster, a major programme on National Landslide Susceptibility Mapping (NSLM) was initiated. Under this initiative, landslide susceptibility mapping on a macro-scale (1:50,000) of all the landslide-prone areas in the Darjeeling-Sikkim Himalaya (7960 sq. km.) has been completed. In this exercise, about 4931 active landslides were mapped (1560 landslides in the Darjeeling Himalaya and 3371 landslides in the Sikkim Himalaya). The landslide susceptibility map classifies the whole mountainous region into three different zones viz., low, moderate, and high, based on the likelihood of susceptibility to landslide initiation (Fig. 8), (<https://bhukosh.gsi.gov.in/Bhukosh/MapViewer.aspx>). Data are also virtually shared via Web Map Service

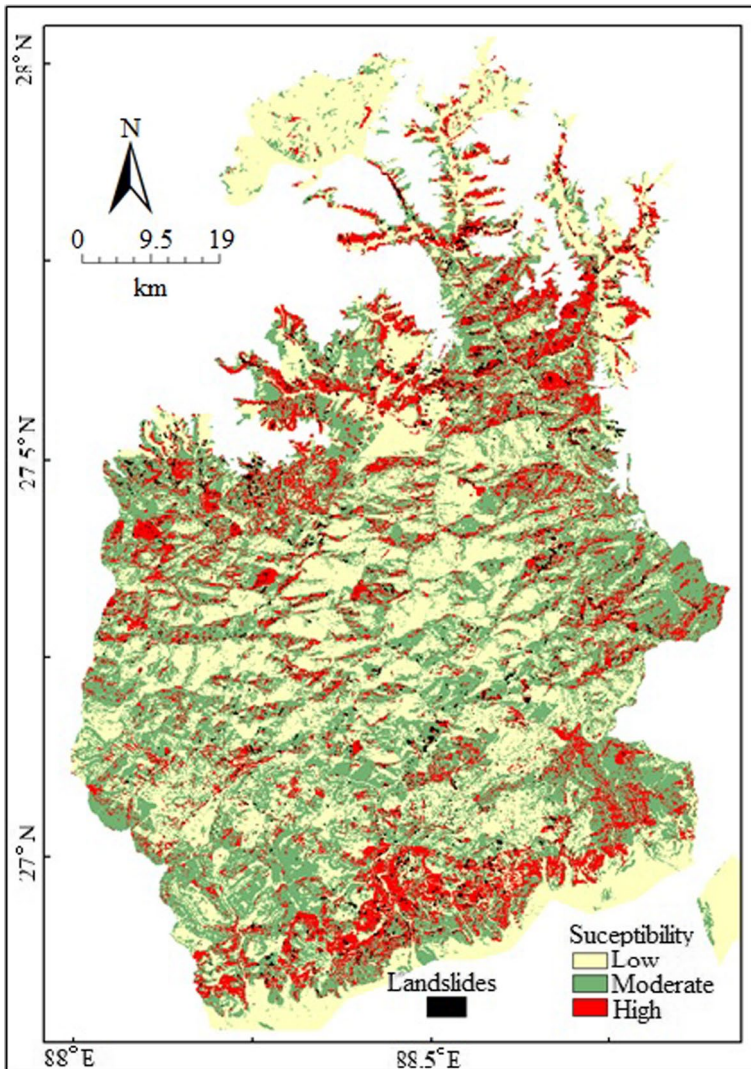


**Fig. 7** The plot shows anomaly in the geomagnetic total field intensity ( $B_{\text{total}}$ ) at different time period—(A) 16-August-18 to 17-August-18, (B) 18-August-18 to 19-August-18, (C) 26-August-18 to 27-August-18, (D) 27-August-18, (E) 28-August-18, (F) 8-September-18 to 9-September-18 and (G) 11-September-18 to 12-September-18 (after Chetia et al. 2020a; b). The horizontal axis (x-axis) represents the time of the day and vertical axis (y-axis) represents the  $B_{\text{total}}$  in  $\mu\text{T}$ . The Blue, Green and Red line represents the Upper Boundary (UB),  $B_{\text{total}}$  and Lower Boundary, respectively. The anomaly in the  $B_{\text{total}}$  at different time is shown by the dotted black sphere

(WMS) with the National Disaster Management Authority’s (NDMA) web portal for integration into respective states’ disaster management plans.

It is evident from Fig. 8 that in the Darjeeling Himalaya, about 17% of the area falls in “High” susceptible zone, containing 53% of landslides, followed by another 41% of the





**Fig. 8** Landslide susceptibility map of Darjeeling–Sikkim Himalaya ( Source: <https://bhukosh.gsi.gov.in/Bhukosh/MapView.aspx>)

area in the “Moderate” susceptible zone, containing 33% of landslides, and the remaining 42% of the area is in the “Low” susceptible zone, with 14% of historical landslides. Similarly, the landslide susceptibility map (1:50,000) of Sikkim Himalaya categorises 18% area into the “High” susceptible zone, which contains 65% of the historical landslides, followed by 42% area classified as “Moderate” having 30% landslides and 40% area in the “Low” susceptible zone with 5% of the historical landslides. Further, mesoscale (1:10,000) landslide susceptibility zonation has also been carried out for Kalimpong, Mirik, and Chibo (Karmakar et al. 2017) townships, the Gorubathan-Lava-Algarah-Rishi road corridor, as well as site-specific studies of 24 major and perennial landslides, suggesting relevant

remedial measures (Paul and Ghoshal 2009). In the Sikkim Himalaya, site-specific (1:1000 scale) landslide studies were carried out for 26 major and perennial landslides with remedial measures (Ghosh et al. 2014a, b). A study by Rawat et al. (2017) has also prepared the landslide hazard zonation map and reported that the 71.24% area of the Sikkim region falls under moderate to very high landslide hazard zone.

GSI and other researchers have also carried out studies on the landslide hazard and risk related to the Arunachal Himalaya. For example, Pandey et al. (2008) reported that 38.7% of the area of Arunachal Himalaya falls under moderate to very high landslide hazard, whereas the remaining 61.3% falls under the low to very low hazard. The study by Patanaik et al. (2019) shows the Mechuka valley of the Arunachal Himalaya as a region of moderate to high landslide susceptibility. Under the NLSM programme of GSI, landslide susceptibility mapping on 1,50,000 scale for Arunachal is in progress and shall be completed soon. Also, GSI has carried out a macro-level landslide hazard zonation along the highway from Bhalukpong to Bomdila, West Kameng district, Arunachal Pradesh (Singh et al. 2014). Besides, numerous landslide susceptibility maps for several smaller areas and national highways have been prepared by GSI. (<https://www.gsi.gov.in/webcenter/portal/OCBIS/pageGeoInfo/pageLANDSLIDEHAZRD>).

### 3.8 Early warning systems

An early warning system is one of the key components of the overall mitigation effort to deal with any natural hazard. Many countries, like, the USA, Japan, Taiwan, etc. have designed and developed early warning systems for earthquakes. However, certain issues still remain unresolved in perfecting the system. Minson et al. (2019) discuss in detail the limitations of earthquake early warning. On the contrary, the early warning systems for landslides are well established and are being successfully used by many landslide-prone countries, like, Italy, Switzerland, Norway, Scotland, China, Taiwan, etc. However, according to a review of the performance of landslide early warning systems (LEWSs) based on a critical analysis by Guzzetti et al. (2020), only five nations, 13 regions, and four metropolitan areas have truly benefited from LEWSs, while many areas with a high incidence of fatal landslides and a high risk to the population lack LEWSs. Some efforts have been made in India towards developing and setting up the LEWS in the EH region. A brief description of these efforts and other recent advancements is summarised in the following section.

- A prototype regional landslide early warning System has been developed by the Geological Survey of India through an ongoing collaborative international research programme “Landslide multi-hazard risk assessment, preparedness, and early warning in South Asia integrating meteorology, landscape, and society”. The LEWS is under testing in Darjeeling, West Bengal, and under this endeavour, experimental daily landslide forecast bulletins were issued by the GSI to the local administration every day in the year 2020 during the monsoon period. The ground validation of regional LEWS showed encouraging results. This system is planned to be tested for a few more monsoon years for further validation and fine-tuning of the model parameters, prior to declaring it operational. Similar systems are also planned to be installed in the Kalimpong district of West Bengal and Sikkim in near future.
- Aimed at advancing Integrated Wireless Sensor Networks for Real-time Monitoring and Detection of Disaster, Amrita University, Kerala, has designed and developed an Internet of Things (IoT) system for effective early warning of landslides. The

IoT system established in Chandmari (in Sikkim), consists of various sensors that measures the meteorological, geophysical, and hydrological parameters, etc. The deep earth probe designed and developed integrates the sensors for measuring rainfall, moisture, pore pressure, strain, tilt, and vibrations for effective understanding of the progress of imminent landslides. Also, a multi-level landslide early warning model (site-specific) has been developed based on real-time data analysis, machine learning and artificial intelligence techniques. The adaptive decision for landslide warning is derived using multiple heterogeneous models for specific sensors, learning models which integrate the spatio-temporal behavioural changes experienced by heterogeneous sensors, slope stability models, forecasting models, etc.

- In recent years, the use of Synthetic Aperture Radar (SAR), particularly interferometry SAR (InSAR), has emerged as a well-established technique in landslide monitoring, identification of precursory signatures for catastrophic slope failures, forecasting and early warning (Carlà et al. 2019; Chae et al. 2017). InSAR's ability to day-and-night observation, remote area detection, cloud-free and wide-swath datasets makes it a potential and powerful tool for early detection of landslide-critical conditions (Moretto et al. 2021). However, there are still limitations and challenges, both technical and operational, which need to be overcome to implement landslide forecasting (Moretto et al. 2021).
- The seismic signals also play an important role in monitoring the landslides and help progress towards potential early warning for catastrophic landslides. For example, Cook et al. (2021) studied the 2021 Chamoli landslide in the Garhwal Himalaya and identified three phases of movement, viz., initial rock slide, debris flow, and the flood, based on the seismic recordings. The flood reached the closest settlements ~ 15 min after the initial failure, suggesting the possibility of an early warning. Such studies may be useful in other landslide-prone regions like, EH for landslide monitoring, modelling, and forecasting. Moreover, like InSAR, there are many challenges in automated data processing, precise locations of landslides, and establishing an effective landslide early warning system using seismic signals (Cook et al. 2021).

### 3.9 Development of earthquake scenario

Earthquake scenarios are widely used to better understand and help plan strategies for the reduction of future losses. A successful scenario tells the story of a defined earthquake and its specific impacts (Gupta et al. 2020). It helps decision makers and the public at large to visualise specific impacts that are based on current scientific and engineering knowledge. Gupta et al. (2020) discuss in detail the initiatives taken by the National Disaster Management Authority (NDMA), Government of India, in collaboration with other agencies to create earthquake scenarios for the repeat of the 1905 Kangra earthquake of  $M \sim 8$  and the 1897 Shillong earthquake of  $M 8.7$ . Wyss et al. (2017) have also carried out such a study for repeat of 1905 Kangra earthquake and reported that the population strongly affected (intensities  $> VI$ ) by such an event would be around 33 million. The estimated fatalities would be 2 million, with three times as many injured. For the NE India, Gupta et al. (2020) estimated human loss of ~0.43 million for the repeat of the Shillong  $M 8.7$  earthquake in the mid of the night. Implementation of such studies and exercises in EH will help in preparing locale-specific strategies.

### 3.10 Education, awareness and community participation

Mass awareness, education and community participation are integral parts of the overall strategy to minimise the losses and destruction due to future large earthquakes and landslides. The Government of India, through academic institutions, universities and Central and State Disaster Management Authorities, has implemented several programmes on education, and awareness. For example, a specific programme on School Earthquake Laboratory Programme (SELP), aimed at creating linkages between research organisations and schools, involving the students and teachers in data collection, its analysis, and generating first-hand information on earthquakes, was implemented in selected areas in the NE and NW Himalayan region, Western India, and in some parts of southern India. Under this programme, low version broadband seismographs were installed in selected schools, mainly operated by the students with the help of their teachers. The SELP has been a very successful venture, not only for basic earthquake education and creating awareness about earthquakes amongst the students, their parents, teachers, etc., it enthused the students for higher learning as well in this field (Bansal and Verma 2012). The parts of eastern Himalayan states, Assam, Nagaland, Sikkim, Arunachal Pradesh, etc. were covered under this initiative. The National Institute of Disaster Management, National Disaster Management Authority and State Disaster Management Authorities have been regularly conducting various training and awareness programmes for engineers, architects, local construction bodies and administration on different natural hazards, including earthquakes and landslides. Community participation has also largely been brought into the system to deal with natural disasters. The NDMA started a regular program, in the form of tabletop exercise, for local state administration with the goal of sharing the information about specific hazards as well as getting their feedback on implementation and constraints, etc. This has been encouraged in the year 2020, especially during the COVID-19 pandemic.

### 3.11 Concluding remarks and future perspectives

Earthquakes and landslides have been occurring since times immemorial in the eastern Himalayan region, necessitating continuous monitoring and putting in place the appropriate measures to minimise the losses due to such events. The earthquakes, which are presently unpredictable, remain a cause of major concern. However, various initiatives outlined in the preceding section have helped taking the necessary measures towards reduction of losses due to such events. For example, augmentation of the seismological network has facilitated detection and locating of earthquake events down to magnitude 3.0 in the region. The network, with VSAT connectivity between field stations and the central receiving station and automation in data processing, enabled estimation of earthquake parameters and disseminating the information to stakeholders within ~ 10 min, which is well comparable with global seismological networks like the U.S. Geological Survey (USGS), European-Mediterranean Seismological Centre, National Earthquake Information Centre, etc. Similarly, the GPS observations along the plate boundary and within the Indian plate have helped in constraining of the movement of Indian plate and estimating the convergence rates in different parts of the region. The studies presented in this paper enabled quantification of Indian plate motion, convergence rates, and strain buildup along major faults. The results presented related to the microzonation of different cities will not only provide the critical inputs for earthquake resistant design of structures, but will also help the disaster

management authorities in land use and urban planning. On the other hand, initiatives like simultaneous observations of different geophysical parameters, described under Earthquake Precursory Research, have opened up a new window for geoscientists to analyse the records to search for the possible precursors and establish their correlation with earthquake occurrence. The MPGO at Tezpur, Shillong and Imphal have produced very useful data to help correlate different anomalies ( $R_n$ ,  $H_e$ ,  $B_{total}$ ,  $TEC$ ,  $\rho$  etc.) with earthquake occurrence. Studies on crustal conductivity imaging and paleoseismological investigations at specific locations have aided in determining the zones with fluid presence and quantification of co-seismic slips during historical earthquakes and their return periods, respectively. In addition, data generated through these initiatives in the last 10–15 years made it possible to undertake specific studies like, earthquake source characteristics, computation of velocity vectors and strain budget, crustal structure, electrical conductivity structure and numerical modelling, developing attenuation relations, simulation of ground motion, estimation of probabilistic hazard etc.

Similarly, the efforts made towards precise mapping of landslides, their zonation and monitoring have helped in better understanding of causes and effects in broader terms and the correlation of specific properties like rainfall, type of soil, topography and anthropological attributes with the occurrence of landslides. The knowledge gained is being utilised in developing better techniques to arrest as well as reinforce the existing landslides and issuing early warning about them at selected locations.

In summary, various initiatives and studies presented in the paper have not only helped in understanding and dealing with the geological hazard, but also enabled identification of study-gaps in this part of the Himalayan region like, knowledge of hidden faults and their depth traverses, mapping of active faults and their characterisation, and science communication, etc. Accurate assessment of hazard levels on larger scale for both earthquakes and landslides is essential for improving our methodology and techniques for better preparedness to deal with these hazards. Also, the gap between research and practise needs to be reduced through science communication. Here, we suggest that, in addition to the ongoing activities, the following initiative will be useful in preparing a strategy for better mitigation of the geological hazard in the region.

1. Strengthening of landslide monitoring and setting up of landslide early warning systems at the most vulnerable sites, to start with.
2. Strengthening of multi-parametric geophysical observatories with add-on observations.
3. Augment GPS measurements across all the major structural features (Lineament/Faults) and evaluation of the current state of stress accumulation.
4. Monitoring, mapping, and characterisation of local/hidden active faults and using this information in overall design and construction of vital structures in their vicinity.
5. Processing and analysis of MPGO data in near real-time in an integrated manner to draw meaningful conclusions and apply the of the latest data analysis tools like AI and ML.
6. Augment advanced radar remote sensing (e.g. InSAR) along with ground and space-based GPS measurements for deformation modelling (e.g. earthquakes), landslide monitoring and early warning, etc.
7. Continue locale-specific geophysical and geological studies for imaging, crustal deformation, seismogenesis, etc. to further refine the knowledge.
8. Develop earthquake scenarios to estimate anticipated damage and losses for advance planning and effective management.

9. Use of existing and updated landslide susceptibility and microzonation maps to regulate land use in hilly regions.
10. Conducting training on the use of local building materials and teaching the masons, engineers/architects about best practices.
11. Undertaking awareness campaigns on a regular basis for the local public through mock drills and organising lectures by the Engineering and Geoscience community about the vulnerability and “do’s and don’ts” regularly.

Taking advantage of the data accrued and the recent studies about the earthquake potential of major lineaments/faults in the region, the concentration of future efforts around specific sites will maximise the outcome. Some of the steps towards achieving the above-mentioned actions have already been initiated, especially towards strengthening of the national seismological network, mapping of active faults, and development of landslide early warning system in collaboration with the countries like Italy, the UK and Norway, etc. These efforts will go a long way to help reduction of losses and damage due to future earthquakes and landslides.

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## Declarations

**Conflict of interest** We do not have any conflict of interest, financial or non-financial that are directly or indirectly related to the work submitted here for publication.

**Ethical approval** The study followed the accepted principles of ethical and professional conduct throughout the research work. No animals or human participants are involved in this research.

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