1 Introduction

Natural disasters inflicted by earthquakes, landslides, flood, drought, cyclone, forest fire, volcanic eruptions, epidemics *etc*. keep happening in some parts or the other around the globe leading to loss of life, damage to properties and causing widespread socio-economic disruptions. EM-DAT, a global disaster database maintained by the Centre for Research on the Epidemiology of Disasters (CRED) in Brussels, records more than 600 disasters globally every year (http://www.cred.be). Earthquakes are the major menace to the mankind killing thousands of people every year in different parts of the globe. An estimated average of 17,000 persons per year has been killed in the 20th century itself. Statistics taken for the period 1973-1997 (http://www.cred.be), organized in 5-year bins, exhibit that earthquakes are amongst the disasters with larger death impact as depicted in Figure 1.1 even though the occurrences of flood events are twice per year. According to the International Disaster database (*i.e.* CRED) the total human fatality occurred in Asia for the period between 1900 to 2015 is estimated to be 18,23,324 persons while in case of only the Indian subcontinent the casualty is estimated to be around 78,209 with total economy loss of 5222.7 million (US$). Thus earthquakes are considered to be one of the worst among all the natural disasters.

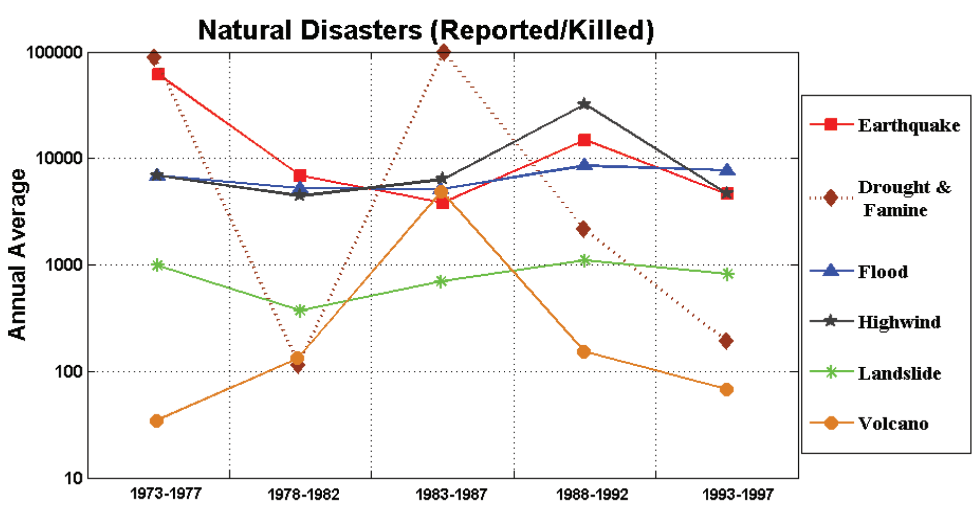


Figure 1.1 **Comparison amongst different types of natural catastrophes (after Ansal, 2004).**

A comparative analysis performed by CRED in terms of total damage in billions of US$ reportedly caused by natural disasters as shown in Figure 1.2 illustrates that Asia is more prone to earthquake disaster than any other continental regions in the world.

From the global earthquake perspective, the 21st century began quite ominously due to the occurrence of some great earthquakes causing damage both in terms of fatalities and

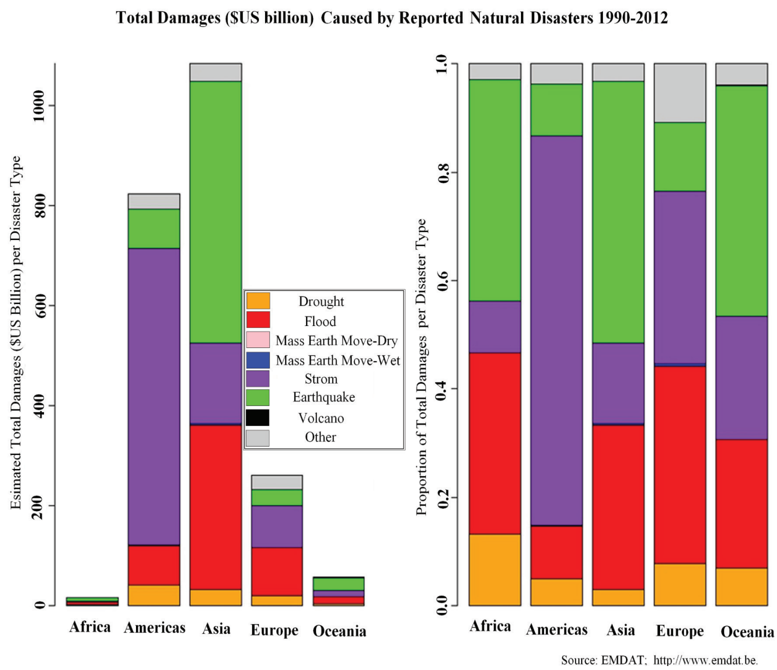


Figure 1.2 **Total damages (US $billion) reportedly caused by natural disasters (source: EMDAT, http://www.emdat.be).**

socio-economic context. In 2001, the Bhuj earthquake of M_w 7.7, killed around 20,085 people with 1,66,836 injuries, approximately 3,39,000 buildings destroyed and 7,83,000 damaged in the Bhuj-Ahmadabad-Rajkot area and other parts of the region. In 2003, the M_w 6.6 Bam earthquake occurred in southeastern Iran which killed 31,000 people, rendered 30,000 injured, 75,600 homeless and 85 percent of buildings damaged or destroyed in the Bam region. The greatest earthquake of the century occurred in 2004, the M_w 9.1 Sumatra-Andaman earthquake which is the third largest earthquake in the world since 1900 and the largest since 1964. In total 2,27,898 people were killed or missing, presumably dead and about 1.7 million people were displaced by the earthquake and the subsequent tsunami that propagated across 14 countries in South Asia and East Africa. In 2005, the M_w 7.6 Kashmir earthquake killed 86,000 people. The Wenchuan, China earthquake of M_w 7.9 occurred in 2008 which killed around 87,587 people and rendered around 3,74,177 injured. The 2010 Haiti earthquake of M_w 7.0 killed 3,16,000 people, rendered 3,00,000 injured, 1.3 million displaced, 97,294 houses destroyed and 1,88,383 damaged in the Port-au-Prince area and in most of southern Haiti. The 2011 Japan earthquake of M_w 9.0 killed 20,896 people and caused wide spread damage and destruction. This earthquake serves as a warning that even developed and well-prepared countries are not immune to terrifying disasters. Though large loss of life in earthquakes has been observed previously also, the occurrence of so many deadly earthquakes within a single decade is unprecedented. These deadly earthquakes have incited assumption that the planet has experienced the consequences of a large population growth in the 20^{th} century (Holzer and Savage, 2013). The global growth of population implies that earthquakes have become increasingly deadly because the expected number of earthquake disaster is proportional to the exposed population and their vulnerability components.

Though large earthquakes cause immense damage & destruction, it also provides an opportunity for the seismologists to get more insight into the internal structure of the earth to gain a better understanding of the mechanism of earthquakes. The studies carried out after the occurrence of strong earthquakes have provided basic knowledge and information on the phenomenon to provide necessary input for the assessment of seismic hazard and its possible mitigation. These post-earthquake surveys gave insight into the destructive pattern of earthquakes caused due to three complex processes. The first process is the solid earth system that is made of (a) seismic source, (b) propagation of the seismic wave through a medium, and (c) the local geology. The second process is the anthropogenic system that consists of the man-made structures like buildings, dams, bridges, tunnels *etc*. and the quality of construction and the last factor is the socio-economic development of the settlement before it is struck by an earthquake (Panza *et al.*, 2001). The amount of loss of life and damages to human properties not only depend on the magnitude of the earthquake but also on the aforesaid three processes. Due to the heterogeneous nature of the earth's crust, the seismic waves undergo multiple reflections, refractions and transformations along their path from the source to the site of observation. The changes are more prominent near the surface underlain by soil, where the geological and geotechnical properties of the soil layers play an important role in the amplification of the seismic energy.

Prediction of an earthquake has been a subject of controversy with divided opinions. Earthquake prediction gained momentum with the prediction of the Blue Mountain Lake earthquake in 1971 and the success claimed at Haicheng which occurred in 1975 but proved to be short lived. Sykes *et al.* (1999) gives an account on the possibility and limitation of earthquake prediction. Researchers like Geller (1997) and Main (1995) argue that short-term prediction with certainty is inherently difficult and that very high resolution is required for mitigation measures. Usually a time scale is involved that corresponds to long-term prediction considering an earthquake with a return period of 50, 100 or 500 years. Prediction of individual earthquake may not be possible but the long-term rates of earthquakes can be forecasted with considerable accuracy especially in the regions of high seismic activities, like the plate margins, such as Japan, Italy, Turkey, Mexico, and California.

Time and again, catastrophic earthquakes across the globe annihilate vast population and cause severe socio-economic breakdowns incurring substantial setbacks in the developmental efforts. They continue to pose significant threat to the sustainable development and growth of civilization. Scientific understanding of the phenomena is of vital importance for mitigation measures to withstand the impacts of the hazard. The seismic hazard paradigm embodies 'where', 'when' and 'how' the earthquakes occur, associated ground motions, and their effects on the structures (McGuire, 2004). In several cases, considerable damages are also caused by secondary effects such as tsunami, landslide, soil liquefaction, rockfall, and ground subsidence. However, structural engineering is based mostly on ground shaking intensity levels that act as primary hazard proxy. Seismologists, therefore, predict the ground shaking intensity from potential earthquakes to support building codes for seismic-resistant constructions, landuse planning, and earthquake insurance purposes. Earthquake occurrences do not have spatial uniformity entailing differential exposures to earthquake effects across large areas. Furthermore, intensities of ground motions also vary widely depending on regional tectonics and local geological conditions. By delineating zones of different hazard levels using state-of-the-art technology, we deliver knowledge products about the expected ground motion quantities.

The vulnerability of modern society towards earthquake hazard is increasing with time. Although the occurrence of earthquakes is inevitable, the reduction of the social and economic setback during earthquakes can be achieved through a comprehensive assessment of Seismic

Hazard Microzonation and Risk. This can be accomplished by creating public awareness and by upgrading or retrofitting the existing buildings & engineering structures and also taking appropriate measures in case of upcoming urban structures.

1.1 Earthquakes in India

India, with its unique geological setting and socio-economic conditions is highly vulnerable to disasters. Seismic vulnerability in India is well evidenced by numerous past earthquake-related calamities. According to the vulnerability atlas of India prepared by Building Materials and Technology Promotion Council (BMTPC), more than 59 percent of the total landcover in the country is susceptible to seismic hazard (BMTPC, 1997). Incidentally, India is the second most populous country in the world. On the other hand, unplanned urbanization is expanding rapidly across the country to accommodate the burgeoning population.

Information regarding earthquake magnitude and frequency are essential for proper assessment of seismicity of a region. There has been a consistent sequence of earthquakes in the Indian subcontinent since ancient times and it is one of the most earthquake prone regions of the world and is susceptible to the seismic vulnerability because of its high population, rapid development and unplanned urbanization. Most of the seismicity is concentrated along the 2500 km long Himalayan arc from Sulaiman-Kirthar zone to Arakan-Yoma subduction zone marking the plate boundary between the Indian and the Eurasian plates. The ongoing collision between these two plates has generated some of the devastating earthquakes in the history with magnitude above M_w 7.0 along the plate margin. In the recent times the occurrences of earthquakes in stable intra-plate region of Indian peninsula have also caused much concern. The earthquakes in peninsular India are of relatively lower magnitudes but are equally devastating as that of the Himalayan earthquakes. Although the earthquake history in India goes back to as early as mythological period approximately to 538 BC; the information about earthquakes occurring prior to 1900 is highly incomplete and the figures of earthquake related causalities in the country are mostly unknown (Bilham, 2004). There are several documented historical events which reveal that India has been affected time and again by earthquakes *viz*. 1819 Kutch earthquake of M_w~7.8 with estimated two thousand fatalities, 1833 Kathmandu earthquake of M_w~7.7 that caused about 500 deaths, 1869 Cachar earthquake of M_w~7.4, and 1897 Shillong earthquake of M_w 8.1 with death-count of over 1500 lives (Rajendran and Rajendran, 2001; Bilham, 2004; 2008; Ambraseys and Douglas, 2004). These earthquakes triggered disasters that destroyed large number of towns. During the last 100 years, major earthquake calamities that struck the country accounts for over 22 thousand deaths as given in Table 1.1. If the total-fatality count of the 2004 Sumatra earthquake is considered, the death tolls add up to over 43,000. Moderately sized earthquakes of $M_w<7.0$ in the country have also caused devastations apparently attributable to buildings not designed to resist probable earthquakes. This suggests that highly destructive and deadly earthquakes raised public outcry about high number of fatalities and thus lack of seismic hazard preparedness in the country.

The Indian subcontinent is characterized by several tectonic units *viz*. the Himalayan collision zone in the north, Indo-Burmese arc in the northeast, rift zones in the Peninsular Indian shield and

Table 1.1 **Major earthquake casualties reported during 1900—2015 in India and the adjoining regions**

Event (YYYYMMDD)	Magnitude (M_w)	Epicentral Region	Casualty report (Deaths)
19050405	7.8	Kangra, Northwest Himalayas	20000
19340115	8.1	Bihar-Nepal, Central Himalayas	10700
19350531	7.7	Quetta, Baluchistan	30000
19410626	8.1	Andaman, India	7000
19500815	8.6	Assam Earthquake	1526
19560721	6.0	Anjar, Gujarat	156
19660815	5.6	Moradabad	15
19671210	6.3	Koyna, South India	177
19750119	6.8	Kinnaur, Himachal Pradesh	47
19800823	5.5	Kashmir	15
19841230	5.6	Cachar, Assam	20
19880820	6.8	Udayapur, North Central India	700
19911020	6.8	Uttarkashi, Northwest Himalayas	2000
19930929	6.2	Latur, South India	9748
19970522	5.8	Jabalpur, Central India	39
19990329	6.6	Chamoli, Northwest Himalayas	103
20010126	7.7	Bhuj, Gujarat	20085
20041226	9.1	Sumatra, Indonesia	227898
20051008	7.6	Kashmir, Northwest Himalayas	86000
20110918	6.9	Sikkim, India	111
20150425	7.8	Nepal, India	9000

Andaman Sumatra trench in the southeast Indian Territory. Thus the subcontinent undoubtedly resonates as one of the most earthquake prone regions in the world. Bilham *et al.* (2001) pointed out that magnitude potential of the overdue earthquakes exceeds M_w 8.0 in most parts of the Himalayan terrain which is a matter of great concern. Feldl and Bilham (2006) also suggested that the rupture areas of recent smaller earthquakes in the region have possibility of nucleating into mega-earthquakes. The geodynamics of the Himalayan region has produced a number of complex tectonic provinces due to continued action of converging stress field in the last 40-50 million years since the collision. The colliding Indian plate compresses towards northeast at an average rate of 50 mm/yr. Incidentally, a fault or a fault-segment along the plate boundaries with previous history of large earthquakes which is passing through a quiescence period has been speculated as 'seismic gap' from where future large/great earthquakes are likely to occur (*e.g*. Sykes, 1971; McCann *et al*., 1979; Wyss and Wiemer, 1999). Using seismicity data and analyses Khattri (1987) established the existence of three seismic gaps along the Himalayas namely 'Assam seismic gap' the stretch between the 1897 Shillong and 1950 Assam earthquakes, ‘Central (Himalayas) seismic gap’ between the 1934 Bihar-Nepal earthquake and the 1905 Kangra earthquake, and ‘Kashmir seismic gap’ to the west of 1905 Kangra earthquake. Khattri (1999) concluded that there is 56% probability that a great earthquake (with M_w>8.5) may occur in the central seismic gap within the next 100 years. Bendick *et al.* (2007) and Gahalaut (2006) found that the recent 2005 Kashmir earthquake is not a gap filling one. However, the ‘seismic gap’ theory has been argued against in the recent times citing cases of failure upon tests producing unacceptable discrepancies between the observed and the predicted earthquakes (Kagan and Jackson, 1991; 1999; Nishenko and Sykes, 1993). Taking note of the occurrences of great earthquakes in the Himalayan terrains, 300–500 years recurrence for M_w~8.0 earthquakes can be projected. On the other hand, in the stable continental region of the peninsular India, earthquakes occur rather infrequently and are located in the seismogenic (and often blind) faults undergoing compressional strains. Furthermore, large earthquakes in the region have higher recurrence period running into millennia (Rajendran, 2000). The consequences of large earthquakes depend on its proximity to and the vulnerability of the built-up environment. As far as the earthquake hazard in the country is concerned, the present situation is rather alarming. Figure 1.3 depicts the locations of significant earthquakes, population data and urban coverage in India. It is apparent that large chunks of population are exposed to highly seismogenic tracts.

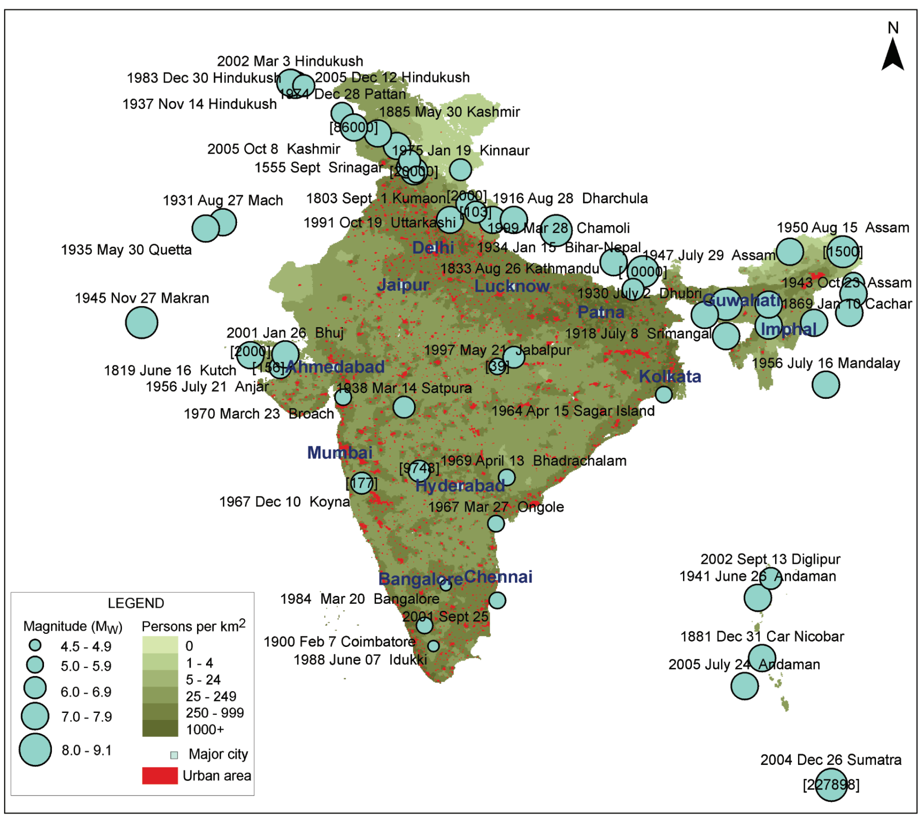


Figure 1.3 **Significant earthquakes in India and the adjoining regions depicted with approximate epicentral locations on the backdrop of population density distribution and urban coverage data for the year 2005 from the Center for International Earth Science Information Network (CIESIN, 2010).**

1.2 Seismotectonics of the Indian Subcontinent

The Indian subcontinent has a complex geological and tectonic setting that consists of Precambrian cratons of Archean age and rift zones filled with Proterozoic and Phanerozoic sediments (Biswas, 1999). The Indian subcontinent can be divided into three main sub-regions based on the geologic and tectonic regime:

(a) The Himalayan frontal arc in the north, which results from the Mesozoic subduction and the collision between the Indian and Eurasian plates. The great Himalayan arc extending from northwest to the Arakan-Yoma mountain ranges covering a distance of 2500 km.

(b) The Indo-Gangetic plains, which are located between the abruptly rising Himalayas in the north and the Indian peninsula in the south, and which extend from east to west. The sub-region is formed by the vast alluvial plains in the north along the basin of river Ganges and Sindhu (Indus).

(c) The Indian peninsula in the south, which comprises the Indian shield with the Deccan traps and the Dharwar cratons.

The seismotectonic regimes across India are significantly diverse and have been discussed in details by Kayal (2008), Balasubrahmanyan (2006), Gupta (2006), Dasgupta *et al*. (2000), Chandra (1978) amongst many. The Indian plate boundary encompasses transverse fault system

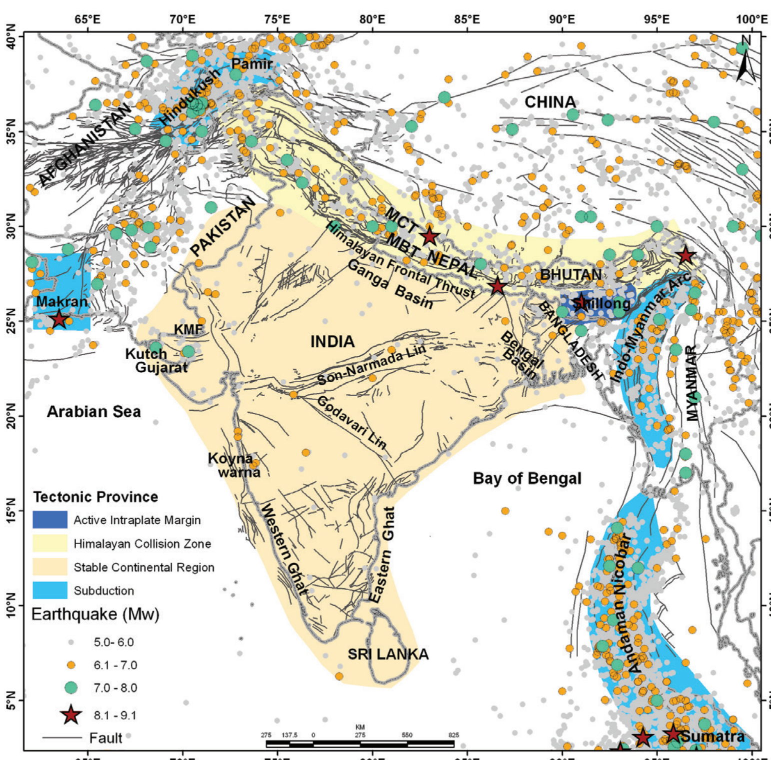


Figure 1.4 **Seismotectonic map of the Indian Subcontinent (modified after Dasgupta *et al.*, 2000; Nath and Thingbaijam, 2011a).**

of Chaman, Ornach Nal, and Sulaiman-Kirthar ranges to the northwest, the Himalayan arc to the north, complex under thrusting and subduction zones of Hindukush-Pamir to the northwest, Indo-Myanmar arc to the northeast, and Andaman-Nicobar-Sumatra tracts to the southeast. The seismotectonic map of India and its adjoining regions is given in Figure 1.4.

1.2.1 Great Himalayan Arc

The 2500 km stretch of the Himalayan arc extending from Kashmir in the northwest to Arunachal Pradesh in the northeast is considered to be the product of ongoing collision of the Indian and Eurasian plates which is a classic example of the continent-continent collision related mountain belt. The Himalayas have an E–W bow-like shape with trend reversal and higher elevations at the terminal ends comprising of Nanga-Parbat in the west (western syntaxis) and Namcha Barwa in the east (eastern syntaxis) (Mukhopadhyay *et al.,* 2011). The structure of the western syntaxis is expressed by a popup antiformal structure of N-W vergence with high-grade gneissic rocks of the Nanga-Parbat–Harmosh massif at its core. The Nanga Parbat is surrounded by Main Mantle Thrust (MMT) and bordered by Kohistan and Ladakh arc in the west and east which are accreted rocks of the Mesozoic Island arc system and to the north by rocks of the Karakoram arc along the Main Karakoram Thrust (MKT) (Naqvi, 2005). The eastern syntaxis defined by a popup antiformal structure verging towards the N-E in the eastern terminal end of the Himalayan arc is generally a small but sharp syntaxial bend compared to the western one. Sharma (1998) discussed the status of the geologic and the tectonic evolution in the light of new observations and data from the N-W Himalaya (Himachal, Garhwal, Kumaun) & Central (Nepal) Himalaya and divided the Himalayas into five well-known and generally accepted lithotectonic units *viz*. (1) the sub or outer Himalaya which forms the low altitude hills limited between Main Frontal Thrust (MFT) in the south and Main Boundary Thrust (MBT) in the north, (2) the lesser Himalaya limited between MBT in the south and Main Central Trust Vaikrita (MCT-V) in the north, (3) the great or higher Himalaya limited between MCT in the south and Tethyan Detachment Fault (TDF) in the north, (4) the Tethys Himalaya confined between TDF in the south and Indus-Tsangpo (ITS) in the north, and (5) the Trans Himalaya or Indus-Tsangpo suture zone consisting the obducted slices of the oceanic crust of the Neo–Tethys. The conceptual tectonic model of the Himalaya was initially suggested by Seeber *et al.* (1981), according to whom a steady state model is suggested that consists of a gently dipping Indian shield, the overriding Tethyan slab and the Himalayan sedimentary wedge which is decoupled from the two converging slabs where the MBT and MCT are considered to be active faults. The evolutionary model suggested by Ni and Barazangi (1984) argued that MCT is dormant now, but MBT is active. In the proposed model, the interface between the subducting slab and the Himalayan sedimentary wedge is named the plane of detachment. However, these two tectonic models are not strictly applicable in the entire Himalaya as in the Sikkim-Darjeeling Himalaya where both the Main Himalayan Thrust (MHT) and the Lesser Himalayan Duplex (LHD) are found to be active. The Seismogenesis beneath the Himalayan region is one of most challenging issues as also the earthquake mechanism of occurrence in various parts of the Himalaya, extending from N-W to N-E, which is not similar because of crustal and subcrustal/lithospheric heterogeneities with appreciable stress perturbation. The tectonic framework of the Himalaya extends from Kirthar-Sulaiman mountain ranges of the northwestern part of the Indian subcontinent where the major fault system is characterized by Chaman fault which is active along its entire length in NE-SW directions (Verma, 1991). The 1935 Quetta earthquake of M_w 7.6 is the major event that nucleated from the Chaman fault systems indicating a strike-slip focal mechanism (Singh and Gupta, 1980). The transcurrent motion of the Chaman fault has a major influence on the tectonics of this region, which is in contrast to the tectonic style in the Himalaya, where the dominant mode of tectonics is thrusting (Parvez and Ram, 1999). The Hindukush region joins the north-south striking western Pamir with the northeast-southwest regions. The focal-mechanism study of mantle earthquakes in the Hindukush Pamir region carried out by Billington *et al.* (1977) suggested subduction in two opposite directions where the Indian plate subducted under the Eurasian plate to the west and the Eurasian plate subducted under the Indian plate in the eastward direction. In the western Himalayan foothills most of the seismic activity related to MBT is along the Punjab thrust in the Kashmir Himalaya, the Jawalamukhi thrust, and the Nahan & Karol thrust in the Himachal Pradesh. In the Garhwal Himalaya teleseismically determined epicenters and locally determined earthquakes by Khattri *et al.* (1984) suggests that most of the seismicity is located to the north of MBT. Deeper earthquakes have hypocenters located between MBT and MCT that have thrust mechanism on the northward dipping planes. The Northeast Indian region is also characterized by high seismic activity. The seismotectonics of Northeast India region is considered to be more complicated (Nandy, 2001). This region presents a juxtaposition of two mobile belts, namely the E–W trending Himalaya due to collision between the Indian and the Eurasian plates, and the N–S trending Arakan Yoma belt due to the under-thrusting of the Indian plate below the Myanmar plate (Dasgupta *et al.,* 2003). The Mishmi region is traversed by Mishmi thrust, Lohit thrust, Po Chu, Tuting and Bame faults, Tsangpo and Tidding sutures. Because of the influence of seismic forces associated with both the eastern Himalayas and Indo Myanmar arc, the Mishmi region is considered as a special zone of seismic activity with block tectonics (Gansser, 1966; Dutta, 1964). The Shillong plateau is characterized by Dauki, Dhansiri, Dhubri, Sylhet, Dudhnai and Kulsi faults, the N-E trending Barapani Shear zone and the Mikir hills to the north. The Brahmaputra River separates the plateau from the Assam valley. The Brahmaputra basin lies on the northern territory edged by the NE-SW trending Naga thrust on the southeastern flank. The Kopili fault is etched on the middle of the Brahmaputra basin followed by Bomdila lineament on the northwest. The Disang thrust is seen southeast of Kopili fault and adjacent to Naga thrust. The 1100 km long Burmese arc is evolved due to the eastward subduction of the Indian lithosphere at the continental margin of the Asian plate. The Indo-Myanmar ranges, which are convex westward, act like a translational link between the Himalayan ranges and the Sunda arc to the south (Mukhopadhyay, 1984). The Indo-Myanmar arc, sidelined by Patkoi–Naga–Manipur–Chin hills, has been associated with oblique subduction seismicity with fault plane solutions of deep focus earthquakes. This ongoing convergence of the Indian plate with the Eurasian plate is considered responsible for the generation of some of the devastating earthquakes causing wide spread damage to the populated regions at the foothills of the Himalayas. The Himalayan region has been rocked by major earthquakes namely 1934 Bihar-Nepal earthquake of M_w 8.1, 1905 Kangra earthquake of M_w 7.8, 2005 Kashmir earthquake of M_w 7.6, 1991 Uttarkashi earthquake of M_w 6.7, 1999 Chamoli earthquake of M_w 6.5 and 1988 Bihar Nepal earthquake of M_w 6.8. The northeast India is one of the most earthquake prone regions in the subcontinent along the Himalayan arc. The region has been visited by several significant earthquakes, namely 1869 Cachar M_w 7.4, 1897 Shillong M_w 8.1, 1918 Srimangal M_w 7.6, 1930 Dhubri M_w 7.1, 1950 Assam M_w 8.7, and 1988 Manipur M_w 7.2 (Bilham and England, 2001; Rajendran *et al*., 2004; Ambraseys and Douglas, 2004; Thingbaijam *et al*., 2008). It has been delineated to be in Zone V of the seismic zonation map of India (BIS, 2002). The Global Seismic Hazard Assessment Programme also classifies the terrain in the zone of high seismic risk; moreover rapid urbanization during the last two decades in the region has increased the vulnerability towards potential seismic threats. The significant devastating earthquakes nucleated along the Himalayan arc are given in Table 1.2.

Table 1.2 List of significant earthquakes in the last two centuries along the Himalayan Arc

Location	Date	Magnitude (M_W)	Latitude (ºN)	Longitude (ºE)
Kumaun	September, 1803	7.7	30	78.0
Kashmir	May 30, 1885	7.5	34.1	74.6
Cachar	January 10, 1869	7.4	25.0	93.0
Shillong	June 12, 1897	8.1	26.0	91.0
Kangra	April 4, 1905	7.8	32.3	76.3
Dharchula	August 28, 1916	7.1	30.0	81.0
Srimangal	July 8, 1918	7.6	24.5	91.0
Assam	January 27, 1931	7.6	25.6	96.8
Bihar-Nepal	January 15, 1934	8.1	26.5	86.5
Assam	October 23, 1943	7.2	26.0	93.0
Assam	August 15, 1950	8.7	28.5	96.5
Kinnaur	January 19, 1975	6.1	32.38	78.49
Dharmshala	April 26, 1986	5.4	32.15	76.4
Manipur	August 6, 1988	7.2	25.13	95.14
Uttarkashi	October 19, 1991	6.8	30.77	78.79
Chamoli	March 28, 1999	6.5	30.38	79.21
Kashmir	October 8, 2005	7.6	34.38	73.47
Sikkim	September18, 2011	6.9	22.72	88.06
Nepal	April 25, 2015	7.8	28.17	84.70

1.2.2 Indo-Gangetic Plains

The Indo-Gangetic basin is formed as a consequence of flexing of the Indian lithosphere due to the continued northward push of the Indian plate and the thrust fold loading of the Himalayan orogen. The structural limit between the Indo-Gangetic plain and the Himalayan region in the north defined by the Himalayan Frontal Thrust (HFT), which is a direct consequence of the compression resulting from collision of Indian and Eurasian plates and present day principal displacement zone between them. The Indo-Gangetic plains constitute the vast alluvium plains of the Ganges (Ganga), the Indus (Sindhu), and the Brahmaputra and their tributaries, and separate the great Himalayan arc from the peninsular India. The Indo-Gangetic alluvium plain is the E-W trending tectonic basin located along the southern margin of the Himalayan fold belt. The central part being the Gangetic plain separated from the Indus plain by Delhi-Aravalli ridge in the west, and in the east from the Brahmaputra plains by Rajmahal hills. The other major subsurface ridges along the Indo-Gangetic plains are the Faizabad ridge, the Munger-Saharsa ridge and the Goalpara ridge (Kayal, 2008). The structural patterns and gravity observations suggest that these ridges are bounded by subsurface faults (Kayal, 2008). Some major faults identified in the Indo-Gangetic basin according to Seismotectonic Atlas of India (Dasgupta *et al.,* 2000) are the Hathusar Fault, the Mahendragarh Dehradun Fault, the Moradabad Fault, the Great Boundary Fault, the Main Frontal Thrust, the Lucknow Fault, the West Patna Fault, the East Patna Fault, the Munger-Saharsa Fault, the Garhmoyna-Khandaghosh Fault (GKF), the Jangipur-Gaibandha Fault (JGF), the Pingla Fault, the Eocene Hinge Zone (EHZ), the Debagram Bogra Fault (DBF), the Rajmahal Fault, the Malda-Kishanganj Fault, the Sainthia-Bahmani Fault, the Jamuna Fault *etc*. It is believed that most of the faults extend northward transversely to the Himalayan belt (Valdiya, 1976). Several earthquakes occurred in or in the close vicinity of the Indogangetic plain notably among them are the 1803 Garhwal earthquake of M_w 8.0, 1885 Bangladesh earthquake of M_w 6.8, 1930 Dhubri earthquake of M_w 7.1, 1934 Bihar-Nepal earthquake of M_w 8.1, 1935 Pabna earthquake of M_w 6.2, 1956 Khurja earthquake of M_w 6.7, 1964 Sagar Island earthquake of M_w 5.4, 1966 Moradabad earthquake of M_w 5.6 and 1988 Bihar-Nepal earthquake of M_w 6.8. While the occurrence of several moderate to large magnitude earthquakes suggests that the Gangetic plains are neotectonically active and so provide a possibility of generating potential earthquakes in the near future.

1.2.3 Peninsular India

The Peninsular shield of India is considered as the most prominent and largest Precambrian shield areas in the world, separated by the extensive Indo-Gangetic plains from the great Himalayan arc. Though the Himalaya region is dominated by compressional tectonics, the Indo-Gangetic Plain is a region of relatively less eventful sedimentary basin, the peninsular India, in contrast, is a region marked by early Archaean cratonization with associated Proterozoic belts with the cratons separated by ‘rifts’ (Mahadevan, 1994). The Peninsular India consists of gneiss and schists which are the oldest rock formations (Radhakrishna and Naqvi, 1986). The Precambrian rocks of India have been classified into two systems (Naqvi, 2005), the Dharwar system and the Archaean system. The Indian shield was described as the stable land mass associated with slight seismicity (Jaiswal and Sinha, 2007). The tectonic feature of the Indian Peninsular shield is considered to be made up of three major cratonic regimes namely, the Aravalli, the Dharwar, and the Singhbhum Protocontinents; these are separated by Proterozoic rifts and mobile belts (Burke *et al.*, 1978). The major prominent rifts are the Narmada Son Lineament and the Tapti Lineament together called the

SONATA (Son-Narmada-Tapti Lineament) zone separating the northern and the southern blocks of the shield. The other rift basins are the Kutch, Cambay, Godavari, Cuddapah *etc*. The northwest striking faults under the Deccan traps are believed to exist in this region (Chandra, 1977). The Cratons are the highly stable interior portion of the Peninsular shield like the Northern, Eastern and the Southern cratons. The Paleorifting regions containing large faults have experienced deformations in their most active phase, which are the Narmada, Cambay and Mahanadi grabens. The seismicity of this region is of intraplate nature and appears to be associated with some local faults and weak zones (Rao and Murty, 1970). Most parts of the Peninsular India are characterized by diffused seismicity. However, several localized seismicity associated with rift and shear/thrust zones can be observed. The Kutch province in the western India has been visited by large earthquakes, namely 1819 Kutch of M_w 7.7, 1956 Anjar of M_w 6.0, and 2001 Bhuj of M_w 7.7 (Bilham, 1999; Bendick *et al*., 2001). The Narmada–Son lineament trending ENE–WSW is a major tectonic feature in the Indian shield and has been associated with several major earthquakes, *viz*. 1927 Son-Valley of M_w 6.5, 1938 Satpura of M_w 6.2, 1957 Balaghat of M_w 5.7, 1970 Broach of M_w 5.4 and 1997 Jabalpur of M_w 5.8 (Rajendran *et al*., 1996; Singh *et al*., 1999; Mandal *et al*., 2000). The fault-plane solutions in the region indicate reverse faulting predominantly corroborating the compressional stress regime and the flexural force buildup within the entire Peninsular India (Bilham *et al*., 2003). However, other factors have also been suggested such as dehydration of serpentinites owing to high pore fluid pressure, fractured rocks at depth, isotropic diffusivity, high strain rate, and presence of weaker mantle (Rao and Rao, 2006; Manglik *et al*., 2008). The Latur region associated with 1993 Latur earthquake of M_w 6.2 also exhibits mainly reverse faulting (Rajendran *et al*., 1996). The Godavari-Graben region experienced 1969 Bhadrachalam earthquake of M_w ~5.7; otherwise, has low level of seismicity. The Eastern Ghat region has diffused seismicity with shallow focus earthquakes. On the other hand, the seismicity of the Western Ghat region clusters prominently in Koyna–Warna region and is characterized by moderate-to-strong earthquakes, *viz*. 1967 Koyna earthquake of M_w 6.3, 1993 Koyna earthquake of M_w 5.2, and 2000 Koyna earthquake of M_w 5.0. The earthquakes in the region have been attributed to reservoir-triggered seismicity (Gupta, 2005). Shallow earthquakes are predominant in south India, *viz*. 1967 Ongole earthquake of M_w 5.1, 1984 Bangalore earthquake of M_w 4.5, and 1988 Idukki earthquake of M_w 4.5 with an exception of a deep focus event, the 1900 Coimbatore earthquake of M_w ~5.7 (Rastogi, 1992; Rao, 2000). The seismic activities suggest significant and ongoing intra-plate deformations. Until lately the Indian peninsular shield was considered as the Stable Continental Regions (SCR). However in the last two decades the region has witnessed several moderate to large earthquakes causing widespread damage to human lives and life line facilities.

1.3 Seismic Hazard

Seismic hazard, in a broader perspective, refers to any kind of natural phenomenon related to earthquakes such as ground shaking, liquefaction, landslides, and tsunami which are capable of imparting potential loss and damages to built-up areas and societal environment. In the specific sense, seismic hazard is the likelihood, or probability of experiencing a specified intensity of any damaging phenomenon at a particular site, or over a region, during some specific time period. In order to mitigate the adverse effect of earthquake hazard, it is essential to predict those and take necessary measures. But unfortunately accurate forecasting of when and where a seismic event will occur is not possible with current scientific knowledge that is based on limited earthquake recordings and geotectonic evidence. An important prerequisite for mitigation of the devastating effects of earthquakes in a region is the accurate assessment of seismic hazard associated with the region so that the potential for future damaging earthquakes can be estimated. The fatalities due to earthquakes and environmental disaster in terms of collapse of building and infrastructure, disruption in economic productivity, human resettlement can be reduced by long term prevention policy *viz*. (a) Assessment of seismic hazard and risk, (b) Implementation of safe building construction codes, and (c) strategy for land use planning considering seismic hazard and occurrence of other natural hazards. Seismic hazard is the first step towards evaluation of seismic risk of a terrain. Earthquake ground motion hazard estimation necessitates the models of seismic sources, earthquake recurrence frequency or prediction of maximum credible earthquake/scenario earthquake, ground motion attenuations and ground motion occurrence probability at a site and strong motion seismometry in a region. The seismic sources are defined based on interpretations of available geological, geophysical and seismological data with respect to earthquake mechanisms and source structures that are likely to be common within specific geographic region. Seismic source delineation is generally premised on geo-science knowledge that relates to geological structures. However, if the causative earthquake faults and the tectonics are not known with certainty, seismic source interpretations are not unique (Thenhaus, 1983; 1986). Frankel (1995) and Frankel *et al.* (2000) proposed methods of seismicity smoothing to avoid arbitrary discussions regarding the placement of area-source boundaries. Woo (1996) on the other hand presented the fractal geometry of distributed seismicity as a self-organized critical-state process. Hence Areal seismic sources define regions of the Earth's crust that are assumed to have uniform seismicity characteristics distinct from the neighboring zones, and are exclusive of active faults that are individually defined.

Seismic hazard may be analyzed deterministically (DSHA) when a particular earthquake scenario is assumed, or probabilistically, in which uncertainties in earthquake size, location and time occurrence are explicitly considered. Prior to the widespread use of Probabilistic Seismic Hazard Analysis (PSHA) most hazard assessments were of Deterministic types. The basis of DSHA is to develop earthquake scenarios considering magnitude and location which would affect the site of interest. By assuming that the maximum credible earthquake will happen at the closest point to the site referred as controlling earthquake the resulting design ground motion is evaluated. However this method has not been adopted in recent times since the aim is to assess the earthquake risk of the terrain considering all possible sources rather than of a specific one. PSHA is considered as the assessment of an infinite number of deterministic hazards, with the hazard being integrated over all potential earthquake sources for all possible scenarios of magnitude and distance. Further, by assigning probability distributions to source and ground motion characteristics, a reasonable ground motion at some accepted level of probability of occurrence can be chosen for the design purposes. The prime aim of this method is to estimate the probability that a particular relevant parameter (*i.e.* acceleration or intensity) will be exceeded during a specified period of time at the site under consideration. This allows for a more intelligent and economic design in comparison to the often overtly conservative, deterministic, “worst-case” scenario approach. The foremost step in PSHA begins with the characterization of earthquake occurrence using two sources of data *i.e.* the observed seismicity (historical and instrumental) and the geological settings. The constituent model of the probabilistic approach for the estimation of earthquake ground motion hazard consists of Seismic source, Earthquake recurrence frequency, Ground motion prediction and Ground motion occurrence probability at a site of interest. Determining the earthquake recurrence frequency of a set of defined seismic sources is an important explicit task in PSHA, while it is either implicit or is disregarded in the deterministic seismic hazard analysis. Earthquake recurrence frequency is based largely on statistical analyses of the historical record of earthquakes. The Earthquake frequency estimates in PSHA typically assume independence of earthquake events, or Poisson arrival times. Another important parameter is the empirical next generation attenuation models which are widely used to predict earthquake ground motion at a site of interest. Proper implementation of next generation attenuation relationships requires that the seismic sources are characterized by the details of a fault-rupture model including depth to the top and bottom of the earthquake rupture zone, fault dip and the style of fault slip. Largely the choice of an appropriate relationship is governed by the regional tectonic setting of the site of interest, whether it is located within a stable continental region or an active tectonic region, or whether the site is in the proximity of a subduction zone tectonics. It is also a major contributor to the uncertainty in the PSHA estimates (Bender, 1984). There are a large number of attenuation relations that can be used to develop engineering estimates of strong ground motion throughout the world. It is not feasible to list all of them here. Several attenuation relationships have been published since around 1990. These attenuation relations are chosen to represent a selection of those commonly used to estimate acceleration response spectra for engineering evaluation and design. For practical purposes and engineering utility, the discussion is restricted to attenuation relations and other related engineering models used to incorporate hanging wall, foot wall, and source directivity effects that provide estimates of Peak Ground Acceleration (PGA) and Pseudo Spectral Acceleration (PSA). A horde of ground motion attenuation and prediction models are available in published literatures. The final step in PSHA is to estimate the probability of exceeding some amplitude of shaking at a site in some specific period necessitating that a probability distribution of the ground motion be assumed. The Poisson model serves as a reasonable assumption in most engineering applications except in rare cases where a single earthquake source may dominate the hazard level at a site. Poisson models have traditionally been used in most seismic hazard assessment studies. The accuracy of the predicted hazard at a site will depend upon the quality of the input information (*viz*. the configuration of sources and their activity rates, the form & parameters of the attenuation relationship being adopted and the treatment of local effects). Mild differences in the model may cause larger effects on the hazard level (Veneziano and Van Dick, 1985; Margottini, 1992). It can, therefore, be concluded, that the input parameters are very critical as compared to the methodology of computation of seismic hazard. The PSHA methodology was developed in the 1970’s for estimating seismic risk with the associated uncertainties in earthquake source, wave propagation path, and site conditions (Cornell, 1968; 1971). A FORTRAN algorithm following Cornell’s method (Cornell, 1968; 1971) has been developed by McGuire in 1976 which has become the standard PSHA computational tool used since then. Thus, modern PSHA is often referred to as the Cornell-McGuire method (Bommer and Abrahamson, 2006). The goal of PSHA is to derive a seismic hazard curve designating a relationship between a ground motion parameter and its frequency of exceedance, utilizing some statistical relationships and their probability distributions (Cornell, 1968; 1971). In the Cornell-McGuire method, the spatial distribution of earthquakes is described by seismic source zones, which are either areal or tectonic. The source zonation is defined based on the seismotectonic information of the region whose PSHA is being estimated. The active faults/lineaments are considered as line sources where geologic information may be used in addition to seismicity to constrain the event size and its rate of occurrence on a fault/lineament. The areas of diffuse seismicity where earthquakes are occurring on a poorly-understood network of buried faults/lineaments are represented as areal seismic source zones where the seismicity is used to establish the rates of occurrence of earthquakes of varying magnitude. The exponential relation of Gutenberg and Richter (Richter, 1958) is used to describe the magnitude recurrence statistics through seismicity analysis. To estimate the probability of exceeding a specified ground motion also termed as hazard curve at a site of interest, the hazard contributions are integrated over all magnitudes and distances for all seismic sources following the total probability theorem. Probabilistic seismic hazard maps generated from hazard curves for a territory depict spatial distribution of ground motion values *viz*. peak ground acceleration and pseudo spectral acceleration at different periods.

Although improved understanding of the seismogenic processes, earthquake occurrences, and ground motion variability are the keynotes of recent advancements in seismic hazard modeling, these have been facilitated by enhanced quality data pool, sophisticated methodologies, and advancement in the computational facility. The methodological advancements are mostly driven by complexity of the problem, improved understanding of underlying principles, region specific solutions, involvement of huge data volume, multi-disciplinary participation, and the need for interactive analysis. The modern-day earthquake science has emerged as a multi-disciplinary subject involving seismology, geology, geophysics, geotechnical earthquake engineering, Geographical Information System (GIS), remote sensing and statistical techniques (Nath and Thingbaijam, 2009).

A developing country like India, with a variety of building practices and social and economic structures needs to evolve its own strategies for seismic hazard assessment. Occurrences of several damaging earthquakes during the last decade have brought out the shortcomings in our existing seismic risk reduction program. The ten-year period of the International Decade for Natural Disaster Reduction (IDNDR) came as a good opportunity for the country to look back at what has been done in the past, new initiatives taken during the decade, and plan ahead accordingly for reducing the impact of natural disasters on its population, settlements and economic development in terms of overall GDP growth.

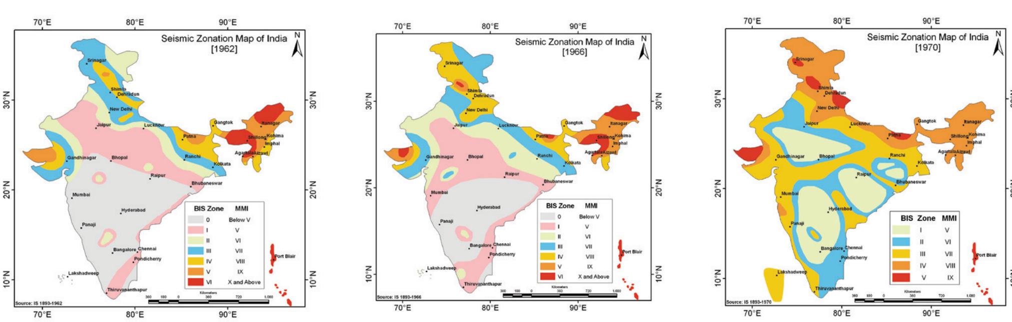
Several attempts have been made by various researchers in the past for seismic hazard assessment in different parts of the country. Using the ground motion prediction equation of Algermissen and Perkins (1976), Khattri *et al.* (1984) developed a Peak Horizontal Acceleration (PHA) distribution map of India for a 10% annual probability of exceedance in 50 years. Bhatia *et al.* (1999), on the other hand, used the ground motion prediction equation of Joyner and Boore (1981) to generate probabilistic hazard map of India based on eighty six areal seismic source zones under the Global Seismic Hazard Assessment Program (GSHAP). However, the results published in both Khattri *et al.* (1984) and Bhatia *et al.* (1999) were under scanner because of the usage of a single ground motion prediction equation for the entire country. Parvez *et al.* (2003) delivered a deterministic seismic hazard map of India. All the earlier results were compared and significant discrepancies were observed in the tectonically active regions of the country. There is a significant underestimation in the hazard level in all the published works. Das *et al.* (2006) prepared a probabilistic seismic hazard map of northeast India with the indication that a single zone factor for the entire region as assigned by BIS (2002) is inappropriate. Based on the consideration of ten areal source zones and their own Ground Motion Prediction Equations, Sharma and Malik (2006) prepared a probabilistic seismic hazard map of the same region. Jaiswal and Sinha (2007) used nine areal source zones and came up with a strikingly different level of probabilistic seismic hazard in the peninsular India as compared with BIS (2002). Menon *et al.* (2010) estimated probabilistic seismic hazard for the State of Tamil Nadu by identifying eleven areal source zones. Mahajan *et al*. (2010) prepared PSHA map for the northwestern Himalaya considering nineteen different seismogenic areal source zones and the attenuation relationship of Abrahamson and Litcheister (1989) developed for USA and the equation of Hasegawa *et al.* (1981) for Canada have been used. Thus the DSHA/PSHA estimated by previous studies are based primarily on a few identified source zones as also for the stable continental region assumed to be free from seismic activities. With significant advancements in the understanding of seismogenesis, seismic source zonation, ground shaking, and site characterization, Nath and Thingbaijam (2012) came up with a modified approach for PSHA using a logic tree framework for the entire country in a regional scale.

The probabilistic seismic hazard maps thus prepared will presumably be useful to earthquake & structural engineers, landuse planners and other agencies involved in disaster mitigation and management.

1.4 Seismic Zonation Map of India

In the Indian subcontinent the earthquake are not evenly distributed. In regions like southern and central India, the occurrence of earthquake is sparse except for the incidence of a few large earthquakes, whereas in the northeastern, the northern and the northwestern part of India there are spontaneous occurrences of earthquakes some of which had been of devastating nature. Since there is a wide variation in the intensity of ground motion also from these earthquakes, a necessity was felt in the past to divide the country into broad zones in terms of expected ground motion representing seismic hazard level of a territory. The initial zoning process in India underwent critical review, revision and modification periodically keeping pace with the quality data acquisition and better understanding of the earthquake dynamics with the passage of time. Geological Survey of India (GSI) first came up with the national seismic hazard map of India in 1935 after the 1934 Bihar-Nepal earthquake (Krishna, 1959). The seismic regionalization studies by Tandon (1956) and Krishna (1959) may be considered as the earliest efforts in the demarcation of areas of potential severe, moderate and light damage in the Indian subcontinent. The map was based on broad concept of earthquake distribution and geotectonics. The severe hazard zone confined to the plate boundary regions, *i.e.* the Himalayan region in the north, Chaman Fault region in the northwest and Indo-Burma subduction zone in the northeast. While minor hazard has been confined to the Indian shield region in the south, the moderate zone covered the transition zone between the two. Subsequent studies include intensity-based mapping by Guha (1962) and Gubin (1968). Several version of seismic zoning map have been carried out by the Bureau of Indian Standard and is considered the official agency to publish seismic hazard zonation map and the building codes in India as shown in Figure 1.5.

In 1962, the Bureau of Indian Standards (BIS) (earlier, called the Indian Standards Institution) published the seismic zonation map of India (IS: 1893–1962) based on earthquake epicenters and the isoseismal map published by GSI in 1935, where India was divided into seven zones ranging from 0 (no damage) to VI (extensive damage) as shown in Figure 1.5(a). The Deccan Plateau was considered more or less a safe zone where the hazard level was assigned '0', but a large portion of the northeast India was assigned 'VI'. The zoning was reviewed in 1966 (IS: 1893–1966) and additional information like geology and tectonic features were taken into account for the modification and revision of the zones given in Figure 1.5(b). The zonation map again underwent a major revision in 1970 after the 1967 Koyna earthquake. The magnitude of the earthquake was M_w 6.5 and it occurred in the Deccan Plateau, which was previously assigned a '0' zone in the earlier maps. There arose the necessity of utilizing both the geological and geophysical data to review the zoning further. The major transformation was the removal of the zone '0' as it was not appropriate scientifically to consider a region with zero possibility of earthquake shaking. Another addition in the revised map was the merging of the Zones V and VI (IS: 1893–1970). The zonation was, therefore, reduced to five zones as depicted in Figure 1.5(c). The upgraded map placed Koyna in Zone IV.



(a) (b) (c)

Figure 1.5 **Seismic zonation map of India prepared in (a) 1962 (IS: 1893-1962), (b) 1966 (IS: 1893-1966), and (c) 1970 (IS: 1893-1970).**

In 1984, the zonation map was further modified (IS: 1893−1984) where the regions of different seismogenic potential were identified on the basis of past earthquakes and the regional tectonics. However, the map does not show seismic hazard at different locations and failed to assess the return periods of the required design seismic coefficients for the source zones. The 1993 Latur earthquake of magnitude M_w 6.3 caused damages equivalent to intensity IX, but prior to the earthquake, Latur was placed in seismic Zone I, where no such magnitude of earthquake was expected. The Latur earthquake further led to the revision of the seismic zonation map of India. The map was revised again in 2002 with only four Zones: II, III, IV and V (BIS: 1893-Part 1, 2002) as shown in Figure 1.6.

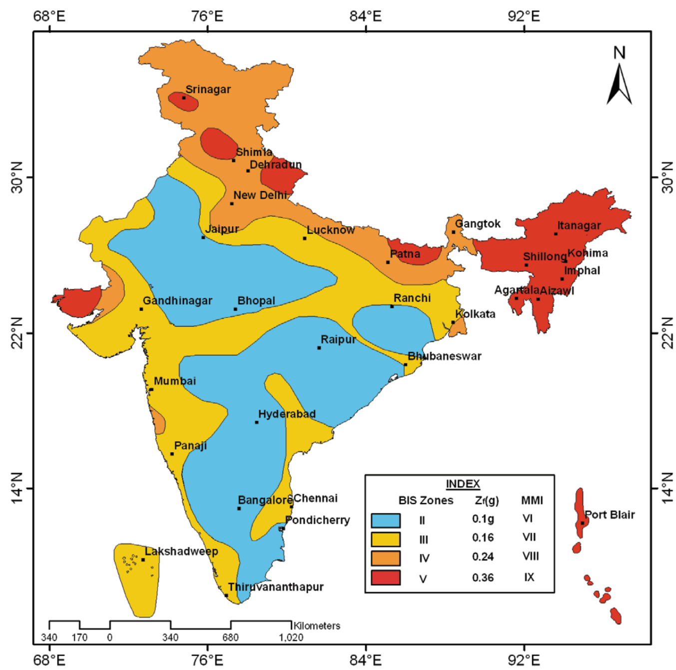


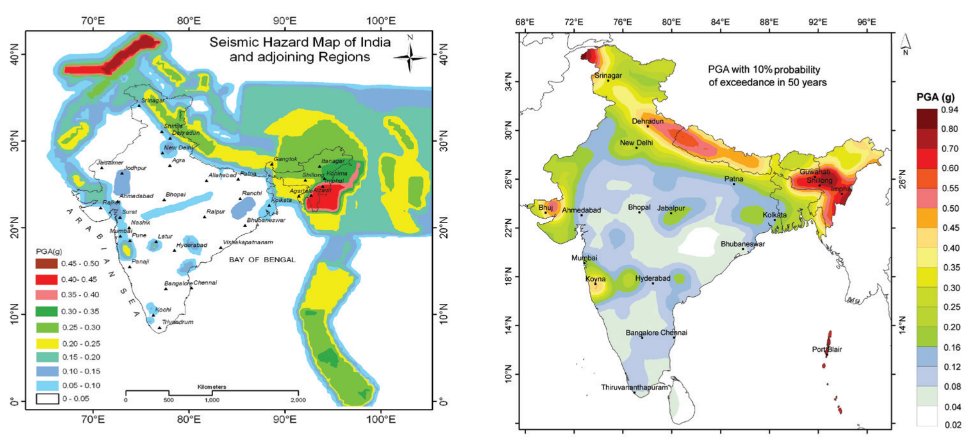
Figure 1.6 **Seismic Zonation Map of India (BIS, 1893-2002).**

Zones I and II were combined and the seismic threat in the Peninsular India was modified. The new zone placed the 1993 Latur earthquake in Zone III. The areas falling under Zone V are considered to be most vulnerable to earthquakes. Some of the country's most devastating earthquakes occurred in Zone V. The areas under this zone are the Andaman and Nicobar Islands, entire northeastern part of India, parts of northwestern Bihar, the Kangra Valley in Himachal Pradesh, the eastern part of Uttaranchal, the Rann of Kutchh in Gujarat and the Srinagar area in Jammu and Kashmir. Two major metropolitan cities, with a high population density, *i.e.* Delhi, lie in Zone IV, and Kolkata, at the boundary of Zone III and IV of this zonation map.

Besides the zoning map of India by the BIS, other non-official seismic hazard maps are available in literatures reported by various researchers (Auden, 1959; Mithal and Srivastava, 1959; Guha, 1962; Gaur and Chouhan, 1968; Kaila and Rao, 1979; Khattri *et al.* 1984; Parvez and Ram, 1999; Bhatia *et al.,* 1999; Nath and Thingbaijam, 2012; Sitharam and Kolathayar, 2013 and Sitharam *et al.,* 2014). The changes in the zonation map of India with the occurrence of significant earthquakes are an indication that the zoning at a national level does not provide the solution of tackling seismic threats.

Global Seismic Hazard Assessment Program (GSHAP) may be regarded as the first global step towards the implementations of earthquake risk reduction strategies. Coordinated at a global level and implemented at regional and local levels through a number of regional centers, it has combined a variety of data that form essential inputs for hazard assessment. The GSHAP compiled maps for the hazard estimation by bringing together the regional map produced for different regions and test areas. The expected PGA in the GSHAP map is shown with a 10% probability of exceedance in 50 years, corresponding to a return period of 475 years. The GSHAP map shows approximately 70 percent of the earth's continental land mass to have lower hazard, 22 percent with moderate hazard and 6 percent having high hazard, while the remaining 2 percent have the highest PGA with an average return period of 475 years. Bhatia *et al.* (1999) preformed a probabilistic seismic hazard analysis of India as depicted in Figure 1.7(a) under GSHAP framework.

Nath and Thingbaijam (2012) also prepared a Probabilistic seismic hazard map with the adaptation of different seismic hazard components namely seismogenic source models, multiple ground motion prediction equations, and seismic site conditions which were integrated by means of a logic tree framework to deliver a preliminary seismic hazard model for the country. Smoothened gridded seismicity and areal source zones with uniformly seismicity were adopted. The layered seismogenic source framework based on hypocentral depth distribution for the areal zonation, and smoothed-gridded seismicity models were employed for the hazard assessment. The GMPEs appropriate for different seismotectonic regimes have been used based on suitability test for the ground motion prediction equations in the regional context. This aspect was overlooked in most of the earlier studies. The computations were performed for firm-rock site conditions. The final deliverables include seismic hazard distributions in terms of peak ground acceleration (PGA) and pseudo spectral acceleration (PSA) for 5%-damped pseudo absolute response spectra. The seismic hazard map with 10% probability of exceedance in 50 years for India is shown in Figure 1.7(b).



(a) **(b)**

Figure 1.7 **(a) Seismic hazard map of India and adjoining regions for 10% probability of exceedance in 50 years (after Bhatia *et al.*, 1999), and (b) Seismic hazard map of India and adjoining regions for 10% probability of exceedance in 50 years (after Nath and Thingbaijam, 2012).**

1.5 Seismic Hazard Microzonation

The Earthquakes are inherently unpredictable because of the chaotic, highly nonlinear nature of source processes. The exact location of the event, and how large they will grow after they are initiated, depends on very delicate and immeasurable details of the physical state of the Earth over a large volume. Even if the prediction of individual large earthquakes were a goal that could be realized, it would still be of questionable utility. People would be far better off living and working in buildings having proper lifeline facilities that were designed to withstand the consequences due to occurrence of earthquakes. The design of earthquake-resistant structures is primarily the job of civil engineers, but seismologists play an important supporting role by providing information on the expected seismic hazard and the levels of strong ground shaking. It is, however, economically impossible to design structures to withstand all credible future earthquakes. This is probably one area where seismologists can make major contributions to public safety through seismic microzonation analyses. Microzonation has generally been recognized as the most accepted tool in seismic hazard assessment and risk evaluation and it is defined as the zonation with respect to ground motion characteristics taking into account source, path and site conditions.

Microzonation involves the division of a region into subregions that have relatively similar exposure to various earthquake related effects. The exercise is often similar to macro level hazard evaluation but requires more rigorous inputs about the site specific geological conditions, ground response to earthquake motions and their effect on the safety of constructions, taking into consideration the design aspects of buildings, ground conditions which would enhance the earthquake effects like the liquefaction of soil, the ground water condition and the static and dynamic characteristics of foundations along with the stability of slopes in the hilly terrain. The seismologists typically assist in mitigating the effects of an earthquake by determining source parameters and acquiring information about local geology & soil profile, topography, depth of water table, characteristics of strong ground motion, and their interaction with man-made structures. Geotechnical site characterization and assessment of site response during an earthquake is one of the crucial aspects in seismic microzonation with respect to shaking intensity, ground motion attenuation, site amplification and liquefaction susceptibility. To be useful, microzonation should provide general guidelines for the types of new structures that are most suited to an area, and it should also provide information on the relative damage potential of existing structures in the region. It follows, therefore, that if the principles of microzonation are correctly and judiciously implemented, it could be useful in establishing criteria for land-use planning and a strategy for the formulation of systematic and informed decision making process, for the development of new communities in areas that are more hazardous by nature. Seismic Microzonation is generally performed based on the choice of scale of mapping and also with the degree and scope of scientific investigation fashioned to minimize uncertainties in seismic hazard evaluation for a specific set of objectives. A microzonation project can be viewed into three levels in order of mapping resolution, precision, data volume, and complexity of the problem (Bard *et al.,* 1995). The elementary level comprises of compilation of available data delivering zonation in the scale of 1:25000 to 1:10000. The next level is achieved with specific surveys that include drilling, trenching, geophysical/geotechnical data acquisition *etc*. with comprehensive analysis/synthesis. The third highest level involves enormous volume of data compilation from a larger number of investigation points, enhanced techniques and exhaustive data processing to deliver high resolution hazard/microzonation maps.

Seismic microzonation and hazard mitigation programs necessitate focused strategic research leading to preparation of user friendly maps describing the current state-of-the-art knowledge about site specific ground shaking with their duration, frequency content, peak ground velocity and acceleration, as well as energy attenuation as a function of earthquake magnitude, epicentral distance and faulting mechanism. Seismic microzonation is always a work in progress and sustained effort to upgrade the maps through investigation, value addition and verification is necessary to raise its degree of reliability. The effort towards enhancing our understanding of seismic hazard and related effects is an ongoing process, and therefore, the framework and tools for seismic microzonation studies needs to be continuously updated in the light of ongoing advancements as well as experiences gained during earthquakes. It is expected that seismic microzonation will enable updating building codes as well as formulate actions for hazard mitigation at sub-regional and local levels.

1.6 Seismic Vulnerability and Risk

In the recent times, there has been a phenomenal rise in the global population and growth of mega cities across the globe. While most urban agglomerations are located in seismically vulnerable zones, there has been a slow progress in updating the building standards (Bilham, 2004; Tucker, 2004). The seismic risk has, consequently, increased manifolds and its necessity has repeatedly been demonstrated by disastrous earthquakes, which had claimed thousands of lives and accrued huge economic losses. According to data from National Geophysical Data Center (NGDC, http://www.ngdc.noaa.gov; Dunbar *et al*., 1992), earthquakes during the last 100 years accounted for more than 1.9 million deaths as depicted in Figure 1.8. The 1995 Kobe earthquake of M_w 6.9 exposed the gravity of possible earthquake disasters with unprecedented economic loss tallying more than US $100 billion. The memory of the tsunamigenic 2004 Sumatra earthquake of M_w 9.1 that wiped out more than 227 thousand lives is still fresh. During the last ten years, earthquakes killed more than 200 thousand people, destroyed properties worth about hundreds of US$ billions, and affected lives of over 100 million people across the globe. Significant events during the period include 2005 Kashmir earthquake of M_w 7.6, 2008 Sichuan earthquake of M_w 7.9, 2009 L'Aquila earthquake of M_w 6.3, 2009 Sumatra earthquake of M_w 7.5, 2010 Haiti earthquake of M_w 7.0, 2010 Chile earthquake of M_w 8.8, 2011 Japan earthquake of M_w 9.0 and 2015 Nepal earthquake of M_w 7.8.

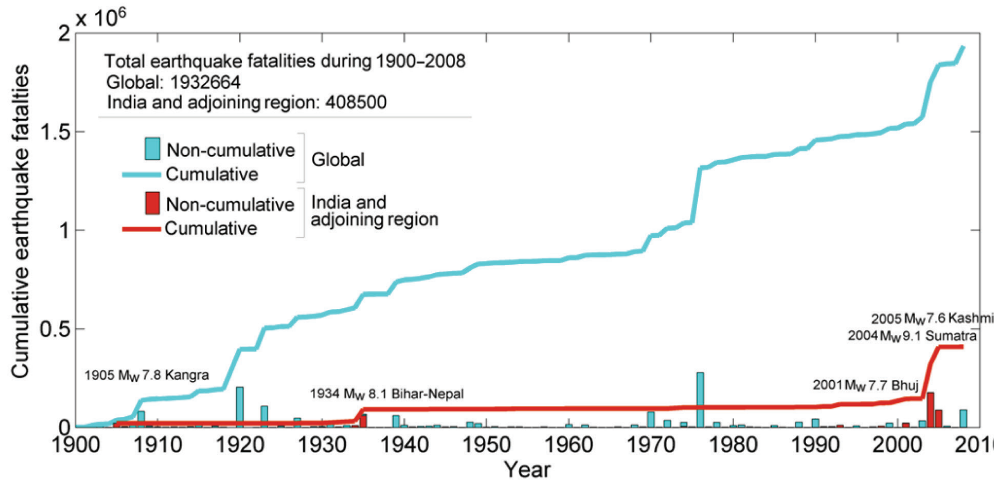


Figure 1.8 **Earthquake related fatalities in India and adjoining regions with respect to the global observations based on the data compiled by Dunbar *et al.* (1992).**

The urban agglomerations, especially in the developing countries, have been exposed to hazard for a short period compared to the long recurrence periods of large earthquakes (Bilham, 2004). It is, therefore, apparent that earthquake catastrophes are waiting to happen anytime in the future unless preventive measures are urgently and seriously taken up. Most of the deaths and casualties in India can be credited, to a large extent, to poor housing constructions, in terms of design as well as the quality of materials and improper planning. The Building Materials & Technology Promotion Council (BMTPC) estimates that 10.9 percent of the land is likely to be affected by earthquakes with an intensity of Medvedev–Spoonheuer–Karnik (MSK) IX or more, 17.3 percent of the land to MSK VIII (similar to Latur) and 30.4 percent to MSK VII (similar to Jabalpur) (BMTPC, 1997). There are about 11 million houses vulnerable in seismic Zone V; while for seismic Zone IV it is alarmingly 50 million. Nearly 80 million building units are in the risk of being damaged in the event of an earthquake. The task is not only to restore the vulnerable houses in order to minimize the loss of human life and property but also to come up with a method of estimating quantitatively the seismic vulnerability of existing built-up environment.

The number of occurrences of large earthquakes has remained fairly constant but the loss of life and property during the recent earthquakes has increased manifolds because the population is constantly on the rise. In the developed countries, the new constructions have better earthquake resistance but, not so, for the other developing or underdeveloped countries. So, there is an increase in the casualties even for the same sized earthquakes depending upon the construction. The life and property of hundreds of millions of people are at risk from the devastating effects of an earthquake. The number of fatalities in an earthquake is associated with the vulnerability of local buildings, population density and the intensity of ground shaking. Hough and Bilham (2005) gave a simple relation discerning between the earthquake magnitude since 1900 and the number of deaths per earthquakes (grey zone) but the consequences of large earthquakes depend on its proximity to urban areas, vulnerability of the dwelling inhabitants, time of the day and on the energy released as shown in Figure 1.9.

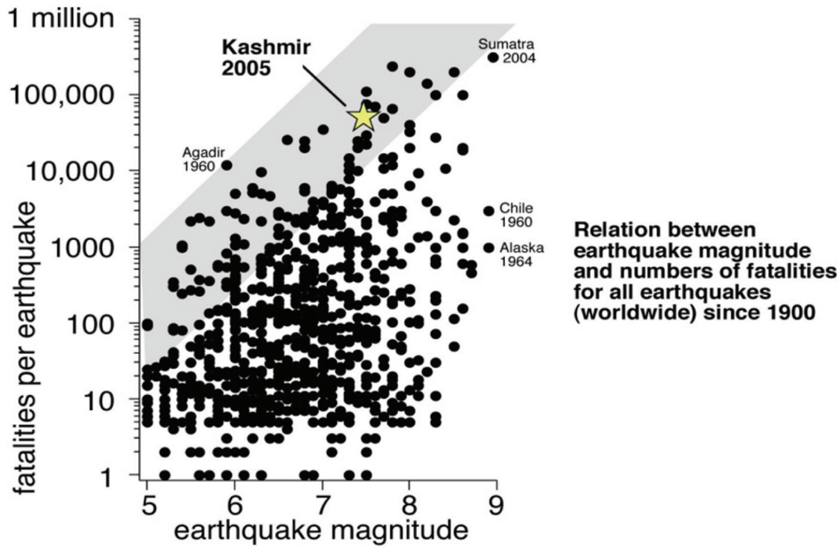


Figure 1.9 **A simple relation discerning between earthquake magnitude and the number of resulting deaths (gray shading) (after Hough and Bilham, 2005; Nath, 2011).**

The term ‘‘Seismic Vulnerability’’ is defined as the susceptibility of a population of buildings to undergo damage due to the effect of seismic shaking that occurred due to the incidence of an earthquake. Regional seismic vulnerability assessment framework is often considered as an essential tool for governments and decision makers to optimally allocate resources and mitigate consequences of earthquakes. The existing vulnerability assessment methodology varies with different assumptions, for example, quantification of seismic hazard, building vulnerability assessment, building type, population density, landuse/landcover, and building age. The seismic risk and vulnerability assessment assumes great importance not only because of its obvious physical consequences in the occurrence of a seismic event, but also because it is the potential aspect, for which the engineering research can intervene, improve and even control seismic behavior of existing buildings, reducing the level of vulnerability and consequently the level of physical damage, loss of life and economy. There is an increasing research going on in the development of seismic vulnerability assessment techniques. The seismic hazard is generally assumed to be stable over a long geological time while the typical vulnerability (and, therefore, the risk) to the hazard changes (McGuire, 2004). The risk is assessed as a convolution function of the hazard, exposure and the vulnerability, *i.e.* Risk = Hazard * Exposure * Vulnerability. For the safety and sustainability of urban regions, it is, therefore, imperative to implement long-range urban planning and risk assessment mechanisms that rely heavily on accurate and multidisciplinary urban modeling. Therefore, the decision to mitigate seismic risk requires a logical but robust approach as given in HAZUS (1999) and RADIUS (2000) for evaluating the effects of future earthquakes on both the population and the infrastructure. To achieve this logic and consistency, the methodology consisting of four steps, as shown in Figure 1.10 have to be adopted. First is the PSHA, which gives a probabilistic description of earthquake characteristics such as the ground motion and the fault displacement. Second is the estimation of earthquake damage to artificial and perhaps natural structures. Third is the translation of the seismic hazard into seismic risk by using the selected damage or loss functions. Fourth is the formal or informal analysis of earthquake mitigation decisions, wherein the options, uncertainties, costs, decision criteria, and risk aversion of the decision maker are incorporated into the decision logic protocol. The ultimate goal of both the seismic hazard and seismic risk analysis is to develop the elements that can be used to make rational decisions on seismic safety. The decision process should incorporate uncertainties in the earthquake process and ground-motion characteristics, uncertainties in the effects of earthquakes on people and structures, costs of seismic safety and potential losses and aversion to risk. Seismic vulnerability and risk assessment of cities enable in characterizing the potential seismic threats that need to be taken into account while designing new structures or retrofitting the existing ones.

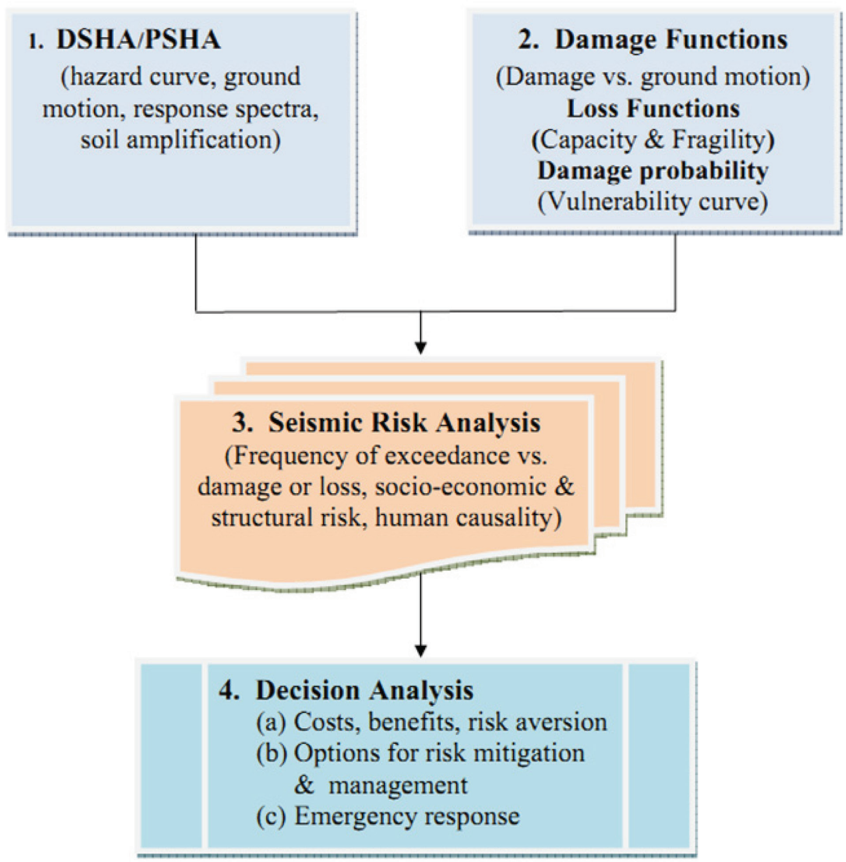


Figure 1.10 **Steps in the mitigation of earthquake risk (modified after McGuire, 2004).**

A significant component of loss estimation model is a methodology to assess the vulnerability of the built-up environment. The aim of the vulnerability assessment as already discussed is to obtain the probability of a given level of damage to a given building type due to a scenario earthquake. Therefore, Vulnerability can be defined as an internal risk factor of an exposed element to hazard events and corresponds to its intrinsic predisposition to be affected or be susceptible to damage. In general, vulnerability is the physical, economic, political or social susceptibility or predisposition of a community to suffer damage in the case of a hazard event of natural or anthropogenic origin. In general, it is expressed in terms of a certain level of damage expected as compared to a given level of foreseen hazard. The aim of risk studies is to predict and map of the expected damage due to a specified earthquake at a territorial scale. For management purposes, such studies have to improve decisions in order to contribute to the effectiveness of risk management, concerning the action and identifying the weaknesses of the exposed element and their evolution in time. The assessment also provides information to policy makers, decision makers and planners about the assets which need mitigation intervention.

1.7 Natural Hazard affecting West Bengal and its capital city of Kolkata

The State of West Bengal is situated in the eastern region of India with the Tropic of Cancer running across it. The State is situated between N 21°30′ & 27° 30′ and E 85°30′ & 89°45′. The physiographic condition of the state is unique with its northern part being in the Himalayan Range, whereas the extreme southern part touches the Bay of Bengal and is covered by the Active Delta of the Sundarbans' Mangrove forest with the greater part consisting of detrital and alluvial plains. West Bengal has been no exception so far as sufferings inflicted by natural and manmade hazards are concerned. The State of West Bengal is vulnerable to natural calamities like flood, cyclone, hail storm, thunder squall, drought, landslide, erosion and earthquakes because of its geomorphological, climatic and seismic conditions. Floods and Cyclonic storms occur almost every year in different parts of the state and inflict huge loss of life and property causing untold hardships and trauma in the lives of the inhabitants. Progressive trends of any region are controlled to a large extent by the requirements of the inhabitants, agriculture, industries, transportation, communication, education, and culture, which generally form the vulnerability attributes. Because of the high population density and concentration of industrial and agricultural activities across West Bengal, risk or vulnerability to natural or manmade disasters are particularly high. With increasing developmental activities in high hazard zones, *e.g.* the coastal regions, the vulnerability scenario appears to be worsening with time.

The State of West Bengal, covering an area of 88,752 km^2 is located in the western foreland of the Assam Arakan orogenic belt, Himalayan foothills and Surma Valley. The Bengal fan basin which was predominantly considered seismically stable is identified with sparse seismicity. However occurrence of the devastating earthquakes *viz*. 1897 Great Shillong earthquake of M_w 8.1, 1950 Assam earthquake of M_w 8.7, 1934 Bihar-Nepal earthquake of M_w 8.1, 1964 Sagar Island earthquake of M_w 5.4 and recent 2011 Sikkim earthquake of M_w 6.9 in and around the region has made the province seismically vulnerable. Historical records also indicate that this region is prone to damages due to moderate to large earthquakes, notable amongst these are enlisted in Table 1.3. The earthquakes mostly occur either in the Himalayan ranges in the north or in Northeast India and a few earthquakes also occur in the Bengal Basin. The Bureau of Indian Standards (BIS, 2002) places West Bengal in the seismic Zones II, III, IV and V, corresponding to peak ground acceleration of 0.1g, 0.16g 0.24g and 0.36g respectively. The southwestern part of West Bengal encompassing Purulia and parts of Paschim Midnapore districts is associated with the least hazard in compliances with Zone II in BIS seismic zonation map. The central part of West Bengal is broadly associated with Zone III. The districts encompassing Kolkata, Murshidabad, Birbhum, Bardhaman, Hooghly, Howrah, Nadia, Bankura and parts of Purba and Paschim Midnapore lies under Zone III. The northern and parts of central region of West Bengal encompassing Darjeeling, North and South Dinajpur, parts of Jalpaiguri & Cooch Behar, North & South 24-Parganas and Malda falls under BIS Zone IV. While parts of southeastern region like Barasat also lie in Zone IV. Zone V is delineated on the eastern parts of Cooch Behar and Jalpaiguri districts. The Bengal Basin has substantial area close to river basins and deltas that are characterized by Holocene alluvium deposits, which are likely to soften and hence are susceptible to site amplification and liquefaction during seismic events which has also been reported in GSI memoir (GSI, 1939) due to the impending 1934 Bihar-Nepal earthquake of M_w 8.1. Similarly, the Global Seismic Hazard Assessment Program classifies the seismic hazard variation the state in terms of PGA distribution from low in the southwest region to high in the northern districts with 10% probability of exceedance in 50 years.

Table 1.3 **List of Significant earthquakes affecting West Bengal and in particular its capital city Kolkata**

Date	Lat (°N)	Long (°E)	M/I_{max}	Date	Lat (°N)	Long (°E)	M/I_{max}
June 04, 1764	24.000	88.000	VIII	July 02, 1930	25.800	90.200	M_W 7.1
April 03, 1822	22.600	88.400	VII	Jan 15, 1934	26.500	86.500	M_W 8.1
July 08, 1828	22.600	88.400	VII	Mar 21, 1935	24.250	89.50	M_w 6.2
July 08,1834	25.800	89.400	VIII	Aug 15, 1950	24.250	89.500	M_W 8.7
Aug 10, 1843	27.000	88.300	VII	Aug 21, 1960	27.000	88.500	M_S 5.5
Aug 06, 1845	22.700	88.400	VII	April 15, 1964	21.600	88.700	M_b 5.2
Feb 27, 1849	27.000	88.300	VIII	June 23, 1976	21.180	88.620	M_b 5.0
Feb 09, 1851	22.600	88.400	VII	Nov 19, 1980	27.400	88.800	M_S 6.1
May 1852	27.000	88.300	IX	Mar 26, 1981	21.180	88.620	M_b 4.9
Feb 16, 1861	22.600	88.400	VIII	June 12, 1989	21.861	89.763	M_W 5.7
Mar 29, 1863	27.000	88.300	VII	June 20, 2002	25.868	88.874	M_W 5.1
Aug 09, 1869	27.000	88.300	VII	Nov 28, 2005	21.015	89.158	M_W 4.7
July 14, 1885	24.800	89.500	M_W 6.8	Feb 06, 2008	23.468	87.116	M_W 4.9
June 12, 1897	26.000	91.000	M_W 8.1	Sept 18, 2009	27.723	88.064	M_W 6.9

Source: Chandra (1977); Bilham and England (2001); India Metrological Department; Geological Survey of India, US Geological Survey (USGS)/National Earthquake Information Center (NEIC); Raj *et al.* (2008); Thingbaijam *et al.* (2008).

Beside earthquakes, West Bengal has also been predominately affected by various other natural calamities. The landslide hazard in West Bengal has been observed mostly in the hilly terrains of Darjeeling district. Incidents of landslides have also been reported on the bank of the Hooghly River. In the year 1968, floods in the Darjeeling area destroyed vast areas of West Bengal and the neighboring state of Sikkim by unleashing some devastating landslides, killing thousands of people. These landslides occurred over a three day period with precipitation ranging from 500 to 1000 mm in an event of a 100 year return period. The 60 km hilly highway from Siliguri to Darjeeling was cut off at 92 places by landslides resulting in total disruption of the road transportation system. According to Geological Survey of India the zones susceptible to vulnerable landslides in West Bengal consist of Gayabari slide, Pangla Jhora Sinking zone, Dalapchand slide, 6^{th} Mile slide, Baparkheti slide zone, Giddapahar slide, Sinking zone on NH 31A, Birik slide and Lukuvir slide. Urbanization especially in the hilly terrain involving construction activities are often perturbed in the hill slopes due to triggering landslides. Prior identification of hazard potential is, therefore, necessary. Major tools employed for landslide triggered hazard delineation include remote sensing and GIS techniques. Various thematic layers describing the geological characteristics, water conditions, material properties, topographical inclinations, seismic activities, prediction of soil behavior under load *etc*. are considered for the thematic integration to achieve landslide hazard zonation.

West Bengal has been no exception to flood disaster and approximately 55.8 percent of the region is susceptible to floods. Furthermore, complicacy is implicated by the origination of major flood producing rivers beyond the state jurisdictional limits, *viz*. Teesta, Torsa, Joldhaka, Kaljani *etc*. from Sikkim and Bhutan are mainly responsible for disastrous flash floods in North Bengal; also heavy rainfall in the catchment area of the river Ganga in Uttar Pradesh results in heavy onrush of water in the downstream of the Bhagirathi causing floods in its adjacent districts. Moreover the heavy rainfall in the Western plateau results in a large inflow in the reservoirs of Maithon, Panchet, Massanjore *etc*. which causes major floods in the adjacent regions. In addition, many of the rivers flowing through the State originate from northern Bangladesh causing flood at the time of heavy rainfall. In recent times with the advancement of satellite and remote sensing techniques the flood forecasting is possible which helps in the evacuation, monitoring and providing early warning in case of flood disaster.

Drought is one of the major concerns in West Bengal especially in the districts of Bankura, Purulia, Birbhum and parts of Paschim Midnapore which have been affected at regular intervals due to deficit in rainfall and adverse soil conditions.

Cyclone has become almost a regular feature in West Bengal, particularly, in the coastal areas and their occurrences cause damage to the life and property every year in the affected areas. East Midnapore, South 24 Parganas, North 24 Parganas, Howrah, Hooghly and Kolkata are most susceptible to the hazard caused due to tropical cyclones. West Bengal is considered as one of the most cyclone prone territories in the country.

Although hazard due to trans-oceanic tsunamis have not been quantified for the coastal areas of West Bengal, because of the presence of mangroves and shallow continental shelf (unlithified fan deposits at the mouth of the Meghna-Ganges estuary) extending to several hundred kilometers, tsunamis are unlikely to pose a significant threat to this state. As such there was no report of damage due to tsunami waves in the territory as far as the catastrophic tsunami earthquake of December 26, 2004 is concerned. However, any future offshore developments off the coast may be affected by tsunamis.

Subsidence hazard has been exhibited in underground coal mining areas of the state such as Raniganj and Asansol. A fundamental preventive approach towards avoidance of adverse impacts of the hazard is the reliable prediction and ensuing geotechnical considerations. The techniques involve tomography and subsurface mapping, subsidence profiles, and behavior model *e.g.* visco-elatsic modeling.

A composite vulnerability as depicted in Figure 1.11 has been prepared by Nath *et al.* (2008a) following an integration of various hazard and vulnerability themes affecting the Bengal Basin. The exercise outlined is essentially a first order attempt based on a rather simplistic approach and macro zoning information obtained from various sources. Consequently, resolution of the composite vulnerability map is rather coarse. In a more elaborate and rational approach, the hazard ratings require normalization on the basis of quantified damages to areas with similar population and industrial densities.

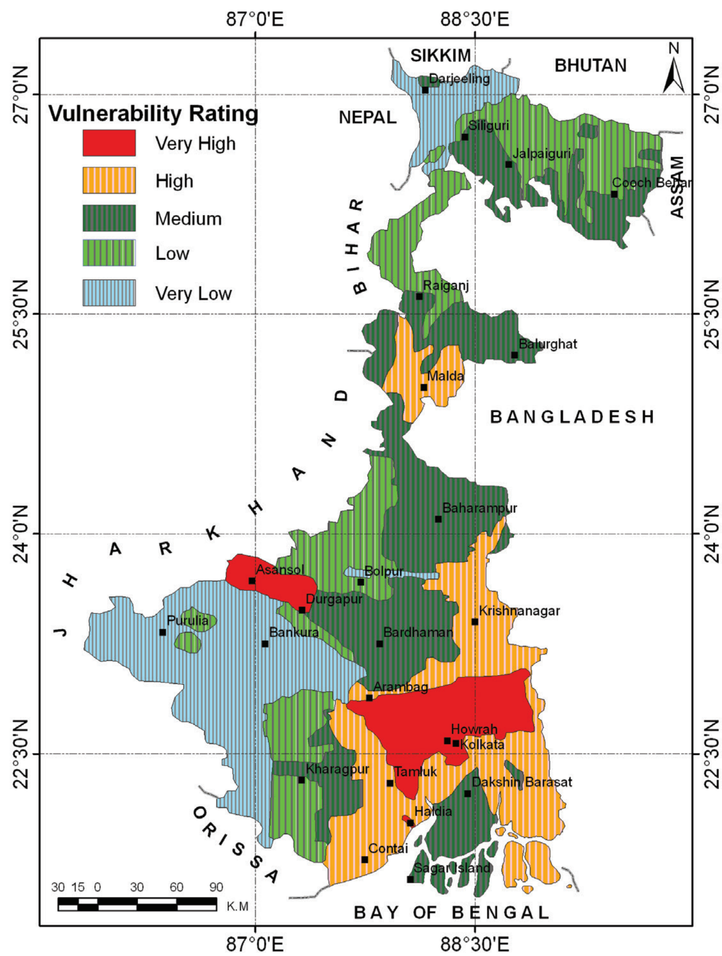


Figure 1.11 **A composite vulnerability macro-zone map of West Bengal computed from integration of hazard distributions - earthquake, flood, wind and cyclone, landslide, and subsidence along with vulnerability components represented by district-wise population density, and Industrial output distribution (after Nath *et al.*, 2008a).**

The initial works of Nath *et al.* (2008a) reflects the relative vulnerability across West Bengal in qualitative terms. The simple approach illustrated can be readily adapted to accommodate microzonation data pertaining to hazard and vulnerability as and when they become available. Hence rigorous attempt has been made to estimate the hazard and risk to develop effective measures covering the entire State of West Bengal.

The Kolkata metropolis (formerly Calcutta), the state capital and the second largest urban agglomeration in India, is bounded by latitudes 22°27′ N - 22°40′ N and longitudes 88°18′ E - 88°28′ E and has developed primarily along the eastern bank of the River Hooghly during the last 300+ years. The City is located about 150 km north of the Bay of Bengal, right over the Ganges delta. The city of Kolkata is one of the most urbanized and densely populated regions in the world, which is a major industrial and commercial hub of the Eastern and Northeastern region of India. The population of Kolkata was 1.5 million in the year 1901 that increased to 11 million in 1991 and to a phenomenal increase to 14 million as per the Census report of 2011. Due to enormous population pressure it has encroached into the back swamp and marshy land to the east filling up extensive areas, especially in the Saltlake and Rajarhat regions and many more in an unplanned manner. More than 80 percent of the City has built-up areas with high rise residential buildings, congested business districts, hospitals and schools *etc*. (Nandy, 2007), some of which are very old and are in dilapidated condition with unplanned construction adhering to non-seismic safety standards. Demography in some parts of the City exhibits population density above 100,000 per square kilometer. The metropolitan city is among the most densely populated regions in the world and supports vital industrial and transportation infrastructure. The Kolkata city being highly developed and an older one have many old buildings, bridges, subways, multi storied buildings, huge shopping malls and several life line facilities. The Kolkata city lies on the border of Seismic Zones III and IV as per the seismic zoning map of India incorporated in the Indian standard criteria for earthquake resistant design of structures (IS:1893 (part-1), 2002). The Kolkata-Mymensingh Eocene Hinge zone associated with gravity high and magnetic low and possibly representing a zone of numerous en-echelon faults over the Eocene Sylhet limestone is the most prominent neotectonic feature posing direct seismic threat to the city of Kolkata. The hinge is about 25 km wide that occurs at a depth of approximately 4.5 km below Kolkata. Total sedimentary thickness below Kolkata is of the order of 7.5 km above the crystalline basement. The hazard assessment study speculates that the deep alluvial deposit in the City increases the seismic hazard due to the amplification of seismic energy. It is very well recognized that site response studies (a part of seismic microzonation studies for urban areas) are the first step towards performance-based foundation design or seismic risk analysis and mitigation strategy. The large population density of Kolkata city, huge man-made infrastructures, situated on very thick and soft soil deposit, and the use of filled-up swampy and marshy lands in an unplanned way calls for an immediate seismic hazard evaluation and its microzonation and risk estimation. Hence, for the improvement of land use management in Kolkata with a view to the mitigation of probable earthquake risk, an initiative has been taken to develop Seismic Microzonation and risk protocol for the city of Kolkata. A new perspective of multi-criteria holistic Seismic Hazard Microzonation has been presented here for Kolkata based on an enriched homogeneous earthquake catalogue, upgraded tectonic database, seismotectonic implications, geological, geotechnical and geophysical database judiciously integrated in a fuzzy protocol using sophisticated analytical technology coupled with Geographical Information System. It has provided an enhanced seismic scenario in micro scale with the development of a set of Next Generation Attenuation Models, NEHRP Site Characterization with associated Generic Site Response Spectra, Liquefaction Scenario, surface consistent PGA distribution with upgraded 5% damped Design Response Spectra depicting an increase in the design values for an appropriate upgradation in the building code of the city of Kolkata. The seismic risk framework adopted here is a multidimensional protocol based on integrated seismic hazard and vulnerability exposures *viz*. population density, landuse/landcover, building typology, building height and building age judiciously integrated on Geographical Information System to identify those structural and socio-economic conditions which are responsible for turning earthquake disaster into a catastrophe. Thus the knowledge of both the Seismic Hazard and Risk in the City based on existing urban built-up environment will immensely benefit the disaster mitigation and management endeavors for the city of Kolkata.