*Over again, earthquakes remind us the destructive power of nature's fury.*

# 1. INTRODUCTION AND BACKGROUND PREPARATION

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 and utility in mitigating 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 are based mostly on ground-shaking levels that act as primary hazard indicator. Seismologists, therefore, predict the ground-shaking level from potential earthquakes to support building codes for seismic-resistant constructions, land-use planning, and earthquake insurance purposes. Earthquake occurrences do not have spatial uniformity entailing differential exposures to the 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 techniques, we provide knowledge products about the expected ground-motion quantities.

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, more than 59% of the total land-cover in the country is susceptible to seismic hazard (BMTPC, 1997). Incidentally, India is the second most populous country in the world. On the one hand, unplanned urbanizations are expanding rapidly across the country to accommodate the burgeoning population. On the other hand, the available seismic hazard maps covering the entire country are more or less a decade old. An updated seismic hazard model is, consequently, imperative and necessitated by new data, recent findings, and methodological improvements.

## 1.1. Global seismic hazard scenario

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, 2004a; Tucker, 2004). The seismic risk has, consequently, increased manifolds. According to the data from National Geophysical Data Center (NGDC, http://www.ngdc.noaa.gov, last accessed August 2009; Dunbar *et al*., 1992), earthquakes during the last 100 years accounted for more than 1.9 millions deaths as depicted in Figure 1.1. The 1995 Kobe earthquake $M_W$ 6.9 exposed the gravity of possible earthquake disasters with unprecedented economic loss tallying more than $100 billion. The memory of the tsunamigenic 2004 Sumatra earthquake $M_W$ 9.1 that wiped out more than 227 thousand lives is still fresh. During the last three years, earthquakes killed more than 200 thousand people, destroyed properties worth about hundreds of $billions, and affected lives of over 100 million people across the globe. Significant events during the period include 2008 Sichuan $M_W$ 7.9, 2009 L'Aquila $M_W$ 6.3, 2009 Sumatra $M_W$ 7.5, 2010 Haiti $M_W$ 7.0, and 2010 Chile $M_W$ 8.8. The urban agglomerations, especially in the developing countries, have been exposed to the hazard for short period compared to the long recurrence periods of large earthquakes (Bilham, 2004a). It is, therefore, apparent that earthquake catastrophes are waiting to happen anytime in the future unless preventive measures are urgently and seriously taken up.

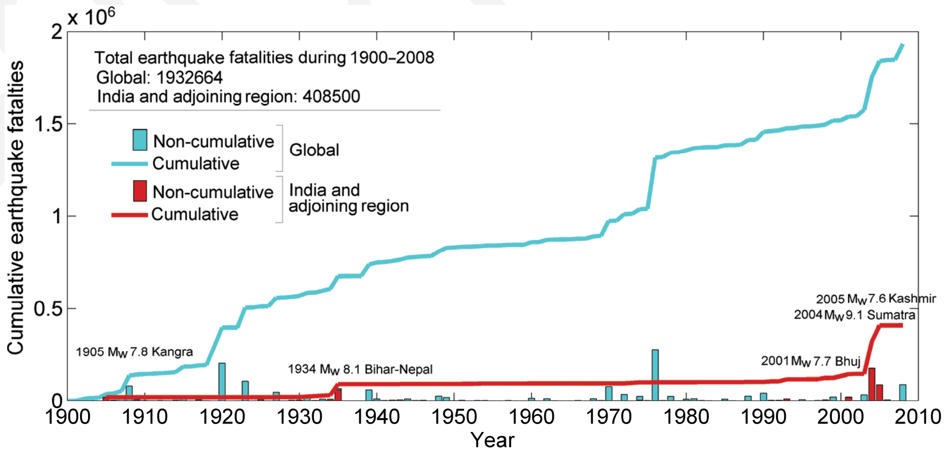


**Figure 1.1.** Earthquake related fatalities in India and adjoining regions with respect to the global observations based on the data compiled by Dunbar *et al*. (1992).

## 1.2. Seismic hazard in India

### *1.2.1. Past and future calamities*

Although accounts of earthquakes in India go back as early as to mythological period and times of Buddha *circa* 538 BC, information about earthquakes occurring prior to 1900 is highly incomplete and the figures of earthquake related causalities in the country are mostly unknown (Bilham, 2004b). There are cases of documented historical events, *viz*. 1819 Kutch Earthquake $M_W$~7.8 with estimated two thousand people dead, 1833 Kathmandu $M_W$~7.7 that caused about 500 deaths, 1869 Cachar earthquake $M_W$~7.4, and 1897 Shillong Earthquake $M_W$~8.1 with death-count of over 1500 lives (Rajendran and Rajendran, 2001; Bilham, 2004b, 2008; Ambraseys and Douglas, 2004). These earthquakes created havoc and destroyed towns. During the last 100 years, major earthquake calamities that struck the country accounts for over 22 thousand deaths (Table 1.1). If the total-fatality count of the 2004 Sumatra earthquake is considered, the death tolls add up to over 43 thousand (Figure 1.1). Moderately sized earthquakes ($M_W$<7.0) in the country have also caused devastations - apparently attributable to buildings not designed to resist probable earthquakes. This suggests that there is a general lack of seismic hazard preparedness in the country.

**Table 1.1.** Major earthquake casualties reported during 1905–2005 in India and adjoining regions.

| Event (YYYYMMDD) | Magnitude ($M_W$) | Epicentral region | Casualty report [a] | |
|---|---|---|---|---|
| | | | Deaths | Buildings |
| 19050405 | 7.8 | Kangra, northwest Himalayas | 20000 | – |
| 19340115 | 8.1 | Bihar-Nepal, central Himalayas | 10700 | – |
| 19350531 | 7.7 | Quetta, Baluchistan | 60000 | – |
| 19500815 | 8.6 | Indo-China border [b] | 1526 | – |
| 19560721 | 6.0 | Anjar, Gujarat | 156 | – |
| 19671210 | 6.3 | Koyna, south India | 177 | – |
| 19880820 | 6.8 | Udayapur, central north India | 700 | ~64000 |
| 19911020 | 6.8 | Uttarkashi, northwest Himalayas | 2000 | 18000 |
| 19930929 | 6.2 | Latur, south India | 9500 | – |
| 19970522 | 5.8 | Jabalpur, central India | 39 | – |
| 19990329 | 6.6 | Chamoli, northwest Himalayas | [c] 103 | extensive |
| 20010126 | 7.7 | Bhuj, Gujarat | 20000 | 339000 |
| 20041226 | 9.1 | Sumatra, Indonesia | [d] 227000 | – |
| 20051008 | 7.6 | Kashmir, northwest Himalayas | 86000 | – |

[a] According to United States Geological Survey, and Dunbar *et al*. (1992); [b] commonly referred to as 1950 Assam earthquake; [c] reported by India Meteorological Department; [d] 10749 deaths in India.

The Indian subcontinent undoubtedly resonates as one of the most earthquake prone region. The northward journey of the Indian plate as it collides with Eurasian plate caused the uplifting of the Himalayas. DeMets *et al.* (1994) estimated the relative motion of the Indian plate to be ~52 mm/yr. The collision generates tremendous stress within the crust, which is relieved by the occasional earthquakes along the faults. The scale of stress buildup in the Himalayas has been a major concern. Bilham *et al.* (2001) pointed out that magnitude potential of the overdue earthquakes exceeds $M_W$ 8.0 in most parts of the terrain. Feldl and Bilham (2006) also suggested that the rupture areas of recent smaller earthquakes in the region have possibility of nucleating into mega-earthquakes. Incidentally, a fault or a fault-segment, especially along the plate boundaries, with previous history of large earthquakes that has remained passive for a considerable period has been speculated as 'seismic gap' where future major/great earthquakes are likely to occur (*e.g.*, Sykes, 1971; McCann *et al*., 1979; Wyss and Wiemer, 1999). Khattri and Wyss (1978) located three seismic gaps along the Himalayas: 'Assam seismic gap' between the 1950 Assam earthquake and the 1934 Bihar-Nepal earthquake, 'Central (Himalayas) seismic gap' between the 1934 Bihar-Nepal earthquake and the 1905 Kangra earthquakes, and 'Kashmir seismic gap' to the west of the 1905 Kangra earthquake. Khattri (1999) surmised that there is 56% probability that a great earthquake ($M_W$>8.5) may occur in the central seismic gap within the next 100 years. Bendick *et al.* (2006) 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 tested producing unacceptable discrepancies between the observed and predicted earthquakes (Kagan and Jackson, 1991; Nishenko and Sykes, 1993; Kagan and Jackson, 1995; Kagan and Jackson, 1999). 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). Nevertheless, it is recalled that even moderately sized earthquakes have been deadly and higher uncertainty prevails owing to involvement of blind faults.

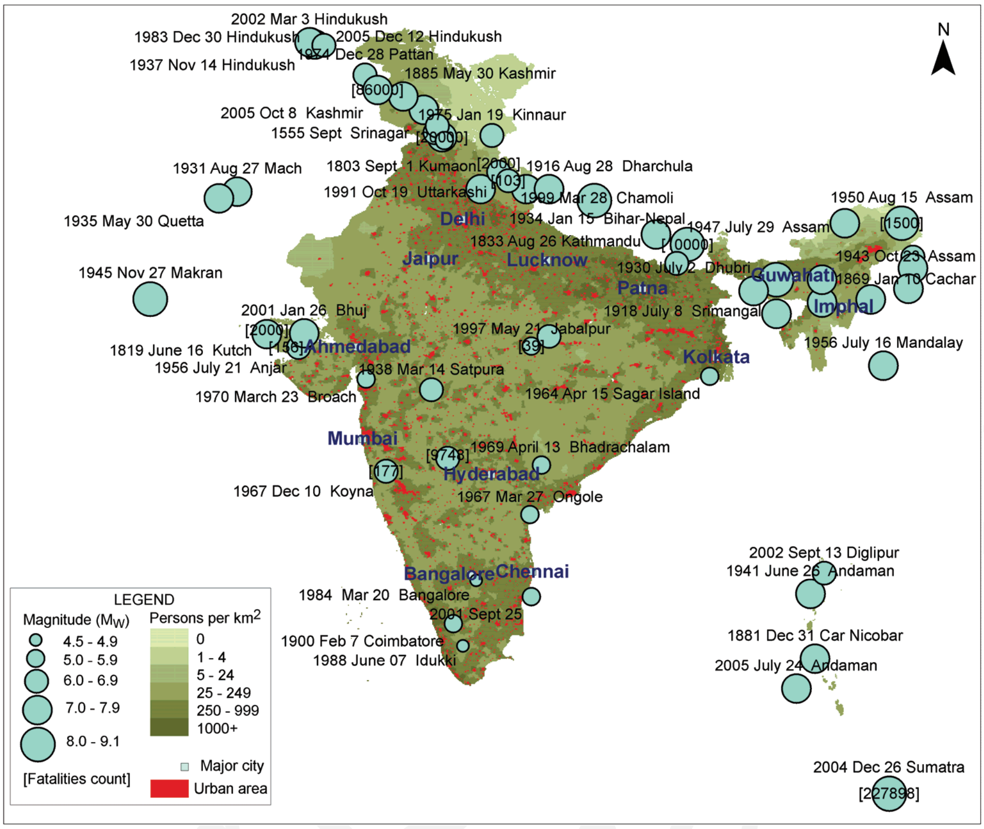


**Figure 1.2.** Significant earthquakes in India and adjoining regions depicted with approximate epicentral locations on the backdrop of population density distribution and urban coverage data for the year 2005 from the Center for International Earth Science Information Network (CIESIN, 2010).

The 2001 Gujarat earthquake inflicted a total economic loss of \$4600 million approximately*. Future scenario could not be less serious, given the population outbreak and rampant unplanned urbanization. Figure 1.2 depicts a juxtaposition of locations of significant earthquakes, population data and urban coverages. It is apparent that millions of populations are exposed to highly seismogenic tracts. The fatalities in the urban agglomerations due to future great Himalayan earthquakes have been predicted to be around 150–200 thousands (*e.g.*, Wyss, 2005; Bilham *et al.,* 2001). Dunbar *et al.* (2003) puts the maximum expected earthquake loss in the country to be about \$350–650 million for the next 50 years at 10% probability of exceedance. The consequences of large earthquakes depend on its proximity to and the vulnerability of the built environment. As far as the hazard in the country is concerned, the present situation is rather alarming.

* According to the National Geophysical Data Center database.

(a)

(b)

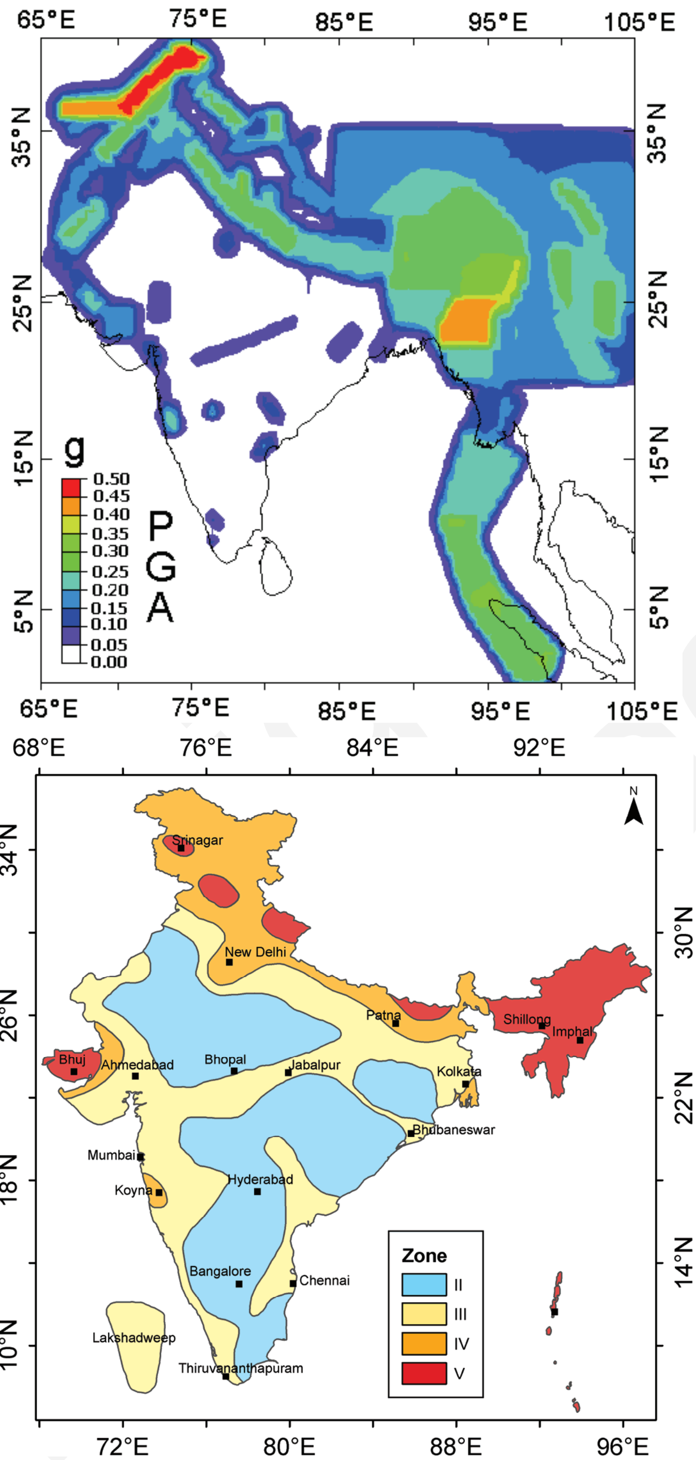


**Figure 1.3.** (a) Probabilistic seismic hazard map of India and adjoining regions in terms of peak ground acceleration for 10% probability of exceedance in 50 years delivered by Global Seismic Hazard Assessment Program (Bhatia *et al.*, 1999). (b) Seismic zonation map of India given by Bureau of Indian Standards (BIS, 2002).

*1.2.2. Previous hazard analyses*

The initial attempts of hazard zonation in the country were mainly mostly subjective (and deterministic assessments) based on historical earthquakes, macroseismic intensity observations, geology and tectonics, *e.g*. Tandon (1956), Krishna (1959), Guha (1962), Gubin (1968), and Varma *et al*. (1970). First attempts of probabilistic hazard seismic analysis were carried out during late 1970s. Basu and Nigam (1977) employed the standard PSHA methodology developed by Cornell (1968) and delivered zonation maps in terms of peak ground acceleration (PGA) for exposure period of 100 years. Kaila and Rao (1979) prepared maps depicting maximum earthquakes, maximum intensity, and peak horizontal ground acceleration. Khattri *et al*. (1984) applied Cornell's method to deliver maps depicting PGA with 10% of probability of exceedance in 50 years. The map exhibits maximum PGA of about 0.05−0.1 g in Indian peninsular regions, and 0.7−0.8 g in the tectonically active regions. More recently, Bhatia *et al*. (1999) delivered a probabilistic seismic hazard analysis of the country as part of Global Seismic Hazard Assessment Program (GSHAP). The program was undertaken under the UN/International Decade of Natural Disaster Reduction project during the period: 1992−1998 in order to formulate a global standard. The hazard zonation map, as given in Figure 1.3(a), delivered by the program depicts PGA computed at 10% probability of exceedance in 50 years. Four zones were identified with zone factors given by PGA equal to 0.1 g, 0.2 g, 0.3 g and 0.4 g, respectively.

As late as 1962, Bureau of Indian Standards (formerly Indian Standards)[†] issued the first seismic zonation map of India based on earthquake epicenters and isoseismal data, which delineated the country in seven zones. There have been revisions during 1966 and 1970 incorporating new information on geology, tectonics and earthquake episodes leading to removal of hazard-free (zero probability) zone and merger of higher hazard zones (V and VI). The current provisions given by BIS (2002) came after an extensive revision of the zonation map in the light of 1993 Latur, 1997 Jabalpur, and 2001 Bhuj earthquakes formalizing four seismic zones namely Zone II, III, IV and V as depicted in

[†] The official agency for publishing seismic hazard maps and codes in India

Figure 1.3(b). These zones have been respectively assigned hazard factor of Medvedev Spoonheuer Karnik (MSK) intensity of VI (or less), VII, VIII and IX (or above).

Khattri (2006) asserted the need to revise the seismic zonation map of BIS (2002) citing cases of several flaws in the hazard estimates, particularly for the Himalayas and adjoining regions. The author pointed out that the absence of probabilistic features in the zonation entails a critical shortcoming. He emphasized on the importance and higher applicability of probabilistic estimations in cases of informed decisions such as cost-benefit ratio of implementing hazard reduction strategies. Several independent studies at regional and sub-regional levels have also been reported. Parvez *et al*. (2003) delivered a seismic hazard map of the country by means of a deterministic approach. They compared their results with those of probabilistic assessments given by Khattri *et al*. (1984) and Bhatia *et al*. (1999), respectively. Discrepancies were observed in several regions, especially in tectonically active regions, indicating possibility of under-estimations in the earlier probabilistic assessments. Das *et al*. (2006) prepared a probabilistic seismic hazard map of northeast India and observed that the single zone factor for the entire region assigned by BIS (2002) to be inaccurate. Sharma and Malik (2006) also reported a probabilistic seismic hazard analysis of the region. Jaiswal and Sinha (2007) performed probabilistic computation of the seismic hazard for the peninsular India. They observed that the higher hazard in some parts of the region compared to that given by BIS (2002). Mahajan *et al*. (2010) prepared an updated seismic hazard map for the northwest Himalayas. They observed that the updated hazard estimates are not only higher but also have significant disparities in the spatial distribution compared to that given by Bhatia *et al*. (1999).

To summarize, the recent studies suggest that the seismic hazard models for the country currently in vogue are inadequate in several cases. A revised evaluation of the prevailing hazard is, consequently, necessary. Furthermore, new findings on the ground shaking, faults, seismicity, and geodesy as well as methodological improvements towards the 'best available science' are expected to facilitate updating the seismic hazard analysis (*e.g.*, Petersen *et al*., 2008).

## 1.3. Seismic hazard analysis

### *1.3.1. Basic principles*

Tectonic earthquakes occur as a result of accumulated stress being released suddenly in the form of fault dislocation driving rupture propagations along a fault plane, and generating seismic waves in the process. A schematic representation of the process is given in Figure 1.4. The seismic waves undergo multiple reflections, refractions and transformations along their propagation path through the heterogeneous earth's crust from the source to the site-of-observation. The associated phenomena are usually described in terms of source, path and site effects in order to simplify the associated complexities (*e.g.*, Nath *et al.*, 2008).

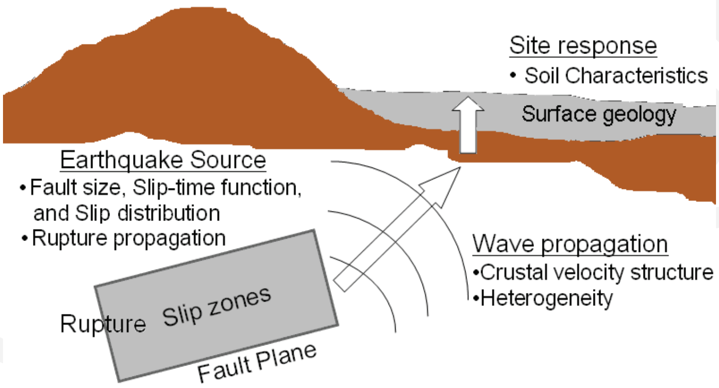


**Figure 1.4.** A schematic illustration of earthquake source, path and site, respectively in the ground motion generation process (after Nath and Thingbaijam, 2009).

The seismic sources are generally characterized by number of parameters namely, earthquake magnitude (or seismic moment), epicentral locations, hypocentral depth, focal mechanism, geometry and dimensions (*i.e.*, length and width) of the fault-rupture, fault-rupture velocity, slip-time function, slip distribution, slip duration, and stress drop (Mai and Beroza, 2000, 2002; McGuire, 2004). Resolving the source complexities towards realistic modeling is presently an ongoing and active research area.

The path characteristics describe the modulations of seismic waves along the trajectory from the source culminating to an observation site (or more appropriately, onset of the site as the site conditions are treated separately). These include geometrical spreading, attenuation of wave amplitude due to inelasticity of the crust, reflection and refraction at the interface of distinct rock types and scattering from lateral inhomogeneities of the crust. The path effects can be modeled by Green's function, *i.e.* response of the earth to a seismic point source calculated for a crustal model (Bouchon, 1981; Luco and Apsel, 1983; Kennett 1983; Olson *et al.*, 1984). Alternately, the path characterization can involve computation of quality factor and geometrical spreading parameters (Herrmann and Kijko, 1983; Burger et al., 1987; Atkinson and Mereu, 1992). The former is related to frequency-dependent attenuation of spectral amplitudes and scattering within the crustal structure while the latter characterizes expanding wave-front and is distance-dependent.

The ground motions often exhibit significant amplifications depending on local geological conditions (Aki, 1988; Su *et al.*, 1992; Kato *et al.*, 1995). The phenomenon is commonly referred to as 'site amplifications', and can be primarily attributed to either reverberations and trapping of seismic waves passing through soil deposits or the scattering and diffraction of the waves caused by undulating topography. Demarcation of spatial zones of similar site amplification is a standard practice of site classification. The scheme given by National Earthquake Hazard Reduction Program (NEHRP, BSSC, 2001) is based on average shear wave velocity for the upper 30 m soil column. Seismic microzonation of an urban center involves hazard evaluation at higher accuracy and resolution through incorporation of site-specific conditions. On the other hand, regional-level hazard analyses are usually performed uniformly for either stiff soil conditions or rock sites. From engineering perspective, it is preferred to predict the ground motions at 'engineering bedrock' on which the foundations of built structures are laid. The engineering bedrock is usually defined with shear wave velocity equal to approximately 500−800 m/s (*e.g.*, Satoh *et al.*, 1995; Kinoshita, 2007).

The main objective of seismic hazard analysis is to quantify the level of ground-shaking due to the earthquakes. This is generally addressed through modeling of the ground motions that incorporate three aspects: (1) seismic wave radiations from a fault-rupture, (2) propagation through the crust, and (3) modifications by site conditions. Ground Motion Prediction Equations (GMPEs) are widely used in predicting the level of ground shaking. These equations relate a specific parameter of ground shaking (*e.g.*, peak ground acceleration) to one or more seismic attributes (*e.g.*, magnitude, distance metrics, faulting type, *etc*). Reviews on the development and application of GMPEs can be found in Douglas (2003), Campbell (2003a), and Power *et al*. (2008). Alternately, computer based simulations are used in generation of synthetic ground motion data, and in scenario earthquake based deterministic seismic hazard analysis (*e.g*., Opršal *et al*. 2005; Nath *et al*., 2009). Recent advances in the numerical techniques and availability of detailed information on the earthquake processes have enhanced the feasibility of realistic ground-motion modeling.

Most commonly used ground motion parameters in seismic hazard analysis are PGA and response spectral acceleration or absolute Pseudo Spectral Acceleration (PSA). The PSA characterize the ground motion in terms of maximum acceleration experienced by a single degree-of-freedom structure as a function of the natural period and the damping ratio of the structure (Kramer, 1996). In this context, PGA corresponds to absolute acceleration of the structure with the natural period equal to zero. The response spectra renders as a simple tool useful in the design of seismic-resistant structures and constitute key elements of modern building codes.

*1.3.2. Earthquake prediction*

There has been some progress in the prediction of future seismic behavior with advances in understanding the crustal deformation, fault-rupture dynamics, and seismogenesis. However, accurate prediction of individual earthquake in terms of its location, timing and magnitude remains a far-fetched goal impeded by several intricate details and complexities of the physical state of the earth (Geller *et al*., 1997; Main, 1999). The interactions between different components of the earth system exhibit complex and chaotic behavior making it difficult to predict (Turcotte, 1992). The faulting process has been suggested to be a non-linear one exhibiting self organized criticality such that small earthquakes have some probability of cascading into a large event (Bak and Tang, 1989; Turcotte, 1992). The emerging possibilities and current trends of the ongoing research on earthquake prediction have been discussed by Sykes *et al*. (1999) and Keilis-Borok (2002). Sykes *et al*. (1999) observed that the stress regimes linked with large events reduce below the self organized criticality state during and after the main-shock event, and thereafter, slowly get re-established by tectonic loading eventually leading to the criticality state. They opined that the complexity of the earth system do not necessarily overrule the possibility of long-term and intermediate-term predictions. At the same time, Keilis-Borok (2002) emphasized on formal definition and testing of prediction algorithms towards improvement in the theoretical modeling and empirical analysis.

There has been some progress on different fronts – forecasting, early warning systems, and precursory studies (Stuart and Aki, 1988; Gasparini *et al*., 2007; Rhoades, 2010; Crampin and Gao, 2010; Roy and Nath, 2007). Precursory studies deals with anomalous observations prior to earthquakes and usually involve hydrologic, geochemical, geophysical and geodetic fields besides seismicity patterns such as swarms, clusters and quiescence. Regarding seismic hazard analysis, approaches to earthquake prediction can be categorized as deterministic, forecasting, time-dependent and time-independent (Main, 1999). Deterministic prediction assumes reliable estimate on timing, magnitude, and location of future events while forecasting is more relevant to general seismic activities of a region. The predictability factors in temporal variation of earthquakes have led to the development of techniques for time-dependent hazard analysis. The probabilistic assessment considers that the probability of occurrence of an earthquake in a given time-period follows a renewal model or depends on the time since the last event (Petersen *et al*., 2007). On the other hand, time-independent assessment considers the occurrence of earthquake to be random *i.e.* Poissonian process. Past seismicity, active faults, fault-geodetic and other relevant information are generally used to constrain the long-term hazard. The time-independent assessments are currently the standard practice for nation-wide evaluations. New data are increasingly available facilitating better constraints and refinement in hazard computation. Preventive measures towards mitigation of the hazard have greater merits considering technical feasibilities and economical implications compared to planned-evacuation of the population likely to be affected by occurrence of an earthquake. This places higher precedence for scientific works related to precautionary measures by emphasizing on 'understanding' rather than 'predicting' the hazard (*e.g*., Saegusa, 1999).

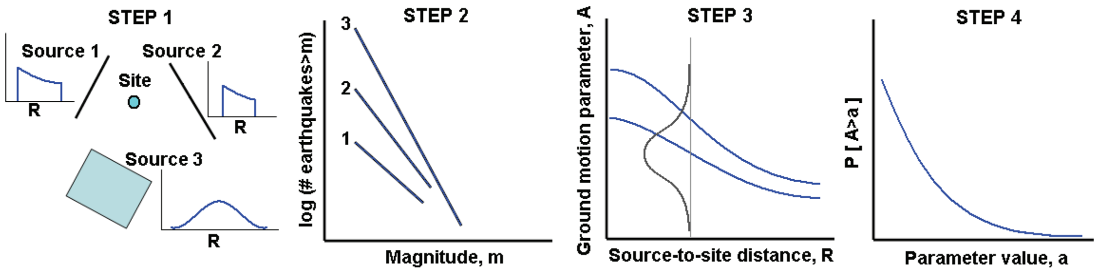


**Figure 1.5.** Four steps of standard probabilistic seismic hazard analysis (after Reiter 1990).

*1.3.3. General methodologies*

There are two different approaches commonly adopted for seismic hazard analysis: probabilistic and deterministic. The probabilistic approach explicitly incorporates uncertainties in the size, location, recurrence and effects of earthquakes in the evaluation of the hazard in terms of probability of non-exceedance (or exceedance) for a specified return period (Cornell, 1968; Esteva, 1970; Reiter, 1990; Gupta, 2002; McGuire, 2004). Figure 1.5 depicts four distinct steps of Probabilistic Seismic Hazard Analysis (PSHA). Identification of seismogenic source zones affecting the site is followed by determination of probability distributions for the earthquake magnitudes and the locations at each source zone. A recurrence model defined by frequency magnitude distribution is used to characterize the seismicity of each source zone. The probability distribution of rupture locations is developed within each source regime, which combined with source geometry yields the probability distribution of source-to-site distance. The ground motions at the site caused by earthquakes occurring in each of the source zone are determined by means of GMPEs. The standard practice assumes the occurrence of ground motions at a specific site to be a random process. Eventually, the models of earthquake location, size, and the ground motion are combined to obtain the probability that the ground-motion quantity will be exceeded in a particular time period. On the other hand, Deterministic Seismic Hazard Analysis (DSHA) involves determination of a controlling earthquake that produces the severest ground motion at the site (Kramer, 1996). The strong-motion quantities are estimated, thereafter, without considering any probability of its occurrence. It can assume a scenario earthquake based approach supported by observable facts and data, and modeling techniques (Klügel *et al.*, 2006). Deterministic approaches are more often applied for seismic design of critical and lifeline facilities (Krinitzsky, 1995).

McGuire (2001) observed that the differences between probabilistic and deterministic approaches are contingent upon purpose, seismic environment, and scope of the assessment. Bommer (2002) suggested that resolving the differences between the two approaches should be directed towards selecting the most appropriate one. In the cases where the nature of decision-making is to be based on quantitative information involving uncertainties according to the applicable scheme; *e.g.*, structural design requirements, financial planning, and insurance for earthquake losses, and investments for urbanization, probabilistic approach would be more appropriate. The uncertainties in the hazard computation are regarded as of two types – epistemic and aleatory. The former is attributed to lack of knowledge while the latter is entailed to the apparent randomness in the nature. The epistemic uncertainties are usually incorporated by considering multiple perspectives and expert opinions using logic tree (*e.g.*, Kulkarni *et al.*, 1984; Coppersmith and Youngs, 1986; McGuire, 2004).

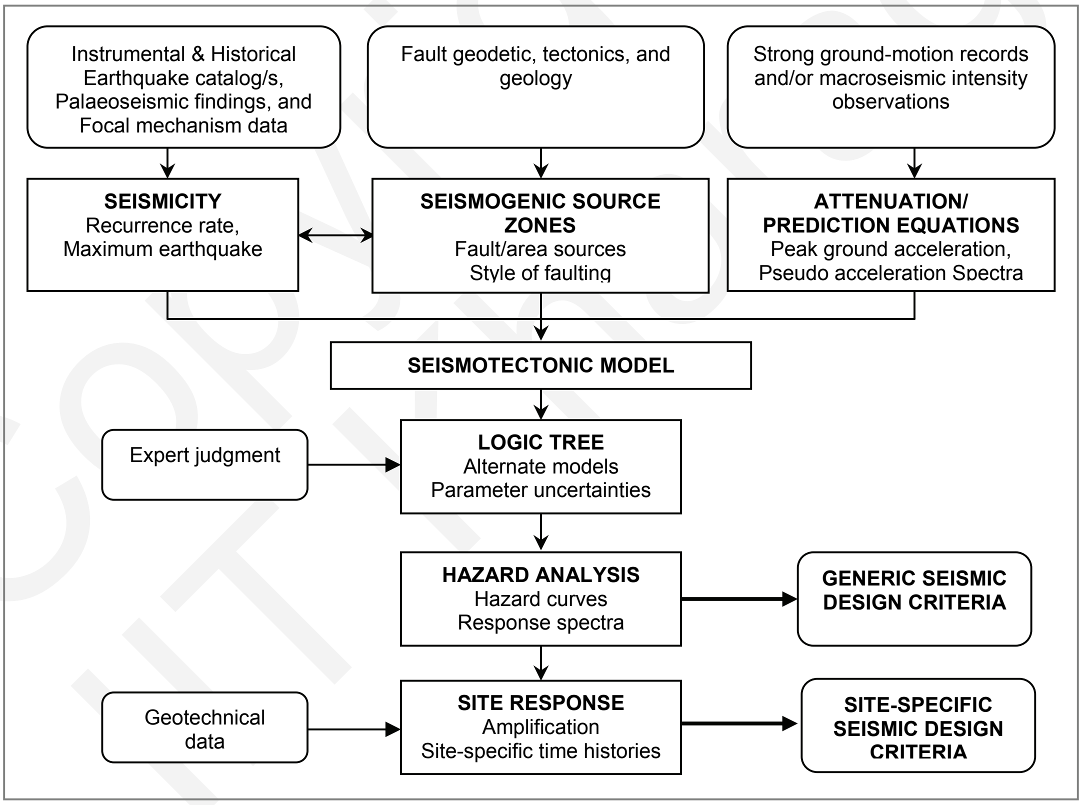


**Figure 1.6.** Key components and workflow of probabilistic seismic hazard analysis towards seismic design criteria (modified after Thenhaus and Campbell, 2003).

In the structural engineering perspective, the major objective of the hazard analysis is to establish seismic design criteria (Thenhaus and Campbell, 2003). The PSHA framework is illustrated in Figure 1.6. The basic data requirements include earthquake catalogs, tectonic and fault data, macroseismic intensity observations, ground-motion recordings, etc. The next step is the derivation of the hazard components pertaining to seismicity, seismogenic sources, and ground-motion predictions. Subsequently, a working seismotectonic model is delivered and the hazard is computed using a logic tree formulation. The final deliverable of the work-flow is the seismic design criteria that may be either general or site-specific. In case of site-specific applications, site-response estimations from seismological/geotechnical investigations are explicitly incorporated.

### *1.3.4. Recent initiatives*

Improved understanding of the seismogenic processes, earthquake occurrences, and ground motion variability are the keynotes of recent advancements in the seismic hazard modeling. These have been facilitated by enhanced data quality and quantity, improved methodologies, and advancement in the computing tools. 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 participations, and the need for interactive analysis. The earthquake science has emerged as a multi-disciplinary subject involving seismology, geology, geophysics, geotechnical engineering, Geographical Information System (GIS), remote-sensing applications, and statistical techniques (Nath and Thingbaijam, 2009).

## 1.4. Scope of the present work

We recognize the obvious need and the motivation to deliver an updated seismic hazard model for India, which defines the primary goal of the present work. This necessitates rigorous formulations, and analysis of the seismic hazard components. Accordingly, major aspects of the present work are identified as follows.

(1) Earthquake reportings have been improving since 1900 due to deployment of seismological observatories and more so, since the advent of World-Wide Standard Seismograph Network during 1963−1964. However, the available earthquake

catalogs are rather heterogeneous in usage of magnitude types and spatiotemporal coverages (Nath and Thingbaijam, 2010a). Tackling these issues comprise major objectives towards compilation of a reliable earthquake catalog required for seismicity analysis.

(2) Computations of seismic hazard are fundamentally based on the knowledge of seismogenesis in more general sense of seismic activity and the expected activity in the future. Investigations of the seismogenic sources require not only extensive but also different kinds of data and hence, accumulation and evaluation of data constitute the foremost exercise. The data include earthquake catalog including historical (*i.e.*, non-instrumental) records, fault database, focal mechanisms, fault-slip rates, and results from palaeoseismic investigations and earlier relevant works. New and enriched data are expected to facilitate seismotectonic detailing and consequently, deliver improved seismogenic source zonation and seismicity models.

(3) Recent research developments have explored the possibility of site classifications on a regional scale (*e.g.*, Wills *et al*., 2000; Wald and Allen, 2007; Yong *et al*., 2008). Data from recently executed microzonation projects at different cities across the country, and available strong ground motion recordings are anticipated to facilitate a review and a first-order evaluation of the seismic site conditions at a regional level across the country.

(4) Proper selection and ranking of GMPEs is critical for successful logic-tree implementation in probabilistic seismic hazard analysis (Bommer *et al*., 2010). It is, therefore, important to address this issue in the Indian context. Available strong ground-motion recordings in the country are rather limited, and consequently available macroseismic intensity data are considered for the purpose.

(5) The final task is the probabilistic seismic hazard analysis of the country. The computations are designed to estimate the hazard at 10% and 2% probability of exceedance in 50 years, which approximately corresponds to return-periods of 475 and 2475 years, respectively. The deliverables envisaged include spatial distribution of PGA and 5% damped PSA at spectral periods of 0.2 sec and 1.0 sec, respectively. The considered spectral periods are as per NEHRP specifications for design response spectra, and site amplification factors.

### 1.5. Organization of the thesis

The thesis is organized into seven chapters. In the first chapter *i.e.* the present one, the research background of this thesis and summarized the major objectives and scope of the research areas are discussed. The subsequent chapters are formulated according to the themes outlined within the scope of the present work; literature reviews on each component of the hazard analysis are provided in the pertinent chapter.

Chapter 2 describes compilation of the existing records of earthquake occurrences in India and adjoining regions; the entire South Asia has been considered for a broader spatial scope in case of instrumental records (*i.e.*, for the earthquakes occurring since 1900). The followings are achieved: (1) appraisal of the existing data sources and errors associated with specific magnitude types, (2) regression analyses to derive relations between different magnitude types, and thereafter, application of the relations to homogenize the magnitude entries, (3) seismicity declustering of the catalog to segregate the main-shock events, and (4) assessment of data completeness at sub-regional level. Additionally, the available records for the historical events (*i.e.* those occurring prior to 1900) in the study region are compiled.

In chapter 3, a seismogenic source framework for Indian subcontinent is developed using earthquake catalog (including historical data), fault networks, fault-slip rates, and reported findings of palaeoseismic investigations. The approaches include delineation of areal source zones, derivation of time-independent seismicity model/s, and seismicity smoothening to obtain seismic activity rates.

Chapter 4 deals with site conditions across India. For the nation-wide site condition assessments, topographic-gradient based approach for site classification that employs correlations between 30 m column averaged shear wave velocity and topographic gradients is considered. Additionally, spectral analyses techniques for site characterization are experimented at strong ground motion stations located across the Himalayas and the northeastern region of the country.

In chapter 5, an appraisal of the ground motion prediction equations in the Indian context are presented. Suites of GMPEs are selected and subjected to efficacy test for prediction of PGA at the rock sites.

Chapter 6 provides the probabilistic seismic hazard analysis of the country. A logic tree framework implementing the fundamental PSHA formulation developed by Cornell (1968) and Esteva (1970) is adopted. The computations are performed at grid-points of 0.2°x0.2° spacing considering 'firm rock' site conditions.

In the last chapter, a summary of the present work and the conclusions drawn in each aspect of the work are provided. Directions for further research in seismic hazard analysis of the country are also discussed.

**1.6. Contributions of the research work**

The following sums up the contributions of the present dissertation in the field of applied earthquake seismology, which are directed towards improved understanding of the prevailing seismic hazard in India.

- Compilation and evaluation of seismological data namely, $M_W$ based earthquake catalog of instrumental records, records of historical earthquakes, focal mechanism database, fault networks, and strong ground motion recordings.
- Extensive review of seismotectonic regimes in the Indian sub-continent.
- An updated seismogenic source framework based on a first order approximation towards volumetric zonation superseding the conventional 2D zoning.
- Site characterization studies at both local and regional levels.
- Appraisal of the ground motion prediction equations for different tectonic provinces.
- A preliminary probabilistic seismic hazard model for the country.