Probabilistic Evaluation of Seismic Hazard in India: Comparison of Different Methodologies

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Summary:
In view of the major advancement made in understanding the seismicity and seismotectonics of this region in recent times, an updated probabilistic seismic hazard map of India covering 6°–38° N and 68°–98° E was prepared and presented in this paper. In present analysis, three types of seismic sources, viz. linear, areal and zoneless models were considered and different attenuation relations were used for different tectonic provinces. The study area was divided into small grids of size 0.1° x 0.1° and the PHA and Sa values were evaluated at the centre of each grid point. A MATLAB code has been developed to estimate the hazard using linear sources and zoneless approach whereas CRISIS software was used to model areal sources. Comparison of different methodologies is presented in the paper. The linear source model predicts higher hazard compared to other two source models and Zoneless approach gives the lower value of hazard at a particular grid point. For most of the cities, gridded seismicity model is giving higher values compared to aerial sources except for Ahmedabad, Chennai, and Kanpur.
Keywords: India Seismic hazard Source model Attenuation Ground motion

1. INTRODUCTION

Earthquakes are known to have occurred in the region of the Indian subcontinent from ancient times. Many great earthquakes have occurred in the northern subcontinent and in the Andaman & Nicobar regions. In the southern peninsula damaging earthquakes have occurred but less frequently and with lower magnitudes than at the plate boundaries. Bureau of Indian Standard has published seismic zonation map in 1962 and revised it in 1966, 1970, 1984 and 2002. It was entirely based on past earthquake history, seismotectonic set up and geophysical data.

Various researchers have attempted to evaluate the expected ground motion due to future earthquakes in and around India. Khattri et al (1984) presented PGA hazard map with 10% annual probability of exceedence in 50 years with the use of the attenuation relation developed by Algermissen and Perkins (1976). PGA hazard map for entire India, with 10% annual probability of exceedance in 50 years was presented by Bhatia et al (1999) using the attenuation relation of Joyner and Boore (1981). Iyengar et al. (2010) developed Probabilistic Seismic hazard map for Indian landmass using linear seismic sources and attenuations relations developed by them for various parts of the country. There were several other efforts by various researchers to estimate the seismic hazard for various isolated regions or provinces in the country using different methodologies.

This paper presents development of hazard maps for India and adjoining areas, using different source models and attenuation relations and comparison of the same. We have attempted to model the seismic sources using three different types of models; linear sources, gridded seismicity model and areal sources. Estimation of the PGA is done using different attenuation relations specific to various tectonic provinces in the country. Specifically, the logic tree approach has not been adopted for this study to avoid further averaging. MATLAB code was developed to estimate the hazard using first two sources, whereas areal sources were modeled using the software CRISIS (Ordaz et al., 2007). The comparison of results obtained from various methodologies is presented in the paper.

2. SEISMICITY OF THE STUDY AREA

2.1. Tectonic provinces

The seismicity of Indian subcontinent can be broadly characterized by three general seismotectonic regions (Fig. 1): Tectonically active shallow crustal region, subduction zones and stable continental region. The subduction zone earthquakes can be further classified as regions with intraslab and interface earthquakes.

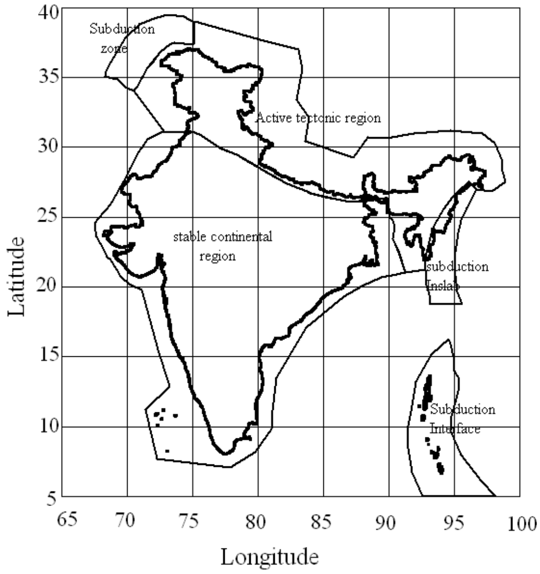

Figure 1. Tectonic provinces in and around India

The tectonically active shallow crustal regions include the Himalayas and southern Tibetan Plateau, northwest frontier province of Indian plate (Nath and Thingbaijam 2010; Kayal 2008). The movement of Indian plate in the North Eastern direction and its collision with the Eurasian plate has created the most gigantic mountain range of the world – the Himalayas with an average height of 4600 m and the biggest and highest plateau region in the world - the Tibetan Plateau. The Indian plate was considered as one of the fastest moving plates in the world. The current movement of Indian plate is estimated to be around 5 cm/year (Kumar et al. 2007). The collision and the subsequent formation of the Himalayas and the Tibetan Plateau are associated with very high seismicity. Seismically active North East Indian Region falls at the junction of N-S trending Burmese arc and E-W trending Himalayan Arc resulting in numerous geological structures (Sharma and Malik 2006).

The subduction zones include that of Hindukush- Pamir in the northwest frontier province, Indo-Myanmar arc, and Andaman-Sumatra seismic belt. The Indo-Burmese arc is an important tectonic feature, the seismicity of which is related to the subduction of the Indian plate underneath the Southeast Asian plate due to northeastward motion of India (Deshikachar 1974). The northeastern corner of India, sandwiched between the Himalayan and Burmese arcs, is characterized by a complex seismotectonic setup and very high level of seismicity (Evans 1964). The earthquakes in this area are of intraslab in nature. The Andaman Nicobar Islands are along the plate boundary between Indian plate and the Burmese plate. These regions come under subduction zones with interface earthquakes.

Peninsular India is delineated as Stable Continental Region (SCR) with low to moderate seismic activity (Chandra 1977). 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). The ENE–WSW trending Son- Narmada-Tapti zone is a prominent tectonic province forming the northern margin of the peninsular shield of India. The major tectonic elements in the southern part of the peninsula can be listed as the massive Deccan Volcanic Province, the Southern Indian Granulite Terrain, the Dharwar Craton, the Cuddapah Basin, the Godavari and the Mahanadi Grabens, and the Eastern and Western

Ghats on the east and west coasts, respectively (Gupta 2006).

2.2 Earthquake database

The hazard estimation can be done based on the past earthquake data of the region and it is important to prepare a comprehensive earthquake catalog for the study area. Recently Kolathayar et al. (2011) prepared a comprehensive earthquake catalog for India and adjoining areas compiling the data from various national and international agencies as well as from the literatures. They have developed correlations connecting various magnitude scales and homogenized the entire catalogue in a unified moment magnitude scale. This declustered earthquake catalog has been taken as a reference to characterize different types of seismic sources in the present study.

3. SEISMIC SOURCE MODELS

3.1 Linear sources

Geological survey of India (GSI) has published the Seismotectonic Atlas (SEISAT, 2000), which is one of the best documents listing the linear seismic sources in India and adjoining areas. This map was prepared after extensive research using remote sensing technique and then cross verification by geological explorations. The details of the faults, lineaments, shear zones and the geological features in India and adjoining areas are presented in SEISAT (2000). This has been taken as an authentic reference manual for identifying the seismic sources by various researchers like, Iyengar and Ghosh (2004) for Delhi, Nath (2006) for microzonation of Sikkim Himalayas, Raghu Kanth and Iyengar (2006) for Mumbai, Boominathan et al. (2008) for Chennai, Anbazhagan et al. (2009) for Bangalore and Vipin et al. (2009) for South India. All the sheets of SEISAT (2000) were scanned and georeferenced and the individual images were merged together to form the complete map India. Georeferencing and digitization of Seismotectonic maps were done using MapInfo Professional version 2006. The declustered earthquake data were superimposed in the map of extracted tectonic features and the maximum reported magnitudes along each of these sources were also noted.

3.2 Gridded seismicity model

The Gridded seismicity model (Frankel 1995, Woo 1996, Martin et al. 2002), comes in to focus is based on the seismic activity rate obtained from the earthquake catalogue and it is one of the most widely adopted methods to model seismic sources for the regions in the absence of clearly identified seismic sources. In this method the study area is divided into grids and the number of earthquakes, which are having magnitude higher than a cutoff magnitude, in each grid is counted. This will give the activity rate for that particular grid cell. In the present study, the grid size was adopted as 0.1° x 0.1° and the cutoff magnitude (Mcut) was selected as $M_W = 4.0$. Based on this value, the recurrence rates for different magnitude intervals were calculated and these values were smoothed using a Gaussian function to get the final activity rate for each grid cell (Equation 3). The uncertainty involved in estimating the location of the earthquake event and the size of the seismic source can be accounted by this smoothing.

$$\hat{n}_i = \frac{\sum_j n_j e^{-\Delta_{ij}^2/c^2}}{\sum_j e^{-\Delta_{ij}^2/c^2}} \qquad (3)$$

Where nj - number of earthquakes in the jth grid cell, $\hat{n}_i$ - smoothed number of earthquakes in ith cell, c - correlation distance to account for the location uncertainties and Δ_{ij} - distance between the ith and jth cells.

3.3 Areal sources

For the hazard estimation using areal sources, the territory under study should be first divided into seismic sources according to geotectonic considerations where it is assumed that, within a seismic source, an independent earthquake-occurrence process is taking place. For each seismic source, magnitude exceedance rates are estimated by means of statistical analysis of earthquake catalogs. These rates are the number of earthquakes, per unit time, in which magnitude M is exceeded, and they characterize the seismicity of the source (Ordaz et al., 2007).

Considering India's complex sesismotectonic set up, Kolathayar and Sitharam (2012) divided entire Indian region into 104 source zones based on the trend of tectonic features, predominant source mechanism solutions and the epicentral distribution of past earthquakes. CRISIS software (Ordaz et al., 2007) was used to model areal sources and to estimate the seismic hazard with polygon-dipping areas. These zones allow for local variability in seismicity characteristics for other two types of source models; linear sources and zoneless approach (changes in b-value, λm, Mmax etc.).

In this method, a spatial integration process is carried out to account for all possible focal locations with an assumption that, within a seismic source, all points are equally likely to be an earthquake focus. CRISIS assumes that, within a source, seismicity is evenly distributed by unit area and to correctly account for this modeling assumption, CRISIS performs a spatial integration by subdividing the original sources. Once subdivided into sub-sources, CRISIS assigns to a single point all the seismicity associated to a sub-source, and then the spatial integration adopts a summation form.

4. GROUND MOTION MODELS

The seismicity of Indian subcontinent is spatially varied and complex as it embraces various tectonic zones with different attenuation characteristics. The North and North West India are active tectonic regions with shallow crustal seismic activity. The seismic activity in Indo-Myanmar subduction zone in North east India is because of intraslab subduction earthquakes. The Andaman Nicobar regions also come under subduction zone, but with earthquakes of interface nature. The south and central India is stable continental region with low to moderate seismicity. Different attenuation relations should be used for these regions. Hence for the selection of Ground Motion Prediction Equations (GMPE) the study area was divided into three categories – active tectonic shallow crustal region, Stable continental region, subduction intraslab region and subduction interface region.

In India, there is scarcity of strong motion data and this in turn has resulted in the development of only very few region specific GMPEs. Some of the important GMPE available for India are Sharma (1998) for Himalayan region, Iyengar and Ghosh (2004) for Delhi region; Raghukanth and Iyengar (2007) for Peninsular India; Nath et al (2005) for Sikkim Himalaya; Nath (2009) for Guwhati and Sharma et al (2009) for Himalayan Region. Since only a few attenuation relations were available for the study area, in the present study we have used some of the well accepted GMPEs which were developed for other regions of the world which are having similar seismic attenuation characteristics. In a recent study, Nath and Thingbaijam (2010) reviewed the ground motion prediction in Indian scenario with reference to existing GMPEs developed for different tectonic environments and those employed by different regional hazard studies.

In the present analysis, different GMPEs were used to model the attenuation properties of the plate boundary region, stable continental region and subduction zones. Several attenuation relations capable of predicting ground motion in these seismic provinces were identified and studied. The best suited attenuation relations were selected based on strong motion records from recent small number of recorded events reported in these areas. The relation used to estimate bed rock level PGA for stable continental region is Atkinson and Boore (2006). Attenuation relations given by Atkinson and Boore (2006) were developed for the Eastern North America (ENA). Based on the study of aftershocks of Bhuj earthquake, Cramer and Kumar (2003) came to the conclusion that the ground motion attenuation in ENA and Peninsular Indian shield are comparable. Similarity of the regional tectonics of ENA and peninsular India has been noted by Bodin et al. (2004) also. The GMPE used for active tectonic regions is Akkar and Bommer (2010). The relation suggested Akkar and Bommer (2010) were developed for the active tectonic regions of Europe and Middle East. For Indo-Myanmar Subduction zone, we used the attenuation relation suggested by Gupta (2010); this is capable of predicting ground motion from intraslab subduction earthquakes. For the subduction zone with interface earthquakes, the GMPE used was of Lin and Lee (2008). The GMPE by Gupta (2010) is developed specifically for Indo-Myanmar subduction zone whereas the relation by Lin and Lee (2008) was developed for the subduction regions (both intraslab and interface) of Taiwan.

5. ESTIMATION OF HAZARD

The seismic hazard evaluation of the Indian landmass based on a state-of-the art PSHA study has been performed using the classical Cornell–McGuire approach. Regional seismic source zones were characterized to allow for local variability in seismicity characteristics (b-value, λm, Mmax). Different ground motion prediction equations were used to suit various tectonic provinces of the country. The hazard curves obtained from PSHA will show the variation of peak horizontal acceleration (PHA) or spectral acceleration (Sa) against mean annual rate of exceedance. For calculating the seismic hazard values, the entire study area was divided into grids of size 0.1° x 0.1° and the hazard values at the centre of each grid cell were calculated by considering all the seismic sources within a radius of 500 km. The occurrence of an earthquake in a seismic source is assumed to follow a Poisson's distribution. The probability of ground motion parameter, Z, at a given site, will exceed a specified level, z, during a specified time, T is represented by the expression:

$$P(Z > z) = 1 - e^{-\nu(z)T} \leq \nu(z)T \tag{11}$$

Where $\nu(z)$ is the mean annual rate of exceedance of ground motion parameter, Z, with respect to z. The function $\nu(z)$ incorporates the aleatory variability in time, size and location of future earthquakes and uncertainty in the ground motion they produce at the site. It is given by:

$$\nu(z) = \sum_{n=1}^{N} N_n(m_0) \int_{m=m_0}^{m_{\max}} f_n(m) \left[\int_{r=0}^{\infty} f_n(r \mid m) P(Z > z \mid m, r) dr \right] dm \tag{12}$$

Where $Nn\ (m_0)$ is the frequency of earthquakes on a seismic source *n*, having a magnitude equal to or greater than a minimum magnitude m_0 (in this study it is taken as 4.0); $f_n(m)$ is the probability density function for a minimum magnitude of m_0 and a maximum magnitude of mmax; $f_n(r|m)$ is the conditional probability density function (probability of occurrence of an earthquake of magnitude m at a distance r from the site for a seismic source *n*); $P(Z>z|m, r)$ is the probability at which the ground motion parameter *Z* exceeds a predefined value of *z*, when an earthquake of magnitude m occurring at a distance of r from the site. The integral in equation (12) can be replaced by summation and the density functions $f_n(m)$ and $f_n(r|m)$ can be replaced by discrete mass functions. The resulting expression for $\nu(z)$ is given by:

$$\nu(z) = \sum_{n=1}^{N} \sum_{m_i=m_0}^{m_i=m_{\max}} \lambda_n(m_i) \left[\sum_{r_j=r_{\min}}^{r_j=r_{\max}} P_n(R = r_j \mid m_i) P(Z > z \mid m_i, r_j) \right] \tag{13}$$

where $\lambda_n(m_i)$ is the frequency of occurrence of magnitude m_i at the source n obtained by discretizing the earthquake recurrence relationship for the source n.

For doing the seismic hazard analysis using linear sources and gridded seismicity source model, a set of new programs were developed in MATLAB and the entire analysis was done using these set of programs. The hazard using areal sources was estimated by using the software CRISIS (Ordaz et al., 2007).

6. RESULTS AND DISCUSSIONS

The spatial variation of PHA values obtained for 10 % PE in 50 years using different source models are shown in Fig. 2 Fig. 3 and Fig. 4. It can be seen that the seismic hazard is high along the plate boundary regions Viz. North and North East India. Along the stable continental region, the highest hazard is observed at Bhuj region and at Koyna region. The Indian seismic code BIS-1893(2002) divides the country into four zones, Viz. Zones II, III, IV and V. It is also observed that linear source model predicts higher hazard compared to other two source models and Zoneless approach gives the lower value of hazard at a particular grid point.

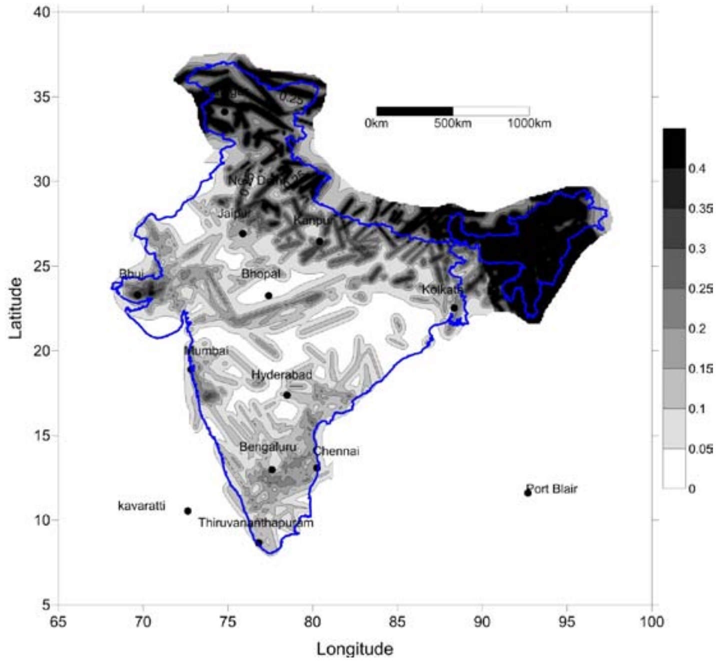

Figure 2 PHA values for India corresponding to a return period of 475 years (10% probability of exceedence in 50 years) estimated using Linear sources

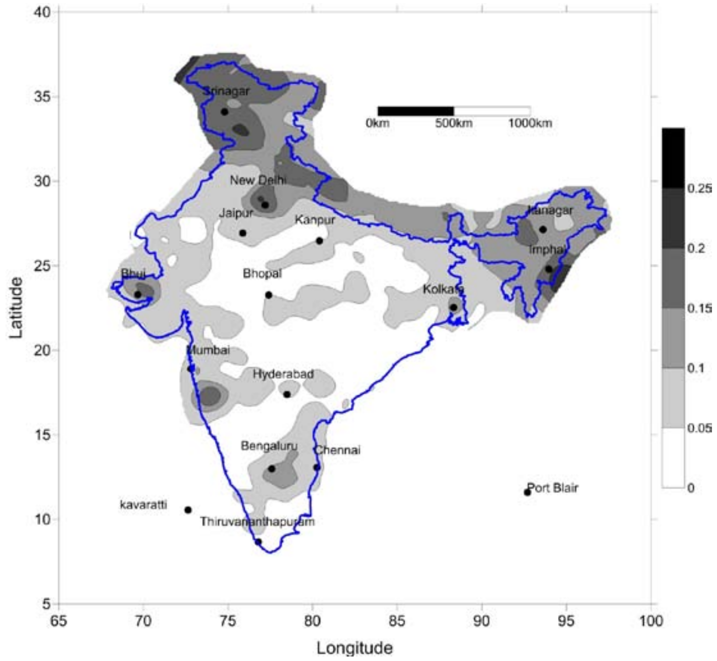

Figure 3 PHA values for India corresponding to a return period of 475 years (10% probability of exceedence in 50 years) estimated using Gridded seismicity source model

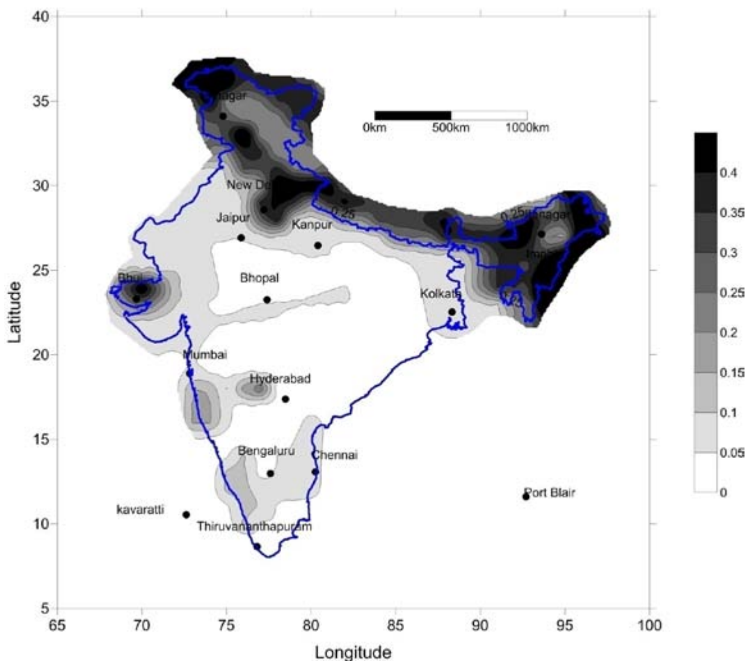

Figure 4 PHA values for India corresponding to a return period of 475 years (10% probability of exceedence in 50 years) estimated using Areal sources

The PHA values obtained for ten most populous cities (Mega cities and Metros) of India for return periods of 475 and 2475 years, using various source models are given in Table 1. For The value of PHA values for plate boundary regions varies from 0.3 to 0.5 where as for stable continental region the values were less than 0.25 except for the Kutch region in Gujarat. The previous PSHA study of India was done by Bhatia et al. (1999). This was done as a part of Global Seismic Hazard Assessment Programme (GSHAP). However the results obtained in the study of Bhatia et al. (1999) is highly debatable because of the use of single attenuation relation for the entire country. The results obtained for South India matches well with the results obtained by Vipin et al. (2009). The results obtained for Tamil Nadu by Menon et al. (2010) and for Maharashtra by Seeber et al. (1999) also match well with the present study. Iyengar et al. (2010) identified 32 seismogenic source zones to estimate the seismicity parameters and linear seismic sources for hazard analysis. They have estimated the PHA values using the attenuation relations developed by them using ground motion simulation technique. Present study uses 104 regional seismic source zones identified based on the seismic event distribution and fault alignment and three different source models for the hazard analysis. We have used well recognized attenuation relations for various sesismotectonic provinces of the country developed by various researchers in recent times. It is observed that the PGA values reported by Iyengar et al. (2010) for most of the regions are much lower than that presented in this study.

It is observed that with the same attenuation relations used, PGA values vary with the use of different source models. From Table 1, it can be seen that linear source model gives PHA values at a higher side compared to other source models. For most of the cities, gridded seismicity model is giving higher values compared to aerial sources except for Ahmedabad, Chennai, and Kanpur. The reason behind this variation in trend is because of the fact that gridded seismicity model takes care of local variation of seismicity at a finer level. In aerial sources, it is assumed that the seismic hazard potential is homogeneous within a source zone, but PHA values at two nearby grid points within a zone will vary as all the sources lying within 500 km radius are taken into consideration at a particular grid point. The limitation of using linear sources is that, there can be hidden faults, especially in the ocean, which have not been identified yet. For Himalayan region, the values obtained using linear sources can be used confidently, as the linear seismic sources are well quantified by different researchers. For South India, either of the other two source models is recommended and it is observed that both give comparable results, but are unequal.

Major cities	Location		PGA value (g)					
	Longitude (^{o}E)	Latitude (^{o}N)	Aerial source Model		Gridded Seismicity Model		Linear Source Model	
			475 years return period	2475 years return period	475 years return period	2475 years return period	475 years return period	2475 years return period
Ahmedabad	72.62	23.00	0.1	0.20	0.07	0.11	0.12	0.23
Bangalore	77.59	12.98	0.08	0.13	0.10	0.21	0.12	0.27
Chennai	80.25	13.07	0.08	0.17	0.06	0.11	0.10	0.21
Delhi	77.20	28.58	0.16	0.43	0.18	0.36	0.33	0.6
Hyderabad	78.48	17.38	0.03	0.05	0.055	0.12	0.143	0.24
Jaipur	75.87	26.92	0.04	0.075	0.074	0.14	0.126	0.21
Kanpur	80.40	26.47	0.06	0.09	0.05	0.1	0.15	0.21
Kolkata	88.33	22.53	0.08	0.14	0.12	0.21	0.13	0.24
Mumbai	72.82	18.90	0.08	0.18	0.09	0.16	0.11	0.2
Pune	73.87	18.53	0.05	0.10	0.07	0.11	0.08	0.13

7. CONCLUSIONS

Present study presents the comparison of different methodologies adopted to estimate seismic hazard in and around India, using a probabilistic approach. The seismic hazard evaluation of the study area based on a state-of-the art PSHA study has been performed using the classical Cornell–McGuire approach with different source models and attenuation relations. The most recent knowledge on seismic activity in the region has been used to evaluate the hazard incorporating uncertainty associated with different modeling parameters as well as spatial and temporal uncertainties. Specifically logic tree approach has been avoided in the reported PSHA methods. PHA estimated from PSHA method handles immeasurable uncertainties. The present hazard maps produced for horizontal ground motion on bed rock show local spatial variation in contrary to uniform hazard value suggested by Indian Seismic code (BIS 1983). The contour maps obtained using different source models in the study are comparable, but show little variation from each other because of the different approaches followed in modeling the sources, which highlights the uncertainties involved in the modeling process. Strong ground-motion records for earthquakes in the region would be very essential to develop region specific attenuation equations for various tectonic provinces in the region.

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