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# Probabilistic Seismic Hazard Assessment for Northeast India Region

RANJIT DAS,[1] M. L. SHARMA,[1] and H. R. WASON[1]

*Abstract*—Northeast India bounded by latitudes 20°–30°N and longitudes 87°–98°E is one of the most seismically active areas in the world. This region has experienced several moderate-to-large-sized earthquakes, including the 12 June, 1897 Shillong earthquake ($M_w$ 8.1) and the 15 August, 1950 Assam earthquake ($M_w$ 8.7) which caused loss of human lives and significant damages to buildings highlighting the importance of seismic hazard assessment for the region. Probabilistic seismic hazard assessment of the region has been carried out using a unified moment magnitude catalog prepared by an improved General Orthogonal Regression methodology (Geophys J Int, 190:1091–1096, 2012; Probabilistic seismic hazard assessment of Northeast India region, Ph.D. Thesis, Department of Earthquake Engineering, IIT Roorkee, Roorkee, 2013) with events compiled from various databases (ISC, NEIC,GCMT, IMD) and other available catalogs. The study area has been subdivided into nine seismogenic source zones to account for local variation in tectonics and seismicity characteristics. The seismicity parameters are estimated for each of these source zones, which are input variables into seismic hazard estimation of a region. The seismic hazard analysis of the study region has been performed by dividing the area into grids of size 0.1° × 0.1°. Peak ground acceleration (PGA) and spectral acceleration ($S_a$) values (for periods of 0.2 and 1 s) have been evaluated at bedrock level corresponding to probability of exceedance (PE) of 50, 20, 10, 2 and 0.5 % in 50 years. These exceedance values correspond to return periods of 100, 225, 475, 2475, and 10,000 years, respectively. The seismic hazard maps have been prepared at the bedrock level, and it is observed that the seismic hazard estimates show a significant local variation in contrast to the uniform hazard value suggested by the Indian standard seismic code [Indian standard, criteria for earthquake-resistant design of structures, fifth edition, Part-I. Bureau of Indian Standards, New Delhi, 2002]. Not only holistic treatment of earthquake catalog and seismogenic zones has been performed, but also higher resolution in spatial distribution could be achieved. The COV maps have been provided with the strong ground-motion maps under various conditions to show the confidence in the results obtained. Results obtained in the present study would be helpful for risk assessment and other disaster mitigation-related studies.

**Key words:** Seismic hazard assessment, northeast India, peak ground acceleration, general orthogonal relation.

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## 1. Introduction

Northeast India region, comprising of 8 northeastern states of India, namely Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, and Tripura, bounded by latitudes 20°–30°N and longitudes 87°–98°E, is one of the most seismically active areas in the world. This region has experienced several moderate-to-large-sized earthquakes, including the 12 June, 1897 Shillong earthquake ($M_w$ 8.1) and the 15 August, 1950 Assam $M_w$ 8.7 earthquake (THINGBAIJAM *et al.* 2008). The seismicity of this region is related to the collision of the Indian plate with Tibet towards the north and the Burmese landmass towards the east. This collision has resulted in the formation of the Himalaya thrust front in the north, Arakan-Yoma, Naga Hills, and Tripura folded belt in the east, and also the uplift of the Shillong plateau. Most parts of the region lie in Seismic Zone V (severest seismic zone) of the seismic zoning map of India [IS: 1893(Part 1)-2002].

In general, large destructive earthquakes cause human casualty, socio economic breakdowns, and pose risk to the sustainable development and human civilization, throughout the world. The potential damage incurred due to such earthquakes necessitates mitigation of the risk and evaluation of seismic hazard a priori. Moreover, the multidisciplinary inputs for such detailed exercise require common key parameters recognized by all stake holders to define seismic hazard. The hazard-relevant parameter is generally estimated in terms of strong ground motion, viz., peak ground acceleration, peak ground velocity, peak ground displacement, or spectral acceleration.

The probabilistic seismic hazard assessment (PSHA) is the preferred mode of carrying out seismic hazard in most contemporary seismic

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standards throughout the world and can be seen as catering to the need of defining compatible seismic input for earthquake engineering design. In addition to influencing the policies for retrofitting of old structures or design of new structures, the results of such analysis have long lasting effects, as they impact the decisions of experts involved in the formulation of building codes. Seismic hazard assessment has, therefore, received much attention during last few decades, and necessity of quantifying uncertainties involved at various steps in PSHA is an obvious condition to achieve more realistic seismic hazard. Most of the seismic hazard estimations are concentrated on the application of the PSHA at different parts of the world and new challenges in the methodologies used in its development, since its formation (CORNELL 1968; VENEZIANO et al. 1984; KEBEDE and VAN ECK 1996; KIJKO and GRAHAM 1999; LINDHOLM and BUNGUM 2000, 2003; SABETTA et al. 2005).

## 2. Previous Seismic Hazard Studies

The seismic hazard assessment studies carried out earlier for the Indian region (e.g., TANDON 1956; KRISHNA 1959; GUHA 1962; GUBIN 1968) had an emphasis towards what is known as 'scenario earthquake', but subsequent studies were focused on intensity-based zoning (e.g., BASU and NIGAM 1977; KAILA and RAO 1979; KHATTRI et al. 1984). Recent seismic hazard assessment studies although use probabilistic seismic hazard methodology, but are based on inappropriately homogenized earthquake catalogs without considering the effect of associated uncertainties in the hazard estimates (e.g., BHATIA et al. 1999; PARVEZ et al. 2003; SHARMA 2003; SHARMA et al. 2004; SHARMA and WASON 2004; SHARMA and MALIK 2006; SITHARAM et al. 2006; SITHARAM and ANBAZHAGAN 2007; JAISWAL and SINHA 2007; MAHAJAN et al. 2010; NATH and THINGBAIJAM 2012; NAIK and CHOUDHURY 2015; DESAI and CHOUDHURY 2014a, b, c, 2015; SHUKLA and CHOUDHURY, 2012a, b, c). DAS et al. (2006) estimated uniform hazard spectra for pseudo spectral velocity for Northeast India.

## 3. Unified Earthquake Catalog

For any PSHA study, a reliable and appropriately homogenized earthquake catalog is one of the basic inputs. An extensive study has been carried out by DAS (2013) for preparing a homogenized earthquake catalog in moment magnitude for the Northeast India region using an improved magnitude conversion procedure proposed by WASON et al. (2012) with events data compiled from various databases (ISC, NEIC, GCMT, IMD) and available catalogs. For the historical seismicity during 1897 to 1962, events data are taken from the catalog by GUPTA et al. (1986). For the period 1964 to 2010, events data have been compiled from global ISC and NEIC databases. Data for the year 1963 have been adopted from International Seismological Summary (ISS). In addition, moment magnitudes data of GCMT and NEIC have been considered for the periods 1978–2006 and 1975–2010, respectively. Some events for the period 1999–2006 are also considered from seismological bulletins of India Meteorological Department (IMD), New Delhi, and the catalog by BAPAT et al. (1983) and CHANDRA (1992). A seismicity map for Northeast India region for events with $M_w \geq 2.1$ is shown in Fig. 1 (DAS 2013).

## 4. Seismogenic Source Zones for the Study Region

One of the pre-requisites for carrying out the seismic hazard assessment is the demarcation of independent seismogenic sources in the area. Due to its high seismicity, this region has received the attention of many scientists and engineers in the past to assess the seismic hazard and risk, but the demarcation of seismogenic sources has been done differently by different investigators. DUTTA (1964) subdivided this region into four main seismogenic source zones: the Eastern Syntaxis (zone I), the Arakan-Yoma Subduction Belt (zone II), the Shillong Plateau (zone III), and Main Central Thrust (MCT) and Main Boundary Thrust (MBT) of the Himalayan frontal thrusts (zone IV). These four zones proposed by DUTTA (1964) have been further subdivided into nine seismogenic zones in this study based on
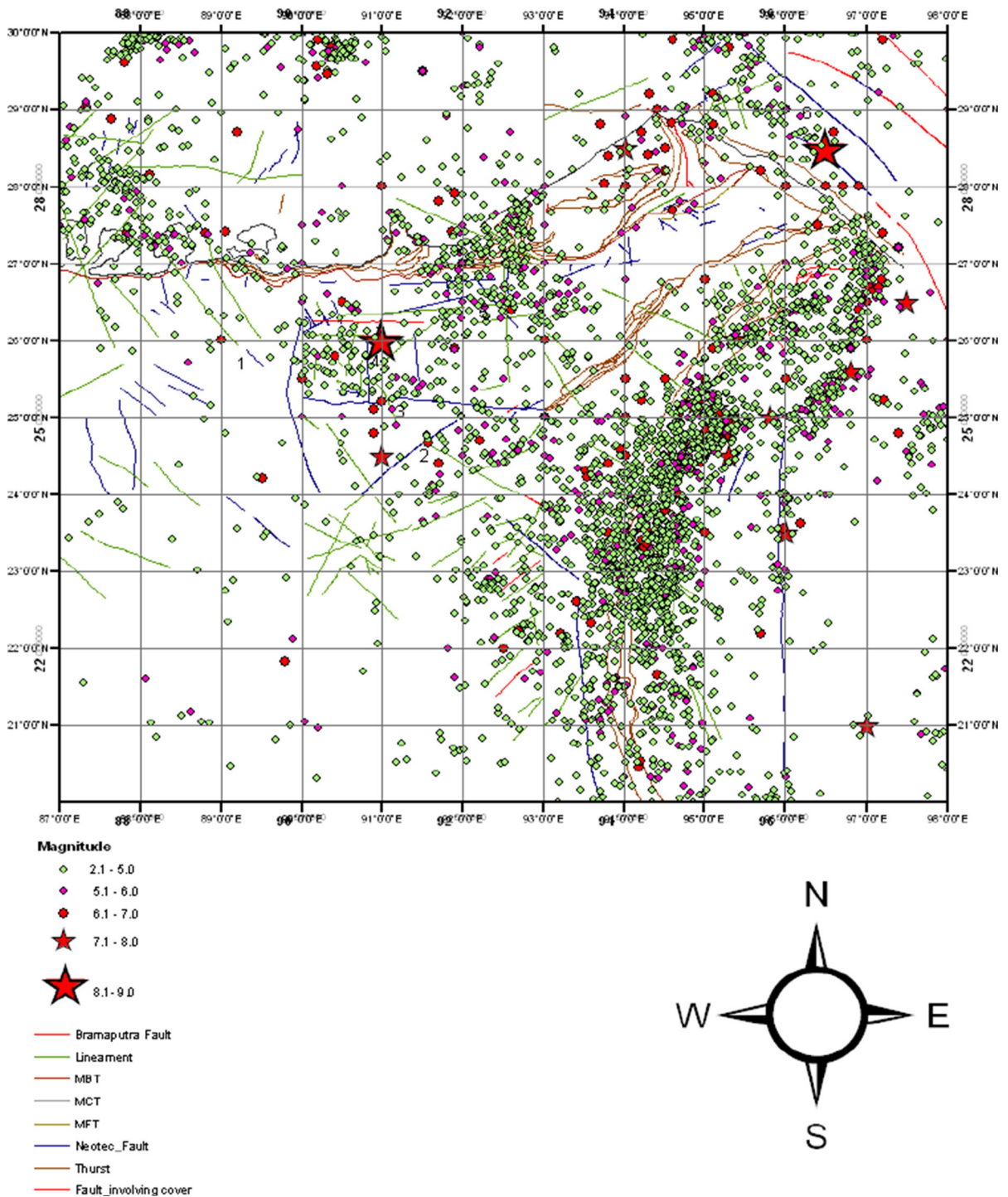
Figure 1
Seismotectonic map showing the epicenters and the tectonic features of Northeast India region on GIS platform depicting seismicity for $M_w \geq 2.1$

regional geology, tectonics, focal mechanism solutions, and spatial distribution of seismicity (ANGELIER and BARUAH 2009; DAS *et al.* 2012), and are shown in Fig. 2. These nine zones are: Zone I—North South Indo Burma fold Belt, Zone II—NE-SW Indo Burma fold Belt, Zone III—Sagging Fault region, Zone IV—NW–SE trending feature, Zone V—Tibetan Plateau, Zone VI—Eastern MCT, Zone VII—Shillong Plateau, Zone VIII—Sylhet Fault, and Zone IX—NE-SW trending Structure. The seismotectonic sources thus earmarked and used in this study are described as follows:

### 4.1. Seismogenic Source Zone I

Zone 1 covers some parts of Assam, entire Mizoram, and some parts of Manipur. From 1897 to 2010, a total of 823 events occurred in this zone. The reported maximum magnitude earthquake experienced in this region is 7.1 which occurred on 16 August 1938. The folded belt of this zone is represented by high anticlinal ridges and synclinal valleys of Surmas and Tipams (Miocene) having major N–S trending strike faults. The average focal depth of the events in this zone is observed to be 75 km. The predominant focal mechanism in this zone appears to be Reverse Fault (ANGELIER and BARUAH 2009).

### 4.2. Seismogenic Source Zone II

Since 1897–2010, a total of 858 events occurred in this zone. The seismicity of this zone is generally thrust type. The thrusts in this zone are dipping towards southeast. This zone is in northern Indo Burma fold belt. The last maximum earthquake occurred in this region is magnitude 7.2 on 6 August, 1988. The maximum time gap for occurrence of large earthquake ($\geq$7.0) is found to be 31 years. A phase of low seismic activity appears to have started from 1988 and is continued so. The regional structural trend of orogenic belt of this zone is mostly NE–SW originating from Arunachal Pradesh and changes gradually to NNE–SSW. The average focal depth of the zone is considered to be 70 km.

### 4.3. Seismogenic Source Zone III

This zone covers Myanmar. This zone is bounded by the major N–S trending Sagging fault. Convergence and subduction of the Indian plate occur along the Indo- Burma arc (MITCHELL and MCKERROW 1975). The last maximum earthquake experienced in this region was magnitude 7.9 on 23 May, 1912. The maximum time gap for occurrence of large earthquake ($\geq$7.0) is found to be 34 years (1912–1946). A total of 179 earthquakes occurred in this zone. The average focal depth for this zone is 66 km.

### 4.4. Seismogenic Source Zone IV

This zone is known as Mishmi Massif, a NW–SE trending feature. The maximum earthquake occurred in this area is magnitude 8.5 on 15 August, 1950. A total of 172 earthquakes occurred in this area from 1897 to 2010. This seismic zone is marked by Mishmi thrust, Lohit thurst, Tiding suture and Pochu Fault, and a few lineaments. The average focal depth of the zone is considered to be 42 km.

### 4.5. Seismogenic Source Zone V

This zone is Tibetan Plateau. A total of 160 events occurred in this area. The maximum magnitude reported in this zone is 7.0. The average focal depth considered in this zone is 37 km.

### 4.6. Seismogenic Source Zone VI

This zone is Himalayan Mountain Belt. This zone consists of eastern MCT. The maximum magnitude observed in this zone is 6.8. The main seismogenic features in this zone are MBT and MCT. The average focal depth of this zone is 39 km. A total of 177 events occurred in this zone.

### 4.7. Seismogenic Source Zone VII

This zone is the Shillong plateau. A total of 119 events occurred in this zone from 1897 to 2010. The maximum reported earthquake experienced in this
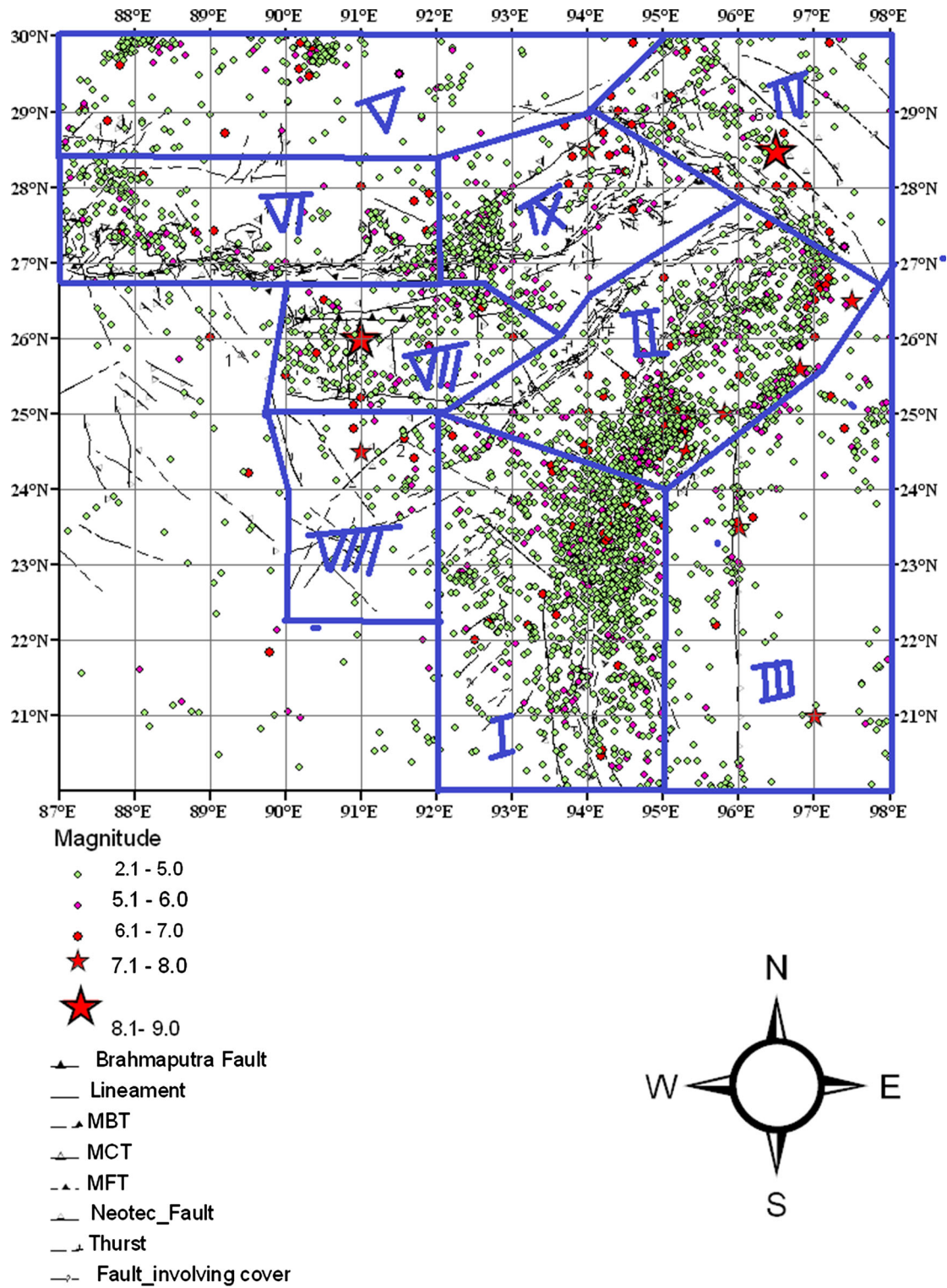
Figure 2
Seismogenic source zones considered for Northeast India region

area is 8.6 magnitude on 26 June, 1897. The maximum time gap for occurrence of large earthquake ($\geq 7.0$) is found to be 26 years. Dauki fault is the prominent fault running through about 450 km and is most likely source of the 1897 great earthquake. Dauki fault was believed to be active during the late Quaternary time by the geomorphic features of the Shillong Plateau and trend along E–W direction. Dudhnoi fault and Ailtherkhet fault are two important faults in this zone. Average focal depth of this zone is assumed to be 37 km.

### 4.8. Seismogenic Source Zone VIII

This zone lies in Bengal basin. This zone occupies Tripura and some parts of Bangladesh. Sylhet fault is the important tectonic feature of this zone. A total of 54 events occurred in this area from 1897 to 2010. The maximum reported earthquake experienced in this area is 7.5 occurred on 8 July, 1918. The average focal depth of this zone is 35 km.

### 4.9. Seismogenic Source Zone IX

This zone lies in Himalayan mountain belt and having NE–SW trending features. A total of 132 events occurred in this area since 1897–2010. The maximum magnitude reported in this area is 7.6 on 29 July, 1947. The average focal depth is considered to be 44 km.

## 5. Completeness of the Homogenized Catalog

Because of the Poissonian assumption of earthquake occurrence intrinsic to the Cornell–McGuire approach for PSHA, dependent events (foreshocks and aftershocks) are required to be removed from the catalog. Several methods have been proposed for declustering a catalog (e.g., GARDNER AND KNOPOFF 1974; REASENBERG 1985; URHAMMER 1986). The declustering algorithm developed by Urhammer (1986) has been used in the present study using a moving space and time window approach. The total number of earthquake epicenters ($M_w \geq 2.1$) lying within the nine seismogenic zones before the

declustering was 3624, whereas 2674 events finally remained after the removal of the foreshocks and the aftershocks in the homogenized catalog (i.e., 74 % main events).

The completeness of the homogenized earthquake catalog was analyzed using the method given by STEPP (1972). The completeness periods for the homogenized catalog for different magnitude ranges are observed to be as 3.1–3.5 during the period 1991–2010, 3.6–4.0 during the period 1980–2010, 4.6–5.0 during the period 1960–2010, 5.1–5.5 during the period 1950–2010, 5.6–6.0 for the period 1920–2010, and for $\geq 6.0$ during the periods 1890–2010 (Fig. 3). The completeness periods for the lower magnitude ranges are smaller as the region was not well instrumented in the past and, therefore, a lot of smaller magnitude events were not recorded. The seismicity parameters have to be evaluated based on the complete part of the catalog.

## 6. Evaluation of Seismicity Parameters

The magnitude of completeness ($M_c$) is estimated for each seismogenic zone. For example, $M_c$ value has been observed to be 4, 5, 6, 7, and 8 corresponding to the years 1965, 1953, 1937, 1911, and 1897, respectively, for the source zone VII, while for the source zone III, the completeness periods are 1965, 1955, 1939, 1910, and 1900 for the same magnitudes. Then, the Gutenberg–Richter magnitude frequency relationship parameters for the different zones are determined. A homogenous declustered catalog has been prepared for each zone separately. Therefore, the complete catalog is used to estimate the seismicity parameters. Maximum magnitude ($M_{max}$) is estimated for all of the zones based on the generic equation given by KIJKO (2004). The seismicity parameters required for estimation of probabilistic seismic hazard assessment are $b$- and $a$-values, seismic activity rate ($\lambda$), $\beta$, $M_{max}$, threshold magnitude ($M_c$), and average focal depth ($D$). The seismicity parameters for different source zones used for PSHA are given in Table 1. The Gutenberg–Richter frequency distributions of the nine seismic zones are also shown in Fig. 4.
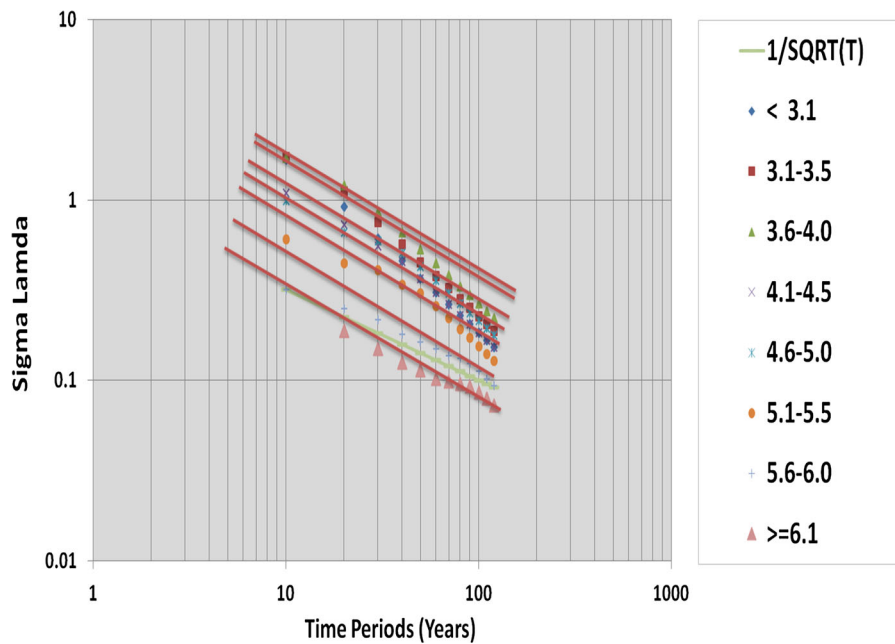
Figure 3
Standard deviation of the estimate of the mean of the annual number of events as a function of sample length and magnitude class

Table 1

*Seismicity parameters for nine seismogenic zones*

| Source | Seismicity parameters estimated for seismic hazard assessment for Northeast India region | | | | | | | | | | D |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $a$ | $b$ | $M_c$ | $\lambda$ | Err | $\beta$ | Err | $M_{max}$ | Err | $M_{obs}$ | |
| Z1 | 5.76 | 1.07 | 4.3 | 14.42 | 0.49 | 2.46 | 0.16 | 7.5 | 0.27 | 7.1 | 75 |
| Z2 | 4.93 | 0.88 | 4.4 | 11.43 | 0.38 | 2.03 | 0.12 | 8.4 | 0.34 | 7.9 | 70 |
| Z3 | 4.8 | 0.87 | 4.6 | 6.28 | 0.23 | 2.00 | 0.09 | 8.3 | 0.26 | 7.9 | 66 |
| Z4 | 3.56 | 0.66 | 4.5 | 3.89 | 0.12 | 1.52 | 0.06 | 8.9 | 0.11 | 8.5 | 42 |
| Z5 | 3.34 | 0.73 | 3.7 | 4.36 | 0.08 | 1.68 | 0.11 | 7.4 | 0.23 | 7.0 | 37 |
| Z6 | 3.96 | 0.83 | 4.2 | 2.94 | 0.15 | 1.91 | 0.06 | 7.5 | 0.32 | 6.8 | 39 |
| Z7 | 1.68 | 0.43 | 4.2 | 0.74 | 0.09 | 0.99 | 0.05 | 9.0 | 0.19 | 8.6 | 37 |
| Z8 | 2.31 | 0.63 | 3.6 | 1.08 | 0.04 | 1.46 | 0.04 | 7.9 | 0.14 | 7.5 | 35 |
| Z9 | 4.79 | 1 | 4.3 | 3.09 | 0.27 | 2.30 | 0.15 | 8.0 | 0.23 | 7.6 | 44 |

## 7. Ground-Motion Prediction Equations

One of the important factors which have high impact on the evaluation of seismic hazard is the ground-motion prediction models. There can be considerable variation between the predicted and the actual acceleration values given by the attenuation models. Hence, for reducing the epistemic uncertainties in the prediction models, two attenuation models are used in this study. GUPTA (2010) proposed an attenuation model based on real data for Northeast India, mainly using subduction events. NATH and THINGBAIJAM (2011) also developed an attenuation relation for Northeast India based on stochastic approach. The ground-motion equation given by BARUAH et al. (2009) has the
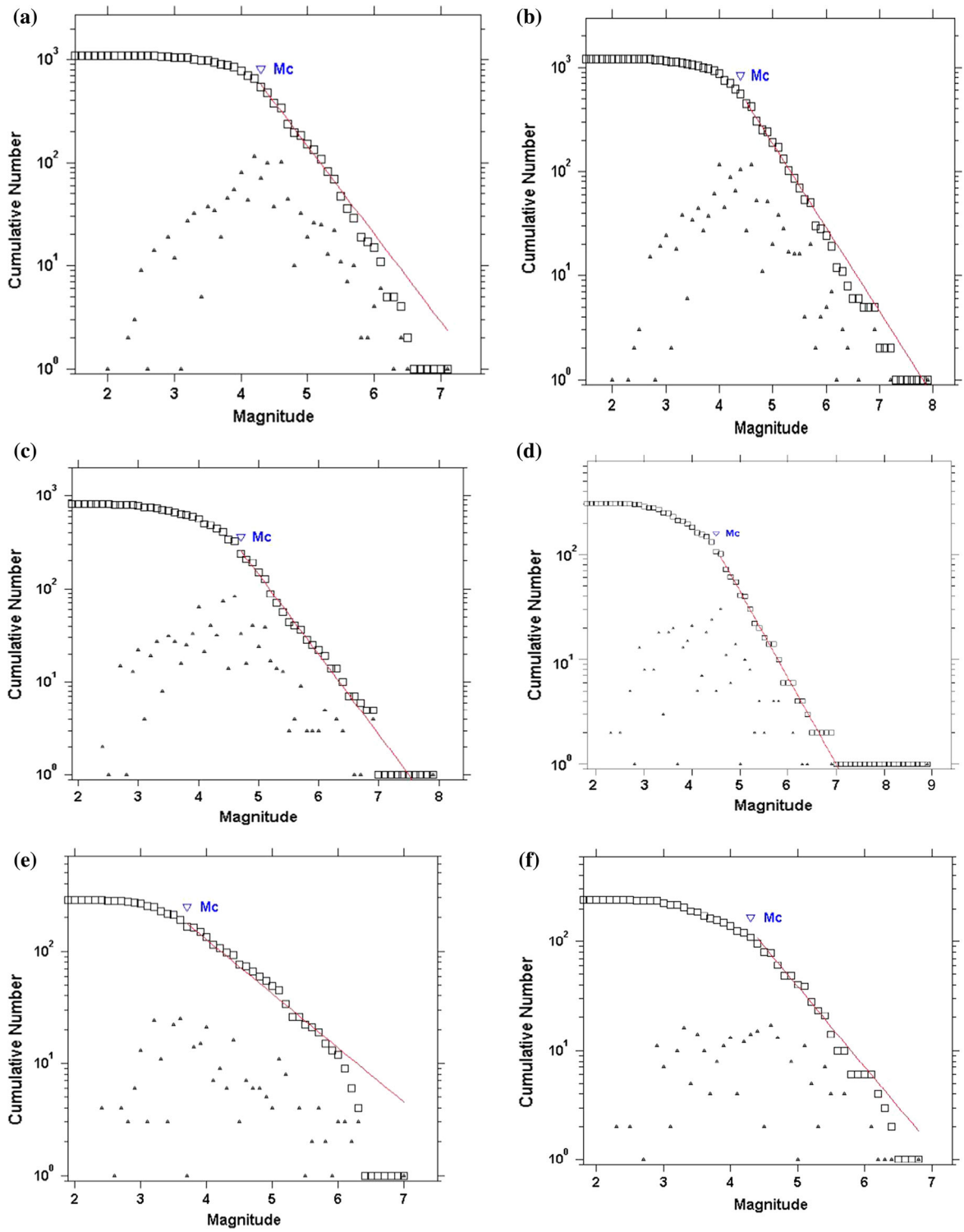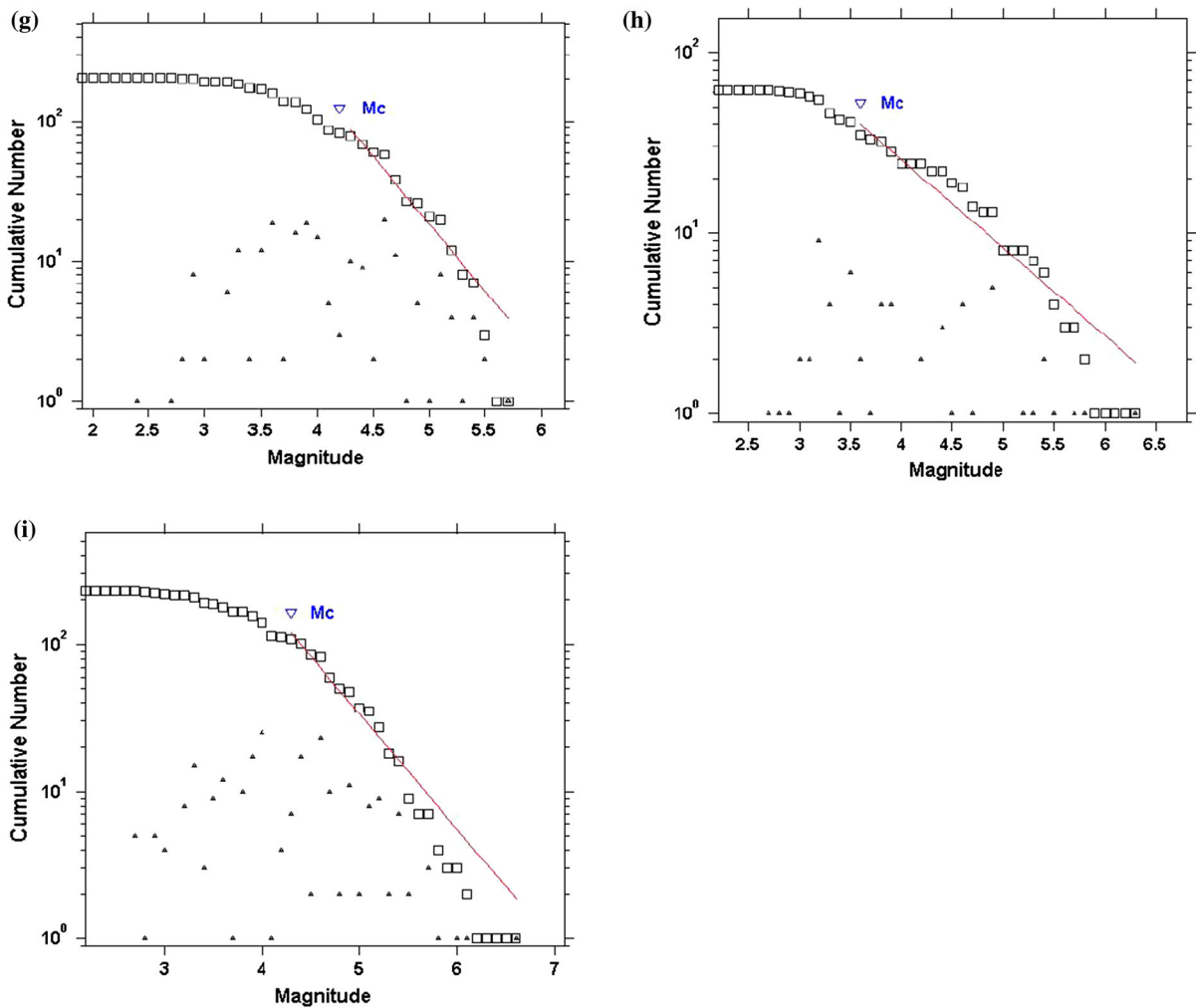
Figure 4
Gutenberg–Richter frequency relationships for nine seismic zones

Figure 4
continued

limitations in the magnitude range and need for magnitude scaling to $M_w$.

Moss and Der (2006) have emphasized about the consideration of epistemic uncertainty in attenuation relationship due to errors in different parameters. In this study, epistemic errors have been considered using the logic tree method using the spectral attenuation relationships developed for this area as well as those developed for similar tectonic environments elsewhere and adopted for the region. In the light of this problem, GMPEs have been chosen based on the following criteria:

a. Compatibility of model with seismotectonic and geological setting of study area,

b. Preferably developed from a database of natural ground-motion records, and

c. Structural period range of the GMPE being appropriate for engineering applications.

The two shallow crustal GMPEs chosen after comparison with Northeast India strong-motion data are those by Gupta (2010) and Boore and Atkinson (2008). Gupta (2010) developed an empirical attenuation relationship by combining the data for both
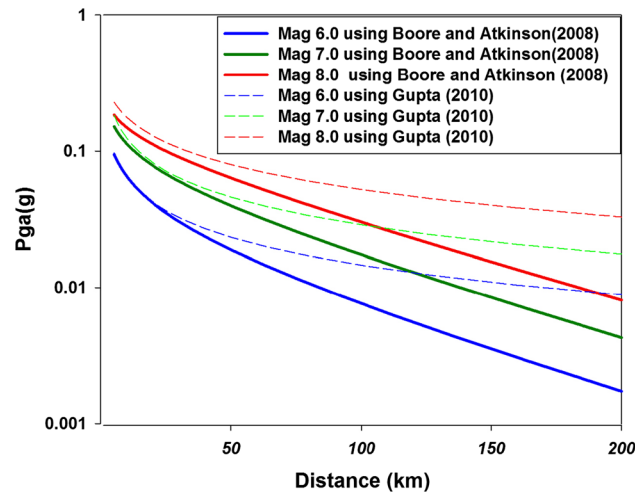
Figure 5
Comparisons of ground–motion attenuation relationships on rock conditions for three different magnitudes

horizontal and vertical components of motion. The plot of attenuation relations of BOORE and ATKINSON (2008) and GUPTA (2010) has been shown in Fig. 5.

## 8. Seismic Hazard Estimates for Northeast India

Seismic hazard calculations have been performed using the numerical code CRISIS2007 based on the classical Cornell–McGuire method implementing the total-probability theorem. The unified source model which consists of nine seismic sources has been used. Each area source is characterized by the seismicity parameters in terms of minimum and maximum magnitudes, G–R earthquake recurrence rates, focal depths, and focal mechanism solutions.

Seismic hazard has been computed by performing hazard computations at a grid interval of 0.1° × 0.1° covering the entire Northeast India region. The PSHA results reported in this study are obtained by assigning equal weights to different branches of the logic tree used (see Figs. 4, 5, 6, 7, 8, 9). Contour maps have been produced for mean values of PGA and mean spectral accelerations at PGA, and 0.2 and 1.0 s spectral periods for 50, 20, 10, 2, and 0.5 % probabilities of exceedance in 50 yrs which are equivalent to return periods of 100, 225, 475, 2475, and 10,000 years, respectively.

From both the scientific and user points of view, the uncertainty estimates are inseparable part of the seismic hazard that are as important as the other hazard products and should provide valuable insights for applying the maps and describe our confidence in the mean hazard estimates. The uncertainties in terms of the COV values have been plotted for the PGA and $S_a$ values with various return periods. A COV value is the standard deviation divided by the mean value obtained at the point of observation. The variation in the parameters namely $b$, $M_c$, and $M_{max}$ was obtained using the Monte Carlo simulations. In all, 200 sets of the values were generated and the seismic hazard was estimated at all the grid points. The mean seismic hazard calculation is the expected value of the underlying distribution of hazard values for a given risk level and is, thus, the best estimate of seismic hazard for the area studied (CRAMER 2001). In addition to the strong-motion parameter estimated at each grid, the COV maps were also generated for the region and for specific condition of the strong ground motion. The accompanying COV maps represent overall variability in seismic hazard for PGA and spectral accelerations ($S_a$) at 0.1, 0.2, and 1.0 s for 100, 225, 475, 2475, and 10,000 years of return periods. Thus, estimated mean strong ground motion and the COV values are plotted in Figs. 4, 5, 6, 7, 8, and 9. The seismic hazard estimated for various
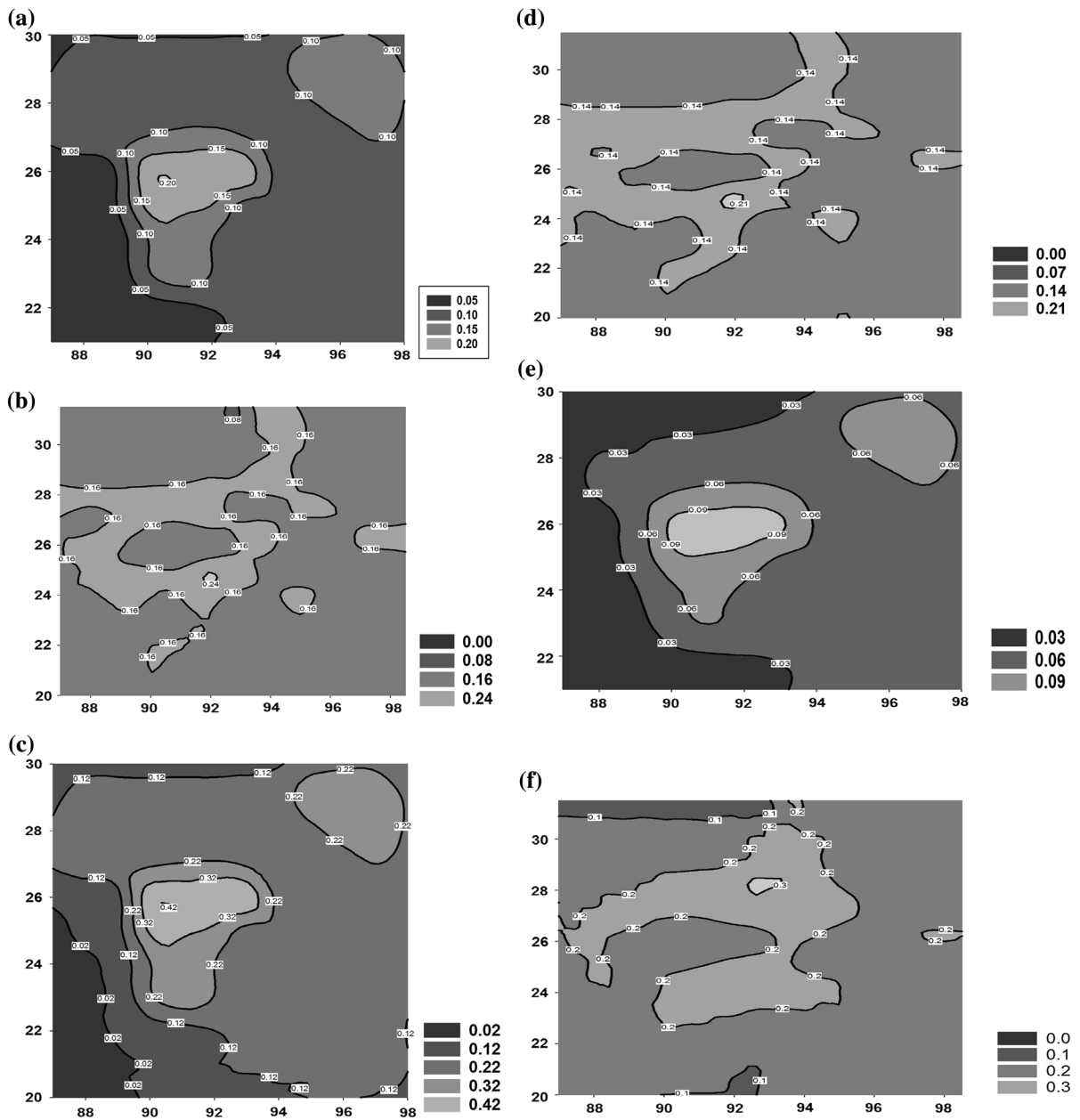
Figure 6

Contour maps for 50 % exceedance in 50 years for: **a** Mean PGA, **b** COV for mean PGA, **c** $S_a$ at 0.2 s, **d** COV for $S_a$ at 0.2 s, **e** $S_a$ at 1.0 s, and **f** COV for $S_a$ at 1.0 s

conditions of exceedance and their COV values have been summarized in Table 2.

The maximum and minimum values obtained for the mean PGA and COV values are given in Table 2 for all the return periods and three spectral periods. From earthquake engineering perspective, the

exceedance values of 0.5 and 2 % exceedance in 50 years are generally considered for Maximum Credible Earthquake (MCE). The Indian seismic code [IS:1893 (Part 1) 2002] classifies most of the Northeast India regions into Seismic Zone V (with effective PGA 0.36 for MCE). The 2 % exceedance
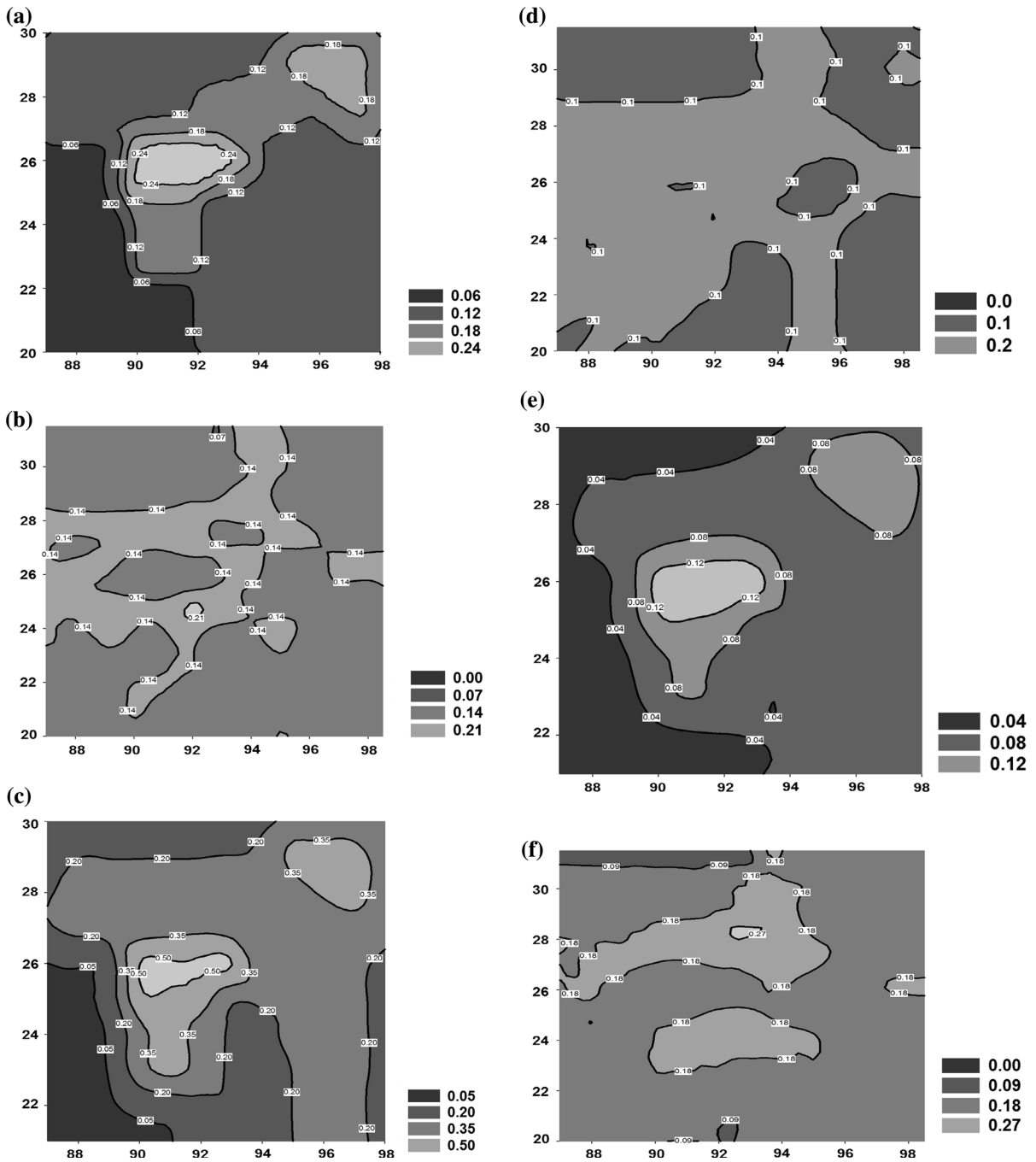
**(a)**



**(b)**



**(c)**



**(d)**



**(e)**



**(f)**



Figure 7

Contour maps for 20 % exceedance in 50 years for: **a** mean PGA, **b** COV for mean PGA, **c** $S_a$ at 0.2 s, **d** COV for $S_a$ at 0.2, **e** $S_a$ at 1.0 s, and **f** COV for $S_a$ at 1.0 s

values are considered as MCE for hydroelectric power projects and other engineering mega projects, while the 0.5 % exceedance in 50 years is sometimes considered by nuclear power industry for SSE (Safe Shutdown Earthquake) value which is equivalent of MCE value. In the present case, the values estimated for 0.5 and 2 % exceedance in 50 years, equivalent to return period of 10,000 and 2475 years, are estimated
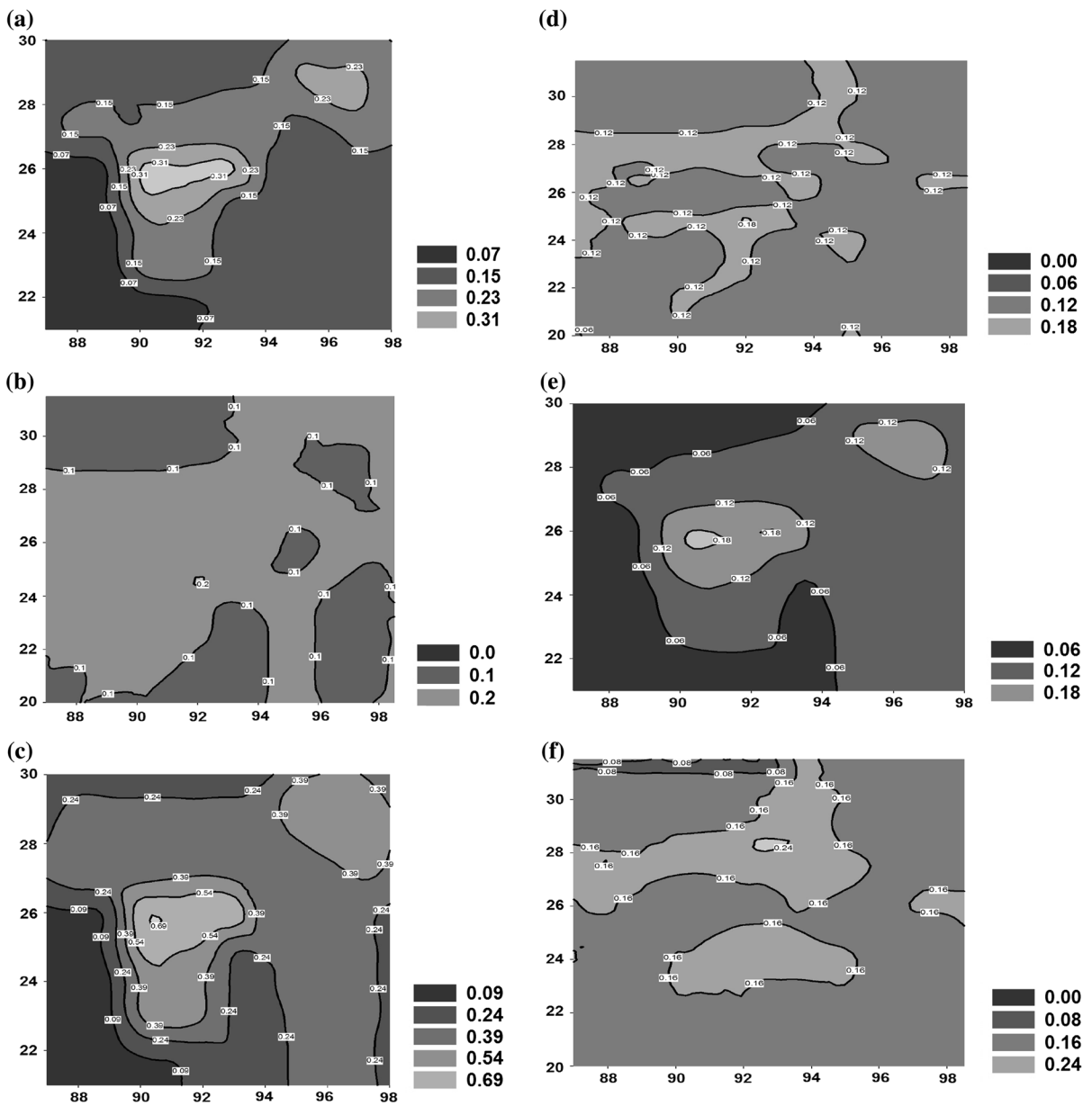
Figure 8

Contour maps for 10 % exceedance in 50 years for: **a** mean PGA, **b** COV for mean PGA, **c** $S_a$ at 0.2 s, **d** COV for $S_a$ at 0.2, **e** $S_a$ at 1.0 s, and **f** COV for $S_a$ at 1.0 s

to be 0.68 and 0.50 g, respectively, at some of the places in this region. The 20 % exceedance and 10 % exceedance values are generally considered for the Design Basis Earthquake (DBE). The values for these exceedance rates, equivalent to return periods of 225 and 475 years, are estimated to be 0.25 and 0.32 g,

respectively. The Indian standard code prescribes the DBE value to be taken as half of the MCE value and the results obtained in the present study match quite well with the Indian standard codal values [IS:1893 (Part 1) 2002]. The treatment to the seismicity data carried out in the present study and the logic tree
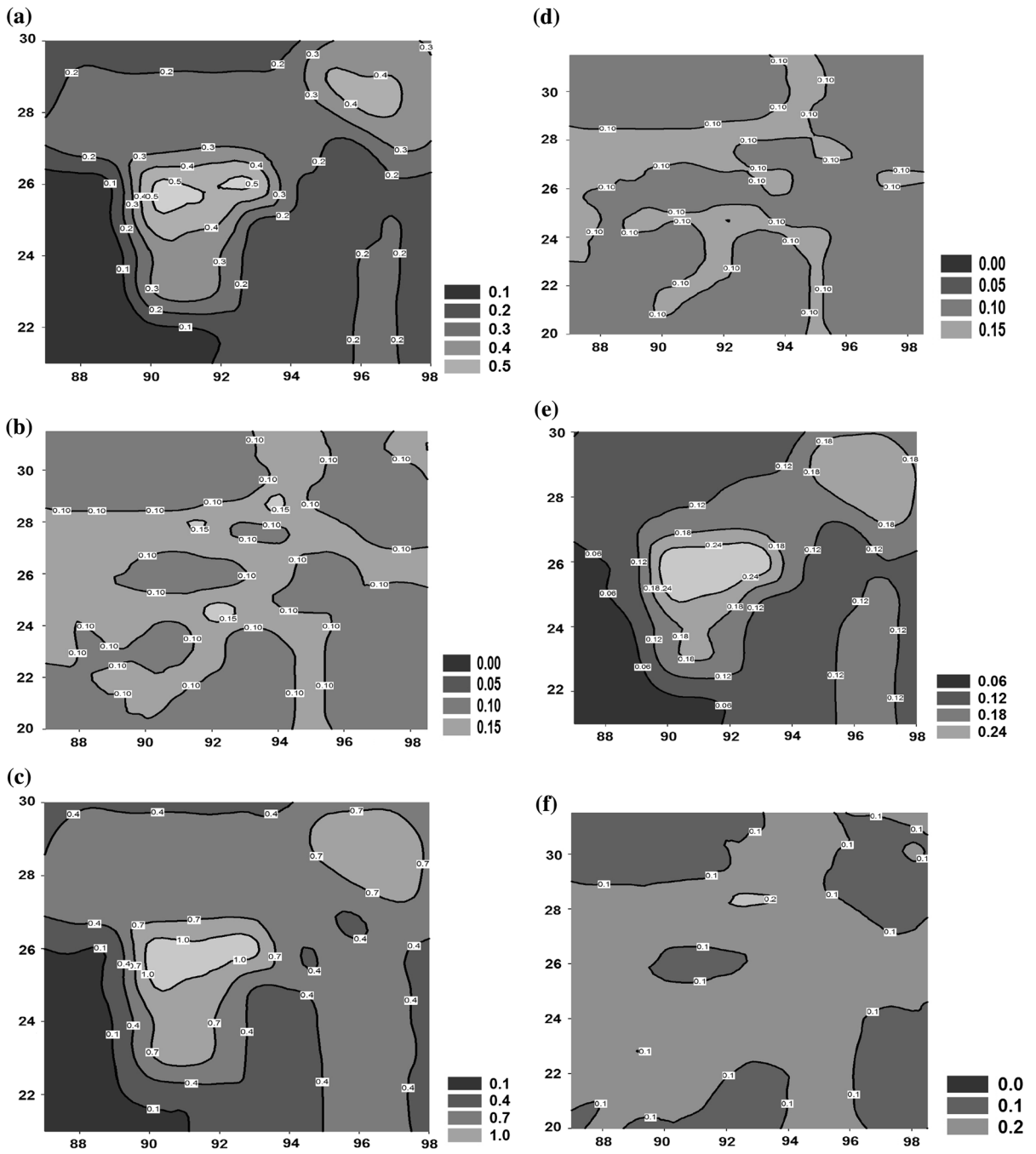
**(a)**



**(d)**



**(b)**



**(e)**



**(c)**



**(f)**



Figure 9
Contour maps for 2 % exceedance in 50 years for: **a** mean PGA, **b** COV for mean PGA, **c** $S_a$ at 0.2 s, **d** COV for $S_a$ at 0.2, **e** $S_a$ at 1.0 s, and **f** COV for $S_a$ at 1.0 s

Table 2

*Maximum and minimum values of seismic hazard and COV for return periods of 100, 225, 475, 2475, and 10,000 years*

|  |  | 100 year | | 225 year | | 475 year | | 2475 year | | 10,000 year | |
|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | Max | Min | Max | Min | Max | Min | Max | Min | Max | Min |
| PGA | Mean | 0.19 | 0.01 | 0.251 | 0.01 | 0.323 | 0.01 | 0.5 | 0.02 | 0.68 | 0.02 |
|  | COV | 0.246 | 0.08 | 0.222 | 0.07 | 0.206 | 0.07 | 0.168 | 0.065 | 0.15 | 0.06 |
| $S_a$ (0.2) | Mean | 0.4 | 0.01 | 0.518 | 0.01 | 0.656 | 0.02 | 1.1 | 0.1 | 1.48 | 0.05 |
|  | COV | 0.214 | 0.07 | 0.195 | 0.07 | 0.177 | 0.07 | 0.15 | 0.06 | 0.127 | 0.06 |
| $S_a$ (1.0) | Mean | 0.103 | 0.01 | 0.143 | 0.01 | 0.178 | 0.02 | 0.287 | 0.04 | 0.42 | 0.16 |
|  | COV | 0.3 | 0.09 | 0.27 | 0.08 | 0.244 | 0.08 | 0.206 | 0.07 | 0.178 | 0.068 |

Table 3

*Comparison of computed PGA with other studies for 10 % probability of exceedance in 50 years at selected cities*

| City | GSHAP BHATIA et al. (1999) | BIS (2002) | SHARMA and MALIK (2006) | NDMA (Iyengar et al. 2011) | NATH and THINGBAIJAM (2012) | Present Study |
|---|---|---|---|---|---|---|
| Guwahati | 0.30 | 0.18 | 0.5 | 0.23 | 0.98 | 0.244 |
| Imphal | 0.45 | 0.18 | 0.4 | 0.35 | 0.99 | 0.144 |
| Agartala | 0.45 | 0.18 | 0.3 | 0.18 | 0.5 | 0.217 |
| Shillong | 0.30 | 0.18 | 0.48 | 0.25 | 1.10 | 0.316 |
| Kohima | 0.3 | 0.18 | 0.5 | 0.2 | 0.6 | 0.148 |
| Gangtok | 0.25 | 0.18 | 0.35 | 0.15 | 0.5 | 0.146 |
| Itanagar | 0.36 | 0.18 | 0.44 | 0.3 | 0.7 | 0.182 |
| Tezpur | 0.3 | 0.18 | 0.4 | 0.2 | 0.75 | 0.2 |
| Pasighat | 0.3 | 0.18 | 0.5 | 0.2 | 0.7 | 0.182 |
| Aizwal | 0.3 | 0.18 | 0.3 | 0.18 | 0.6 | 0.114 |

approach has yielded PSHA estimates different from those reported in most of the studies carried out for this area (DAS et al. 2006; SHARMA and MALIK 2006; IYENGAR et al. 2011; MAHAJAN et al. 2010; NATH and THINGBAIJAM 2012). A comparison of PSHA results for 10 % probability of exceedance has been shown in Table 3. The classification adopted by the intensity-based zoning in the code, for most part, is comparable to the PSHA results presented here.

## 9. Results and Discussion

The updated earthquake catalog for the study region has been homogenized in terms of unified moment magnitude ($M_w$) using general orthogonal regression (GOR), conversion relations derived specifically for the study region and global GOR relations obtained following an improved GOR estimation procedure for conversion of different magnitude types to cover entire magnitude range involved.

The seismic hazard analysis of Northeast India region has been carried out by dividing the entire study area into grids of size $0.1° \times 0.1°$. Peak ground acceleration (PGA) and spectral acceleration ($S_a$) values (for periods of 0.2 and 1 s) have been evaluated at bedrock level corresponding to probability of exceedance (PE) of 50, 20, 10, 2, and 0.5 % in 50 years. These exceedance values correspond to return periods of 100, 225, 475, 2475, and 10,000 years, respectively. For each grid point, all the sources within a radius of 300 km were considered for the evaluation of PGA and $S_a$ values. Estimation of the seismic hazard has been done using the software CRISIS2007 (ORDAZ et al. 2007). The spatial variations of PGA values obtained for 50, 20, 10, and 2 % exceedance in 50 years are
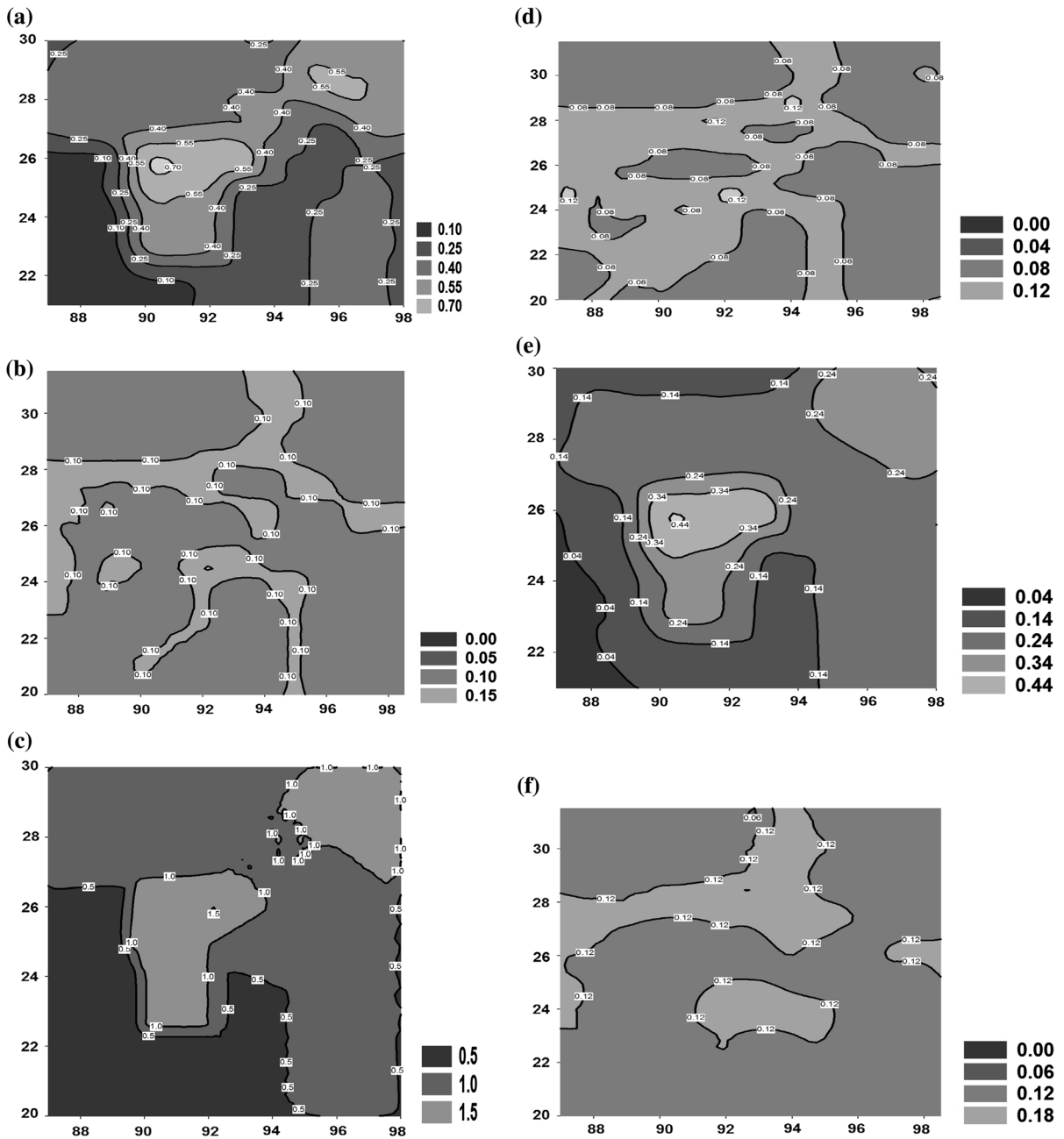
Figure 10
Contour maps for 0.5 % exceedance in 50 years for: **a** mean PGA, **b** COV for mean PGA, **c** $S_a$ at 0.2 s, **d** COV for $S_a$ at 0.2, **e** $S_a$ at 1.0 s, and **f** COV for $S_a$ at 1.0 s

shown in Figs. 4, 5, 6, 7, 8, and 9. The $S_a$ values for 0.2 and 1 s periods obtained for 50, 20, 10, 2, and 0.5 % exceedance in 50 years are also shown. Figures 6, 7, 8, 9 and 10 present thematic maps showing the spatial variation of PGA values estimated for various return periods using the gridded seismicity source model and GMPE by GUPTA (2010) and BOORE and ATKINSON (2008). The computed PGA values along with those obtained in other studies are given in Table 3.

## 10. Conclusions

The aim of this study was to obtain the probabilistic seismic hazard map based on an improved earthquake catalog for the Northeast India region. The catalog used for PSHA is first homogenized into unified moment magnitude ($M_w$) using the GOR relations and declustering of the catalog is performed to remove aftershocks and foreshocks. The study area has been subdivided into nine regional source zones to account for local variation in tectonics and seismicity characteristics. The seismicity parameters are estimated for each of these source zones, which are essential inputs into seismic hazard estimation of a region.

The seismic hazard maps have been prepared at the bedrock level, and it is found that the hazard shows a significant local variation in contrast to the uniform hazard value suggested by the Indian standard seismic code. The seismic hazard model presented in this study shows significant improvements over the probabilistic hazard maps reported in other studies. Not only holistic treatment of earthquake catalog and seismogenic zones has been performed but also higher resolution in spatial distribution could be achieved. The COV maps have been provided with the strong ground-motion maps under various conditions to show the confidence in the results obtained. Results obtained in the present study are more reliable estimates as compared to those given by other investigators. It is envisioned that the present study will facilitate updating of the regional building code provisions for earthquake-resistant construction in this high seismicity region.

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