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ORIGINAL PAPER

On the Bayesian analysis of the earthquake hazard in the North-East Indian peninsula

Imtiyaz A. Parvez

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Abstract The Bayesian extreme-value distribution of earthquake occurrences has been used to estimate the seismic hazard in 12 seismogenic zones of the North-East Indian peninsula. The Bayesian approach has been used very efficiently to combine the prior information on seismicity obtained from geological data with historical observations in many seismogenic zones of the world. The basic parameters to obtain the prior estimate of seismicity are the seismic moment, slip rate, earthquake recurrence rate and magnitude. These estimates are then updated in terms of Bayes' theorem and historical evaluations of seismicity associated with each zone. From the Bayesian analysis of extreme earthquake occurrences for North-East Indian peninsula, it is found that for T = 5 years, the probability of occurrences of magnitude (M_w = 5.0–5.5) is greater than 0.9 for all zones. For M_w = 6.0, four zones namely Z1 (Central Himalayas), Z5 (Indo-Burma border), Z7 (Burmese arc) and Z8 (Burma region) exhibit high probabilities. Lower probability is shown by some zones namely Z4, Z12, and rest of the zones Z2, Z3, Z6, Z9, Z10 and Z11 show moderate probabilities.

Keywords Earthquake occurrences · Bayesian estimators · Extreme values · North-East Indian Peninsula

1. Introduction

Earthquakes constitute the most feared of natural hazards and they occur with no warning and can result in great destruction and loss of life. It is understood that an earthquake occurs when a propagating rupture suddenly releases the accumulated stress on a pre-existing fault. But, it is not known when the rupture will occur or on which of the many faults in a region it will occur. One way to mitigate the destructive

I. A. Parvez (✉)
CSIR Centre for Mathematical Modelling and Computer Simulation,
NAL Belur Campus, Bangalore 560 037, India
e-mail: parvez@cmmas.ernet.in

impact of earthquakes is to conduct a seismic hazard analysis and take the appropriate remedial measures.

Assessment of earthquake hazard represents a very crucial and important problem. The earthquake prediction in terms of location, time and magnitude of a future event in a seismogenic zone is difficult because of the complexity and incomplete understanding of the mechanism that determines the occurrence of earthquakes. However, in this complexity, there is also some feature, we are able to describe through deterministic or stochastic models by statistical summaries or by probability of occurrence of events of specified magnitudes in the region under investigation. Several investigators have addressed the problem of assessing the seismic hazards in the Indian subcontinent (e.g. Auden 1959; Gaur and Chouhan 1968; Kaila and Rao 1979; Khattri et al. 1984; Parvez and Ram 1997, 1999; Parvez et al. 2001, 2002, 2003). Various probabilistic models namely Poisson, Gamma, Normal, Weibull, Lognormal, Exponential, Gumbell etc. assuming recurrence interval as the random variable have been used by different authors to assess the earthquake hazard in different regions (Hagiwara 1974; Rikitake 1976, 1991; Papazachos and Papaioannou 1993; Parvez and Ram 1997, 1999).

In the present study, probabilities of earthquake occurrences in the North-East Indian peninsula are presented. The Bayesian probability theory provides a means of incorporating the statistical uncertainty of the parameters used to quantify the seismicity, in addition to the probabilistic uncertainty associated with the randomness of earthquake occurrences (Campbell 1982, 1983). Its most important aspect is the updating of current probabilities when new information becomes available. This feature allows the user to combine seismotectonic information on seismicity, such as geological data with historical observations. Such applications are very useful when historical data are incomplete, cover too short time period or are insufficient to define rates of seismicity.

Bayesian probability theory has been applied by several authors to the probabilistic assessment of earthquake hazard (Benjamin 1968; Esteva 1976; McGuire 1977; Mortgat and Shah 1979; Eguchi and Hasselman 1979; Campbell 1982, 1983; Stavrakakis and Drakopoulos 1995; Papoulia et al. 2001; Galanis et al. 2002). Campbell (1982, 1983) combined the Bayesian probability theory with a probabilistic model of extremes to develop a Bayesian extreme-value distribution of earthquake occurrences. In this model, prior evaluation of seismicity is obtained using seismotectonic data based on relationships between the seismic moment, slip rate, earthquake recurrence rate and magnitude. These estimates are then updated by applying Bayes' theorem and historical estimates of seismicity associated with the region of interest.

In the present study, the Bayesian extreme-value distribution is applied in order to estimate the seismic hazard associated with 12 seismogenic zones in North-East Indian peninsula. Seismic hazard is expressed in terms of probabilities of occurrence and earthquake magnitude distribution. Prior evaluation of seismicity parameters are developed from the slip rates derived from the seismic moment of the observed earthquakes, using Brune's formula (Brune 1968).

2. Bayesian extreme value distribution

According to Campbell (1982), the Bayesian distribution of extreme earthquake occurrences is developed by assuming that earthquakes have a Poisson distribution with exponential distribution in time and exponential distribution of magnitudes. The Bayesian distribution represents the probability that $M_{\max}$, the size of the largest earthquake expected to occur within a period of t years, will exceed some specified magnitude m and this may be computed from the relationship,

$$P(M_{\max} > m|t) = 1 - \left(\frac{t''}{t'' + t[1 - F(m)]}\right)^{n''}, \tag{1}$$

where n'' and t'' represent updated values of the number of earthquake occurrences and the time period of observation, respectively, and $F(m)$ is the Bayesian distribution of magnitudes.

Commonly, the temporal occurrence of earthquakes may be represented by a Poisson process if it is assumed that earthquakes are independent random events and no two events can occur at the same instant in time. The distribution is given by the expression,

$$P(N = n|v, t) = \frac{(vt)^n \mathrm{e}^{-vt}}{n!}, \tag{2}$$

where $P(N = n|v, t)$ is the probability that the number of earthquakes occurring within a specified period of time t will be equal to n, given that the mean rate of earthquake occurrences is v.

To account for the statistical uncertainty in the estimation of v, Eq. 2 is more accurately represented by the Bayesian (compound) distribution (Benjamin 1968; Benjamin and Cornell 1970; Campbell 1982) and may be obtained by evaluating the integral equation:

$$P(N = n|t) = \int_0^{\infty} P(N = n|v, t) f''(v) \mathrm{d}v, \tag{3}$$

where $f''(v)$ represents the posterior probability density function of v, updated from the prior distribution of v by incorporating through Bayes' theorem observations on the occurrence of earthquakes (i.e. the no. of occurrences within a specified period of time).

By assuming that earthquake occurrences are a Poisson process and that the uncertainty in v may be represented by a gamma distribution, Campbell (1982) proposed Eq. 3 as Bayesian Poisson–gamma distribution,

$$P(N = n|n'', t'', t) = \frac{\Gamma(n + n'')}{n!\Gamma(n'')} \left(\frac{t''}{t + t''}\right)^{n''} \left(\frac{t}{t + t''}\right)^{n}. \tag{4}$$

The parameters n'' and t'' may be computed by the relationships

$$n'' = n_0 + \left(\frac{v'}{\sigma'_v}\right)^2, \tag{5}$$

$$t'' = t_0 + \frac{v'}{(\sigma'_v)^2}, \tag{6}$$

where n_0 is the number of earthquakes observed within a time period of t_0 years, v' and σ'_v represent the prior "best estimates" of the mean and standard deviation of the rate of occurrence parameter v.

The distribution of earthquakes with respect to their size, usually represented by their magnitude, has been found empirically to obey the Gutenberg–Richter relationship given by,

$$\log_{10} N = a - b(m - m_1), \tag{7}$$

where N is the number of earthquakes of $m \geq m_1$ occurring within a specified period of time, m is the earthquake magnitude and a and b are empirical constants. Campbell (1982) proposed to account for the uncertainty in magnitude frequency parameter β through the evaluation of the Bayesian distribution,

$$F(m|m_1) = \int_0^\infty F(m|\beta, m_1) f''(\beta) \mathrm{d}\beta, \tag{8}$$

where β is related to b through the relationship $\beta = b\ln 10$. $F(m|\beta, m_1)$ represents the probability that an earthquake has a magnitude less than or equal to m, given a specified value of β and a threshold magnitude m_1 below which earthquakes may be neglected. $f''(\beta)$ represents the posterior probability density function of β, updated from its prior distribution by incorporating observations on the number and magnitude of earthquakes through Bayes' theorem. By assuming that earthquakes are independent, exponentially distributed and that the variation in β may be represented by a gamma distribution, Campbell (1982) has shown that $f''(\beta)$ may be always represented by a gamma distribution,

$$f''(\beta) = K_2 \beta^{\eta''-1} \mathrm{e}^{-\beta m''}, \tag{9}$$

where the normalizing constant $K_2 = m''^{\eta''}/\Gamma(\eta'')$.

The parameters η'' and m'' represent updated Bayesian evaluation of the number of earthquake occurrences greater than the minimum value m_1 and the sum of the differences between their magnitude and m_1, respectively, and are obtained by the expressions,

$$\eta'' = n_0 + \left(\frac{\beta'}{\sigma'_\beta}\right)^2, \tag{10}$$

$$m'' = n_0(\bar{m} - m_1) + \frac{\beta'}{(\sigma'_\beta)^2}, \tag{11}$$

where $\bar{m}$ is the mean magnitude of the historically observed earthquakes. β' and σ'_β represent the prior "best estimates" of the mean and standard deviation of the magnitude frequency parameter β.

Campbell (1982) proposed the final expressions for the doubly truncated Bayesian exponential–gamma distribution of earthquake magnitude,

$$F(m|m_l, m_u) = K''\left[1 - \left(\frac{m''}{m'' + m - m_l}\right)^{\eta''}\right], \tag{12}$$

where

$$K'' = \left[1 - \left(\frac{m''}{m'' + m_u - m_l}\right)^{\eta''}\right]^{-1}. \tag{13}$$

In the above relationships, m_u is the upper bound magnitude and m_l is the lower bound magnitude considered in the analysis. Using Eqs. 12 and 13, the Bayesian distribution of extreme earthquake occurrences may be estimated from Eq. 1.

3. Seismotectonic (prior) and posterior (updated) evaluations of seismicity

In many seismogenic zones, the historical data are most frequently not sufficient or complete to estimate the seismic hazard reliably. In such cases, additional information, e.g., geologic, geodetic data, are necessary in estimating the probabilities of exceedance of a given earthquake magnitude. The advantage of Bayesian distribution (Eq. 1) is that it can combine prior evaluations of seismicity with historical earthquake occurrences. The formulation of the Bayesian extreme value distribution is described in detail by the previous researchers (Campbell 1982, 1983; Stavrakakis and Tselentis 1987; Stavrakakis and Drakoploulos 1995; Papoulia et al. 2001). The formulation of seismotectonic, and posterior evaluations of seismicity is briefly described below using the parameters seismic moment M_0, slip rate s, magnitude bounds and earthquake recurrence rate.

3.1. Seismotectonic estimate of v' and β'

According to Shedlock et al. (1980), Campbell (1982), Stavrakakis and Drakoploulos (1995), the prior mean of v parameter of the Poisson distribution for the number of earthquakes with magnitudes greater than m_l is given by the relationship,

$$v' = \frac{\mu A s}{M_0(m_u)} \cdot \frac{C_2 - b'}{b'} 10^{b'(m_u - m_l)}, \tag{14}$$

where μ is the shear modulus, A is the fault area, s is the slip rate, M_0 (m_u) is the seismic moment corresponding to the upper bound magnitude. The parameter b' represents the prior estimate of b from the relationship $\text{Log}_{10}N(m) = a - bM$, and the coefficient C_2 is defined from the expression $\text{Log}_{10}\, M_0 = C_1 + C_2\, m$.

The seismotectonic estimate of the magnitude frequency parameter β' is computed by the relationships $\log_{10}N(m) = a - bM$ and $\beta' = b\ln 10$.

3.2. Posterior (update) evaluations of v'' and β''

The next step in fitting the Bayesian model is to compute the posterior estimates of the parameters v'' (the mean rate of earthquake occurrences having magnitudes $> m_1$) and β''. Following Campbell (1982), they are given by the expressions,

$$v'' = \frac{n''}{t''}; \quad V''_v = \frac{1}{\sqrt{n''}}, \tag{15}$$

$$\beta'' = \frac{\eta''}{m''}; \quad V''_\beta = \frac{1}{\sqrt{\eta''}}, \tag{16}$$

σ is the standard deviation defined by $V'_v = \sigma'_v/v'$ or $V'_\beta = \sigma'_\beta/\beta'$.

After computing the seismotectonic, and updated estimates of the seismicity parameters (v, β), the Bayesian probability represented by Eq. 1 can be estimated for a seismogenic zone of interest.

4. Application of the method in the North-East Indian peninsula

The Bayesian extreme value distribution presented above has been used to estimate the seismic hazard in the North-East Indian peninsula. The geological, topographical and seismicity map of this peninsula is shown in Fig. 1. The NE Indian peninsula has been characterized by a series of North hading thrusts; the most important amongst these are Main Boundary Thrust (MBT) and the Main Central Thrusts (MCT). The earthquake dataset of magnitude $M_w > 5.0$, spanning the time interval from 1963 to

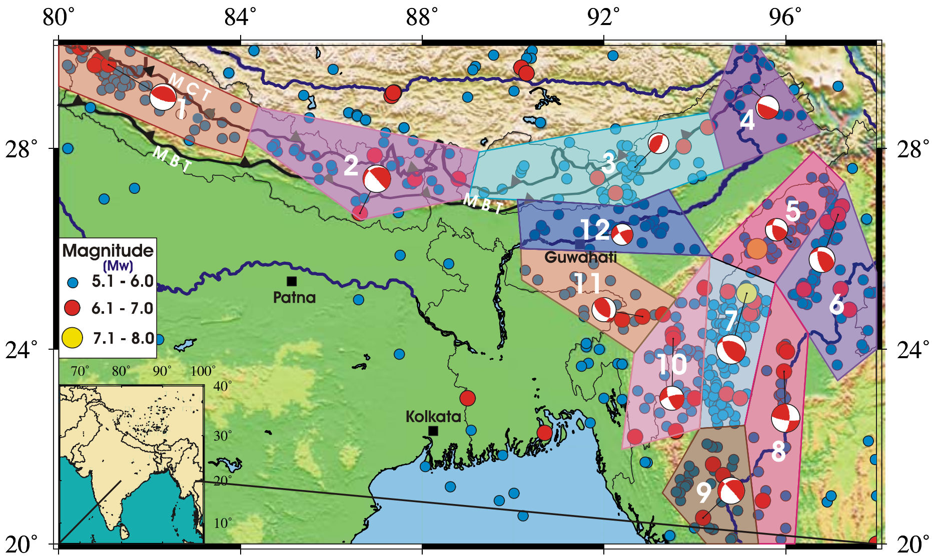

Fig. 1 Topographical and geological map displaying 12 seismogenic zones of North-East Indian peninsula, for computation of the Bayesian probabilities of occurrence of earthquakes with $M_w \geq 5.0$

2004 has been used in the present study to estimate the parameters related to hazard assessment. The source of earthquake data is the final output of the compilation of National Oceanic & Atmospheric Administration (NOAA), International Seismological Centre (ISC), National Earthquake Information Centre (NEIC) and Centroid Moment Tensor (CMT) catalogues. Additional data available in literature were also incorporated in our catalogue (Chandra 1977, 1978, Srivastava and Ramachandran 1985).

The seismic moments and moment magnitudes have been taken from CMT catalogue for the events that occurred during 1977–2004. Empirical relationships are established between mb or M_s and M_w in order to estimate the seismic moment and moment magnitude of the events that occurred during 1963–1977 and also of those which are not listed in CMT catalogue. For North-East Indian peninsula, the empirical relationship $\log M_0 = 1.4947M_s + 16.126$ was obtained using the CMT catalogue of 1977–2004, and it was used to estimate the seismic moments of earlier events. The shear modulus μ is usually taken to be equal to 3×10^{11} dyn/cm^2, which is commonly adopted for the Earth's crust.

The entire region in the present study is divided into 12 seismogenic zones on the basis of seismic clustering, geological lineament trends and possible similar focal mechanisms. A characteristic focal mechanism was adopted in each zone, representing an average solution among the similar mechanisms available for that particular area. All the seismogenic zones mapped have polygonal shapes. Therefore, the area of each zone has been estimated using Surveyor's formula giving vertices of the polygon. The other important parameter is the slip rate, which is estimated $s = \sum(M_0/\mu)/A$ (Brune 1968) for each seismogenic zone in order to apply it to the seismic hazard assessment of North-East India. The area and slip rate of each seismogenic zone estimated for the period 1963–2004 is shown in Table 1. The slip rates obtained in the present study vary from one zone to another. The accuracy of this parameter may be affected by the short time interval considered; the level of seismicity in the area during the investigated period is possibly not representative for a large time interval. The historically observed maximum magnitude in each zone is also listed in Table 1.

The lower bound magnitude, m_l, is adopted as equal to 5.0 for all zones. However, the b-values of the Gutenberg–Richter formula $\log N = a - bM$ were obtained by considering the events with magnitude greater than or equal to 4.0. The frequency

Table 1 Slip rate and area of seismogenic zones under study

Zone	s (cm/yr)	A (km^2)	Max. observed historical magnitude
Z1	4.66508	49451.906	7.7 (Aug. 28, 1916)
Z2	1.98782	63083.496	8.0 (Aug. 26, 1833)
Z3	1.41204	68005.375	7.9 (Jul. 29, 1947)
Z4	0.27034	34156.492	8.7 (Aug. 15, 1950)
Z5	4.68953	32319.336	7.0 (Aug. 31, 1906)
Z6	1.78559	50485.840	8.2 (Dec. 12, 1908)
Z7	10.6920	39571.531	7.4 (Mar. 03, 1954)
Z8	3.92963	51162.719	7.5 (Dec. 09, 1946)
Z9	3.00995	36484.375	7.2 (Oct. 23, 1943)
Z10	2.01646	43162.844	7.3 (Jul. 01, 1957)
Z11	1.36678	38532.715	8.7 (Jun. 12, 1897)
Z12	0.33246	38613.281	6.8 (Jan. 27, 1941)

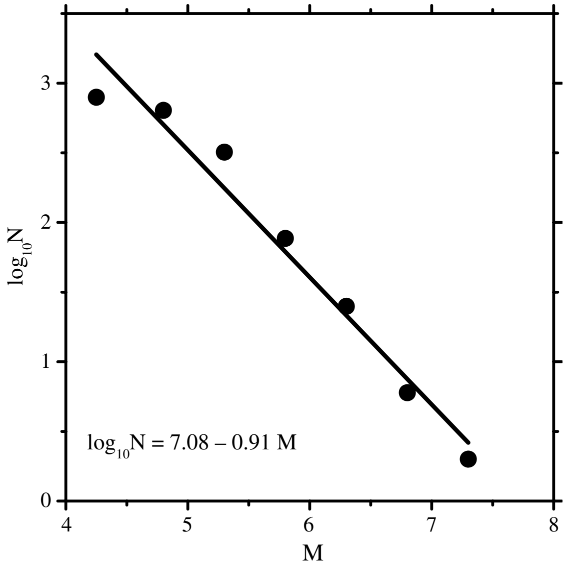

Fig. 2 The frequency magnitude distribution of the events occurred in the period 1963–2004 within the study region, to estimate the *b* value

magnitude graph for the entire study region is shown in Fig. 2. The assigned upper bound magnitude is the observed maximum magnitude in each zone during the period 1963–2004. Table 2 summarizes the input parameters of each seismogenic zone, where m_u is the maximum observed magnitude, $\bar{m}$ is the average magnitude, n_0 is the total number of earthquakes with $M_w \geq 5.0$, which occurred during 1963–2004 and b is the parameter derived from the Gutenberg–Richter formula.

The seismotectonic evaluation of the mean rate of earthquake occurrences ν' is performed using Eq. 14. The seismotectonic estimate of the magnitude frequency parameter β' is obtained from the observed data. Then, the posterior (updated) evaluations of these parameters are calculated using Eqs. 15 and 16. The output of the updating process on the estimation of seismicity parameters is listed in Table 3 for each seismogenic zone. Three values of the coefficients of variation $V_\nu^{'}$ and $V_\beta^{'}$ are assumed: 0.1, 0.25 and 1.0. The Bayesian probabilities that a specific earthquake magnitude will be exceeded in $T = 1$ year and $T = 5$ years have been computed from Eq. 1. The results are presented graphically in Fig. 3a–f. The plots show the

Table 2 Summaries per zone of the observed data set (1963–2004): maximum magnitude, average magnitude, no. of events, and estimate of Gutenberg–Richter parameter

Zone	m_u	$\bar{m}$	n_0	b
Z1	6.7	5.46	61	0.730
Z2	6.8	5.37	30	0.794
Z3	6.7	5.38	41	0.833
Z4	5.8	5.24	20	0.631
Z5	7.0	5.37	40	0.694
Z6	6.5	5.38	59	0.941
Z7	7.2	5.36	109	0.977
Z8	6.9	5.49	27	0.722
Z9	6.6	5.43	40	0.912
Z10	6.6	5.41	44	0.936
Z11	6.5	5.46	22	0.797
Z12	5.8	5.30	27	0.543

Table 3 Prior and posterior estimates of v and β parameters for zones 1–12

Prior estimates			Posterior estimates		
v'	β'	V'_v, V'_β	v''	β''	V''_v, V''_β
Zone 1					
90.31	1.68	0.10	4.22	1.84	0.08
90.31	1.68	0.25	2.07	2.06	0.11
90.31	1.68	1.00	1.68	2.17	0.13
Zone 2					
44.93	1.83	0.10	3.31	1.98	0.09
44.93	1.83	0.25	1.23	2.32	0.15
44.93	1.83	1.00	0.84	2.66	0.18
Zone 3					
42.90	1.92	0.10	3.58	2.08	0.08
42.90	1.92	0.25	1.53	2.39	0.13
42.90	1.92	1.00	1.13	2.62	0.15
Zone 4					
19.72	1.45	0.10	2.85	1.63	0.09
19.72	1.45	0.25	0.95	2.26	0.17
19.72	1.45	1.00	0.57	3.76	0.22
Zone 5					
33.25	1.60	0.10	3.50	1.81	0.08
33.25	1.60	0.25	1.49	2.24	0.13
33.25	1.60	1.00	1.11	2.63	0.16
Zone 6					
59.19	2.17	0.10	4.11	2.31	0.08
59.19	2.17	0.25	2.01	2.50	0.12
59.19	2.17	1.00	1.62	2.60	0.13
Zone 7					
122.45	2.25	0.10	5.53	2.50	0.07
122.45	2.25	0.25	3.37	2.70	0.09
122.45	2.25	1.00	2.97	2.78	0.10
Zone 8					
54.63	1.66	0.10	3.27	1.73	0.09
54.63	1.66	0.25	1.15	1.88	0.15
54.63	1.66	1.00	0.76	2.03	0.19
Zone 9					
63.92	2.10	0.10	3.63	2.15	0.08
63.92	2.10	0.25	1.50	2.24	0.13
63.92	2.10	1.00	1.11	2.29	0.16
Zone 10					
50.78	2.16	0.10	3.70	2.23	0.08
50.78	2.16	0.25	1.61	2.34	0.13
50.78	2.16	1.00	1.22	2.41	0.15
Zone 11					
30.74	1.84	0.10	3.03	1.89	0.09
30.74	1.84	0.25	1.01	2.01	0.16
30.74	1.84	1.00	0.62	2.14	0.21
Zone 12					
29.38	1.25	0.10	3.14	1.44	0.09
29.38	1.25	0.25	1.15	2.07	0.15
29.38	1.25	1.00	0.76	3.18	0.19

probability of occurrences of events of magnitude 5 and above for three values of V'_v 0.1, 0.25 and 1.0. The upper graphs represent the results for $T = 1$ year and the bottom ones for $T = 5$ years. In all the figures, the probability is decaying gradually till the magnitude 6 or 6.5, while the decay is sharp in the vicinity of the maximum (upper bound) magnitude (Table 4).

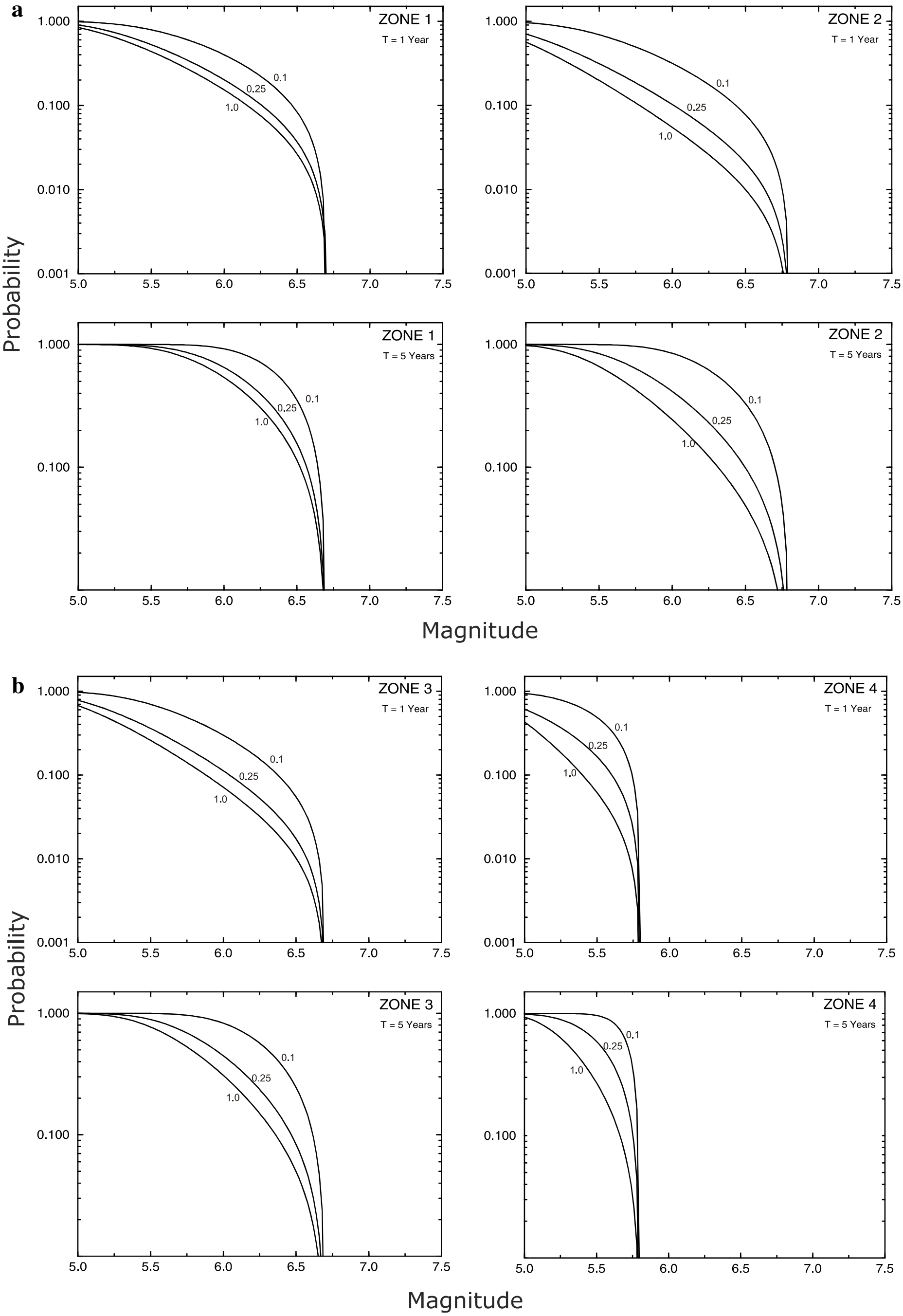

Fig. 3 (**a–f**) Probabilities of occurrence of earthquakes with $M_w \geq 5.0$ for 12 seismogenic zones of North-East Indian peninsula. The upper graphs correspond to $T = 1$ year and lower ones to $T = 5$ years. The number on each curve represents the value of coefficient of variation V'_v—(0.1, 0.25 and 1.0)

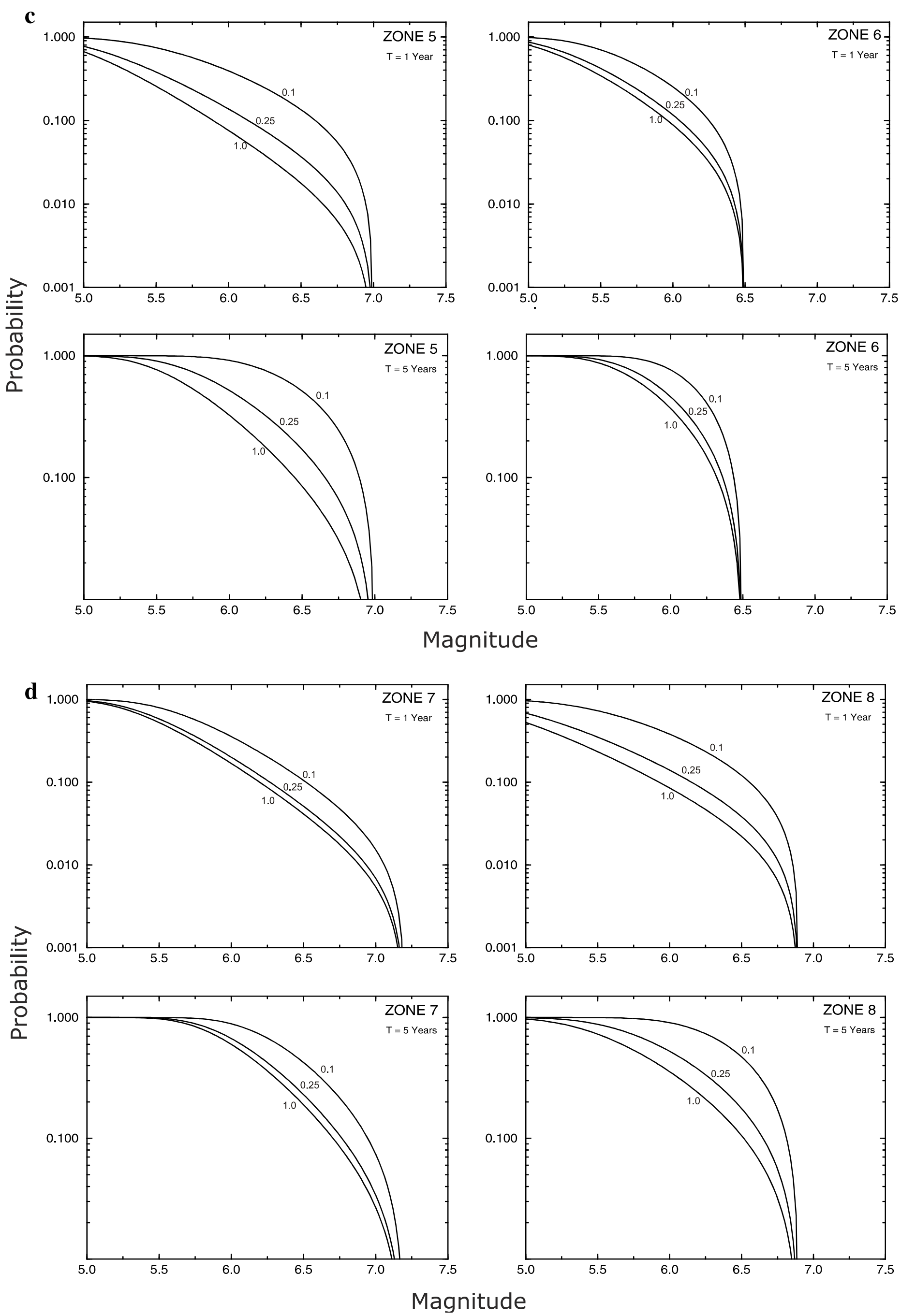

Fig. 3 continued

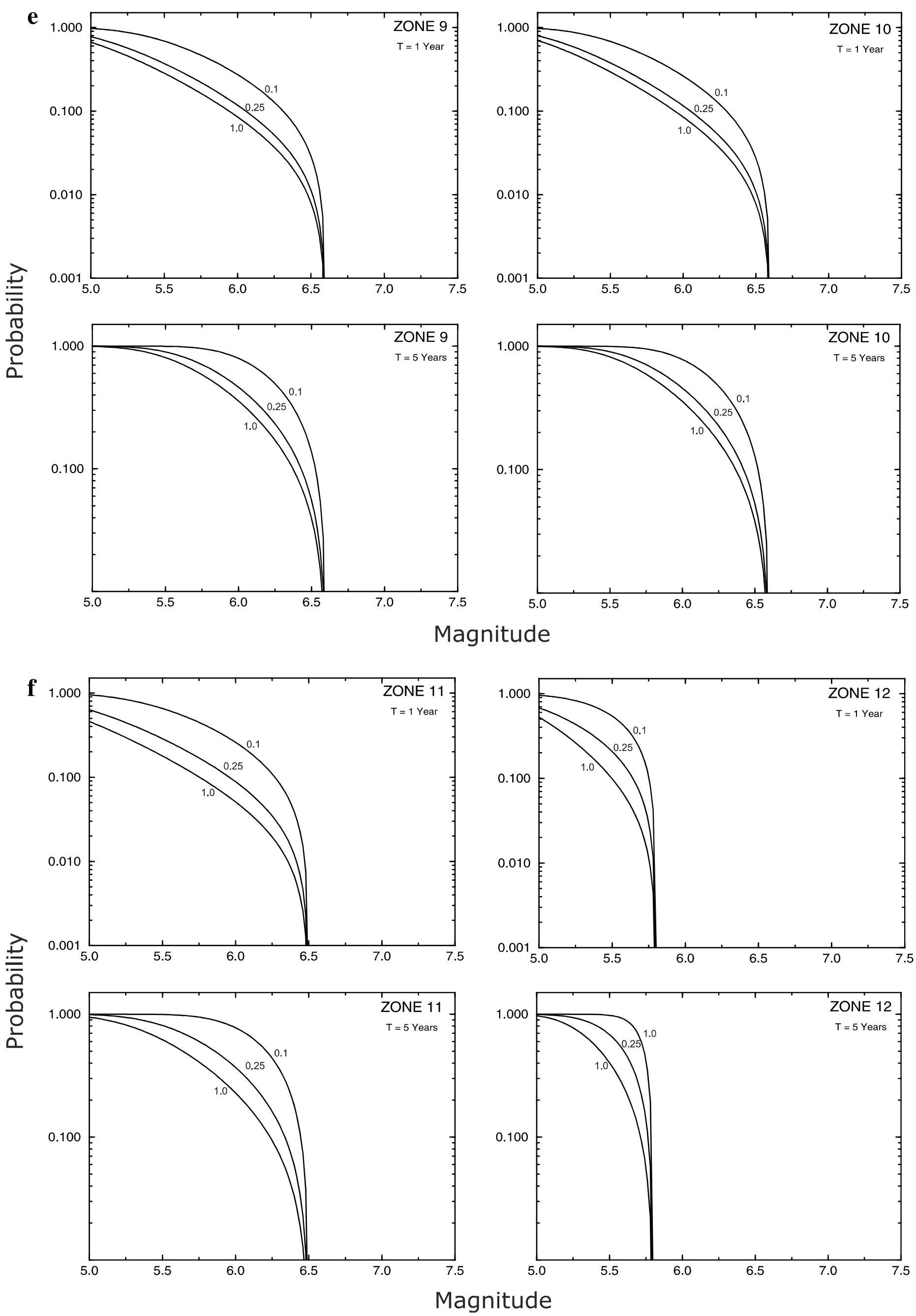

Fig. 3 continued

5. Discussion and conclusions

Earthquakes are regarded as the most dreaded natural hazard as they occur without warning, and sometimes in unexpected areas, resulting in great destruction and loss of lives. Earthquake risk is particularly high in developing countries. A rational approach to mitigate the destructive impact of earthquakes in seismically vulnerable regions is to estimate their hazard potential and take appropriate remedial measures. The present study is aimed to evaluate the seismic hazard in 12 seismogenic zones of North-East Indian peninsula by using Bayesian extreme value distribution of earthquake occurrence. The methodology incorporates different sources of information, such as dimension of seismic source, the slip rate and seismic moment of the events that occurred in the seismogenic zone with the conventional *b* parameters. Using these parameters, the seismotectonic, historical and updated estimates of seismicity have been obtained. Further, using these estimates, the probability of occurrence of an earthquake of a defined magnitude within a time period of 1 and 5 years has been computed for each seismogenic zone for selected coefficients of variation.

The study period is chosen 1963–2004 because for the Indian subcontinent a reliable catalogue of earthquakes with magnitude 5 and above is available only in this period after the installation of WWSSN seismic network. The zoning is done on the basis of clustering of events, geological and tectonic trends and possible similar focal mechanisms, which permits to divide the area of study into 12 seismogenic zone. The number of events ($M_w \geq 5.0$) available in each zone (listed in Table 2) varies from 20 (Zone 4) to 109 (Zone 7).

The probability of occurrence of M_w = 5.0–5.5 is greater than 0.9 for all zones for T = 5 years and V'_v = 0.1 as shown in Fig. 3. For M_w = 6.0 and the same parameters four zones namely Z1 (Central Himalayas), Z5 (Indo-Burma border), Z7 (Burmese arc) and Z8 (Burma region) exhibit very high probabilities, above 0.9. The other regions like Z2, Z3, Z6, Z9, Z10 and Z11 show also high probabilities ranging between 0.7 and 0.9, for Zone 4 and Zone 12 the maximum magnitude observed within the study period is less than 6.0 (although significantly higher magnitudes

Table 4 Prior and posterior estimates of v and β parameters for zone 1 using different upper bound magnitude thresholds

Prior estimates			Posterior estimates		
v'	β'	V'_v, V'_β	v''	β''	V''_v, V''_β
M_u = 7.0					
99.60	1.68	0.10	4.34	1.83	0.08
99.60	1.68	0.25	2.18	2.01	0.11
99.60	1.68	1.00	1.78	2.10	0.12
M_u = 7.5					
81.34	1.68	0.10	4.32	1.82	0.08
81.34	1.68	0.25	2.18	1.98	0.11
81.34	1.68	1.00	1.78	2.07	0.12
M_u = 8.0					
69.52	1.68	0.10	4.29	1.81	0.08
69.52	1.68	0.25	2.18	1.96	0.11
69.52	1.68	1.00	1.78	2.04	0.12
M_u = 8.5					
18.17	1.68	0.10	3.88	1.63	0.09
18.17	1.68	0.25	2.14	2.26	0.17
18.17	1.68	1.00	1.78	2.01	0.12

have been historically observed—8.7 for Z4 and 6.8 for Z12, respectively). When the value 1.0 of the coefficient of variation V_v' is considered, the probability of occurrence of magnitude $M_w = 6.0$ is low to moderate in all zones, whereas for $M_w = 5.5$ it displays high probability (>0.7) in Z1, Z6, Z7, Z9 and Z10 and low probability in Z4 and Z12 (as expected due to the low magnitude of the strongest events that occurred within these two regions during the analyzed period). The rest of the zones come in the moderate probabilities.

This is the first time the Bayesian extreme value distribution of earthquake occurrences has been introduced to India and surrounding regions; it has already been used in Hellenic arc, Greece and surrounding, Mexico, United States, South America etc. by different researchers (e.g. Campbell 1982; Stavrakakis and Drakopoules 1995; Papoulia et al. 2001; Galanis et al. 2002). Our results are similar to some of those obtained by Stavrakakis and Drakopoules (1995) for Greece and surrounding regions, however, the probability of occurrences in our region is generally higher than in the seismogenic zones of Greece; this is not unexpected as the two regions are tectonically different.

Among the parameters used for hazard assessment, the basic parameter of the Bayesian model is the magnitude frequency coefficient *b* estimated mainly from observed data, which are often incomplete and heterogeneous in time. Besides, it is significant only when the difference $M_{max} - M_{min} > 1.4$ in each zone (Papazachos 1974). In the present study, the cut-off magnitude for the analysis is 5.0 (which is commonly taken as threshold of damaging earthquakes in seismic hazard studies); however *b* values are obtained using the events with magnitude greater than or equal to 4, taking into account the completeness of the catalogue for the period of 1963–2004. The *b* value obtained for the entire region using the earthquakes that occurred in the period 1963–2004 is illustrated in Fig. 2. The other important parameter is the slip rate, which plays a very important role in estimating seismotectonic mean rate of occurrence of earthquakes. In the present study the slip rate is obtained by using Brune's model, which is appropriate along the major plate boundaries (Tselentis et al. 1988). In general, the slip rate in Himalayan and North-East Indian regions are 3–5 cm/year, which agrees with our results. The selection of upper bound magnitude may also influence the result because the model does not extrapolate the result beyond the maximum magnitude and the probability decays very fast close to the maximum magnitude. The present study uses the catalogue of the period 1963–2004 and the maximum observed magnitude within this period, in each seismogenic zone was considered. The choice of upper bound magnitude would be different if earlier events were taken into consideration (see maximum magnitude listed in Table 1). To investigate the effect of higher values accepted for the maximum magnitude on the hazard parameters estimated, calculations were performed separately for Zone 1, keeping the other input parameters unchanged. Table 3 shows the model parameters obtained for $M_{max} = 7.0$, 7.5, 8.0 and 8.5. The new results display some differences but nevertheless the overall hazard estimate has not been previously underestimated.

Campbell (1983) evidenced that the coefficient of variation of seismic rate V_v is another very critical parameter of the Bayesian model. It is pointed out that this coefficient may bias the result in favour of either the prior estimate or the historical data. For $V_v = 1.0$ the historical earthquake occurrences control the seismic hazard, whereas for $V_v = 0.0$ the obtained probabilities are based only on the seismotectonic estimates. In the light of the physical interpretation of this parameter, the present study is aimed to analyze the results for three different values of V_v = 0.1, 0.25 and 1.0. Stavrakakis and Drakopoulos (1995) pointed out that the common feature of the probability distributions is that the seismic hazard seems to be overestimated using solely historical data and underestimated using only seismotectonic data. The sensitivity of the Bayesian extreme value distribution to a certain number of parameters does not diminish, however, its merit in the probabilistic seismic hazard analysis. It should also be stressed that information from different sources (geophysical and geological) is combined with the available historical data in the framework of the Bayesian statistics to assess reliably the seismic hazard within a seismogenic zone.

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