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Map of seismic hazard of India using Bayesian approach

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Abstract A straightforward procedure of estimating maximum values of seismic peak ground acceleration and quantiles of its probabilistic distribution on a future time interval of 100 years is applied to territory of India. The input information for the method is seismic catalog and regression relation between peak ground acceleration at a given point and magnitude and distance from the considered site to hypocenter (seismic effect attenuation law). The method is based on Bayesian approach, which simply allows account the influence of uncertainties of seismic acceleration values. The main assumptions for the method are Poissonian character of seismic events flow, a frequency-magnitude law of Gutenberg–Richter's type with cutoff maximal value for estimated parameter and a seismic catalog, having a rather big number of events. The results obtained in this study show high hazard values in terms of peak ground acceleration in northeast India, Himalayan belt, Andaman region and Kachhach region.

Keywords Bayesian approach · Seismic hazard assessment · Peak ground accelerations

1 Introduction

The problem of seismic hazard assessment has a lot of tools for its solution. Here, we emphasize on purely statistical procedures (Cornell 1968; Benjamin and Cornell 1970) and do not touch methods, which involve direct solution of wave. The advantage of statistic approach is based on its generality. It does not need to identify values of different parameters, which we must know if we try to solve differential equations the most of which could not be defined with sufficient accuracy. Among statistical methods, Bayesian

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approach has a special interest that comes from its ability to take into consideration uncertainty of parameters in fitted probabilistic laws and a priory given information (Mortgat and Shah 1979; Campbell 1982, 1983). Here, we present results of processing seismic catalog of India by Bayesian procedure, which was elaborated in previous works (Pisarenko et al. 1996; Pisarenko and Lyubushin 1997; Lyubushin et al. 2002), with the purpose of estimating maximum seismic peak ground acceleration. The advantages of the method used consist in its simplicity: it does not need such intermediate steps of investigation as earthquake scenarios, estimates of bimodal recurrence model of magnitude distribution, bootstrap procedures (Mortgat and Shah 1979; Lamarre et al. 1992). The method is rather straightforward and needs only seismic catalog and attenuation law. At the same time, it allows take into consideration uncertainty of seismological information and thus possesses the main advantage of Bayesian approach.

It should be noticed that the map of statistical estimates of seismic hazard in India and adjacent areas was published by Khattri et al. (1984), which was based on using other attenuation law and other methods of estimates. Later, Bhatia et al. (1999) prepared the probabilistic seismic hazard map under the GSHAP, which showed underestimated hazard after the Bhuj, 2001, and Pakistan, 2005, earthquakes. More recently, Parvez et al. (2003) have published the first ever deterministic seismic hazard of India using realistic ground motion modeling at the sites of interest, using the available knowledge of the physical process of earthquake generation (source position and orientation of focal mechanism), level of seismicity (distribution of maximum observed magnitude) and wave propagation in anelastic media. Thus, it is interesting to compare the final results with the other approaches.

In this paper, the inputs used to estimate the seismic hazard are earthquake catalog and seismic attenuation law i.e. the variation of peak ground acceleration of various magnitudes with hypocentral distances. We have compiled the earthquake catalog of the Indian subcontinent from National Oceanic and Atmospheric Administration (NOAA), International Seismological Centre (ISC), National Earthquake Information Centre (NEIC) and several publications from Indian and international reputed journals. The seismic attenuation law has been taken from Parvez et al. (2001, 2002).

2 Method of estimate

The used technique is described in detail in papers (Pisarenko et al. 1996; Pisarenko and Lyubushin 1997; Tsapanos et al. 2001; Lyubushin et al. 2002). That is why here we will give the main assumptions and key equations only.

Let R be the value decimal logarithm of maximum seismic peak ground acceleration at a given site, which was estimated according to the used attenuation law as a sequence on a past time interval $(-\tau, 0)$:

$$\vec{R}^{(n)} = (R_1, \ldots, R_n), \quad R_i \geq R_0, \quad R_\tau = \max_{1 \leq i \leq n} (R_1, \ldots, R_n) \tag{1}$$

where R_0 is a minimum cutoff value, i.e. such value that is defined by possibilities of registration systems or was chosen as minimal value up from which values sequence (1) is statistically representative.

Let us assume that values (1) obey the Gutenberg–Richter type law of distribution:

$$\Pr\{R < x\} = F(x|R_0, \rho, \beta) = \frac{e^{-\beta \cdot R_0} - e^{-\beta \cdot x}}{e^{-\beta \cdot R_0} - e^{-\beta \cdot \rho}}, \quad R_0 \le x \le \rho \tag{2}$$

Here, ρ is the unknown parameter that has a sense of maximal possible value of R. Unknown parameter β usually is called as “slope” of Gutenberg–Richter type law at small values of x when the dependence (2) is plotted in doubly logarithmic axes.

The second assumption is that the sequence (1) is a Poissonian process with some intensity value λ, which is unknown parameter also. It should be noticed that the initial earthquake sequence is not a Poissonian process, of course. That is why a preliminary operation similar to aftershocks removing is applied before the estimates. This operation is described below.

Thus, the full vector of unknown parameter is the following:

$$\theta = (\rho, \beta, \lambda). \tag{3}$$

For brevity all functions of distribution and statistics of the sequence (1), we shall denote as $\cdot(\cdot|\theta)$, for example, (2)—as $F(x|\theta)$, argument R_0 will be omitted.

Probabilistic density of distribution, according to the law (2):

$$f(x|\theta) = F'(x|\theta) = \frac{\beta \cdot e^{-\beta \cdot x}}{e^{-\beta \cdot R_0} - e^{-\beta \cdot \rho}} \tag{4}$$

Let’s introduce now an error ε, with which we know values (1), which are defined by formula:

$$\tilde{R} = R + \varepsilon \tag{5}$$

and let $n(x|\delta)$ be a density of probabilistic distribution of the error ε, where δ is a given scale parameter of the density. Unlike previous applications of the method (Pisarenko et al. 1996; Pisarenko and Lyubushin 1997; Tsapanos et al. 2001; Lyubushin et al. 2002) where a uniform probability distribution function was used (for increasing a speed of computations), now we use a normal distribution function that is more traditional in seismic hazard assessment:

$$n(x|\delta) = \frac{1}{\delta\sqrt{2\pi}} \exp\left(-\frac{x^2}{2\delta^2}\right) \tag{6}$$

The Bayesian approach for estimating parameter is based on Bayes formula (Rao 1965):

$$f_p(\theta \big| \vec{R}^{(n)}, \delta) = \frac{g_c(\vec{R}^{(n)}|\theta, \delta) f_a(\theta)}{g_0(\vec{R}^{(n)}|\delta)} \tag{7}$$

Here, $f_a(\theta)$ is an a priori probability distribution function (p.d.f) of parameters vector θ, which carries our information about the statistical model that is based on some the most general assumptions. We want to make this information more precise taking into account vector of observations $\vec{R}^{(n)}$. The more precise information about the vector θ is containing within its a posteriori p.d.f. $f_p(\theta \big| \vec{R}^{(n)}, \delta)$. Usually, when the number of observation $n \to \infty$, the variance of a posteriori p.d.f. is tending to zero that means more and more precise estimate.

Function $g_c(\vec{R}^{(n)}|\theta, \delta)$ is a p.d.f. of observations $\vec{R}^{(n)}$, which is following from the used statistical model. Function $g_0(\vec{R}^{(n)}|\delta)$ is a p.d.f. of observations $\vec{R}^{(n)}$, which is considered without connection to any model. It could be calculated according to the formula of full probability:

$$g_0(\vec{R}^{(n)}|\delta) = \int\limits_{\Pi} g_c(\vec{R}^{(n)}|\vartheta, \delta) f_a(\vartheta)\, d\vartheta \tag{8}$$

where Π is an a priori domain where vector of parameters θ can take its values.

When p.d.f. $f_p(\theta\Big|\vec{R}^{(n)}, \delta)$ is computed, the estimate of the vector θ could be calculated as a mean value over a posteriori distribution:

$$\hat{\theta}(\vec{R}^{(n)}|\delta) = \int\limits_{\Pi} \vartheta f_p(\vartheta\Big|\vec{R}^{(n)}, \delta)\, d\vartheta \tag{9}$$

Moreover, the variance of the Bayesian estimate could be calculated as well:

$$\mathrm{var}(\hat{\theta}(\vec{R}^{(n)}|\delta)) = \int\limits_{\Pi} (\vartheta - \hat{\theta}(\vec{R}^{(n)}|\delta))^2 f_p(\vartheta\Big|\vec{R}^{(n)}, \delta) d\vartheta \tag{10}$$

The expression for p.d.f. $g_c(\vec{R}^{(n)}|\theta, \delta)$ for uniform distribution of errors has a rather long although not very complex derivation, and it is given in the papers (Pisarenko et al. 1996; Pisarenko and Lyubushin 1997; Lyubushin et al. 2002). A priory p.d.f. $f_a(\theta)$ is taken as uniform within rectangular 3-dimensional domain:

$$\Pi = \{\lambda_{\min} \le \lambda \le \lambda_{\max}, \beta_{\min} \le \beta \le \beta_{\max}, \rho_{\min} \le \rho \le \rho_{\max}\} \tag{11}$$

The rules for obtaining boundary values $\lambda_{\min}, \lambda_{\max}$, $\beta_{\min}, \beta_{\max}$ and $\rho_{\min}, \rho_{\max}$ for maximum peak ground acceleration problems are given at the papers (Pisarenko and Lyubushin 1997; Lyubushin et al. 2002).

Besides the Bayesian estimate of vector (3), the following problem could be solved by Bayesian approach as well. Let's denote by R_T a maximal value of R on the time interval [0, T]. Then $\Pr\{R_T < x\} = \exp(-\lambda \cdot (1 - F(x|\theta)) \cdot T)$. But into this probability, a case when there are no events on [0, T] is included as well. Let v_T be the number of events with $R \ge R_0$ on the interval [0, T]. Then

$$\Pr\{v_T = 0\} = e^{-\lambda \cdot T}, \quad \Pr\{v_T \ge 1\} = 1 - e^{-\lambda \cdot T}$$

That is why:

$$\begin{gathered} \Phi_T(x|\theta) = \Pr\{R_T < x|v_T > 0\} \\ = \frac{\exp(-\lambda T(1 - F(x|\theta)) - \exp(-\lambda T)}{1 - \exp(-\lambda T)} = \frac{\exp(\lambda T F(x|\theta)) - 1}{\exp(\lambda T) - 1} \end{gathered} \tag{12}$$

where function $F(x|\theta)$ is given by formula (2)

Let us consider a priori quantile $Y_T(\alpha|\theta)$ of probability α for maximal values of R on time interval [0, T].

$$\Phi_T(Y_T(\alpha|\theta)|\theta) = \alpha, \quad 0 \le \alpha \le 1 \tag{13}$$

Applying the same formulae (8), (9) and (10) where θ is substituted for $Y_T(\alpha|\theta)$, we can compute a priory p.d.f., mean value and variance for quantile $Y_T(\alpha|\theta)$ for any given values of T and α.

All 3D integrals within formulae (7–10) were calculated using simple integral sum by splitting a priori domain (11) into small cubes by grid of 30 × 30 × 30 nodes and taken the values of integrated functions within centers of these small cubes.

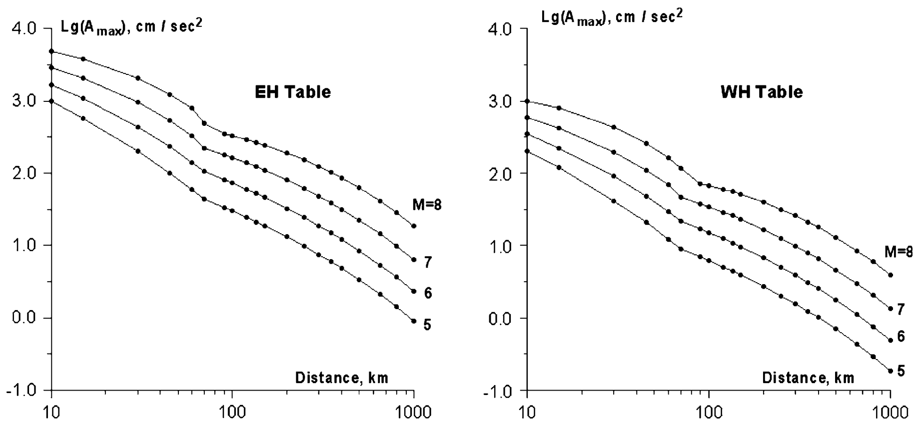

Fig. 1 Graphics for attenuation law

3 Seismic hazard estimate for India

The problem for maximum peak ground accelerations estimates essentially differs from those concerning maximal magnitudes. First of all, direct measurements of seismic accelerations are very rare and fragmental. That is why there is no catalogs, containing values of maximal accelerations for most interesting sites, but there are a lot of so-called attenuation laws, which represent some functions between logarithm of maximal accelerations $R = \lg(A_{\max})$) and magnitude M of the earthquake and distance D (km) from the considered site to epicenter of the earthquake:

$$R = \lg(A_{\max}) = \Psi(M, D) \quad (14)$$

Usually, functions (32) are empirical regression laws, obtained by collecting data from a specified region and fitting to them some class of functions (Joyner and Boore 1981; Fukushima and Tanaka 1990; Theodulidis and Papazachos 1992).

In this calculation, we have used the semi-empirical attenuation law of Parvez et al. (2001, 2002), which was defined for magnitudes $M \geq 5$ by tables and is presented in Fig. 1. In the strong-motion data analysis, instead of empirical formulae, they used a theoretical magnitude-dependent semi-empirical distance attenuation by the data reduction for distance and magnitude. They found a pronounced inhomogeneity of the observed data, which ascribed to differences between the two sub-regions of the eastern Himalayas (EH) and western Himalayas (WH). Of these, the western Himalayas region is comparable, in terms of near-source amplitudes, to the Japan region, whereas the amplitudes in the eastern Himalayas are three times larger. They also compared the intensity attenuation of Indian and the global earthquakes and found good agreement with their observed PGA and PGV attenuation law. Finally, it is concluded that the so-called EH is not the part of Himalayas, but it is part of Shillong plateau. The attenuation law of EH agrees very well with the attenuation of Indian shield, which is very old, higher strength shield crust. Thus, in this study, we have applied the WH attenuation law for the seismogenic zones of Chaman fault, Kirthar Sulaiman ranges, Hindukush and Himalayan Mountains, Arakan Yoma range and Andaman and Nicobar and EH attenuation law for the Indian shield. Fig. 2 presents the areas for applying EH or WH attenuation laws.

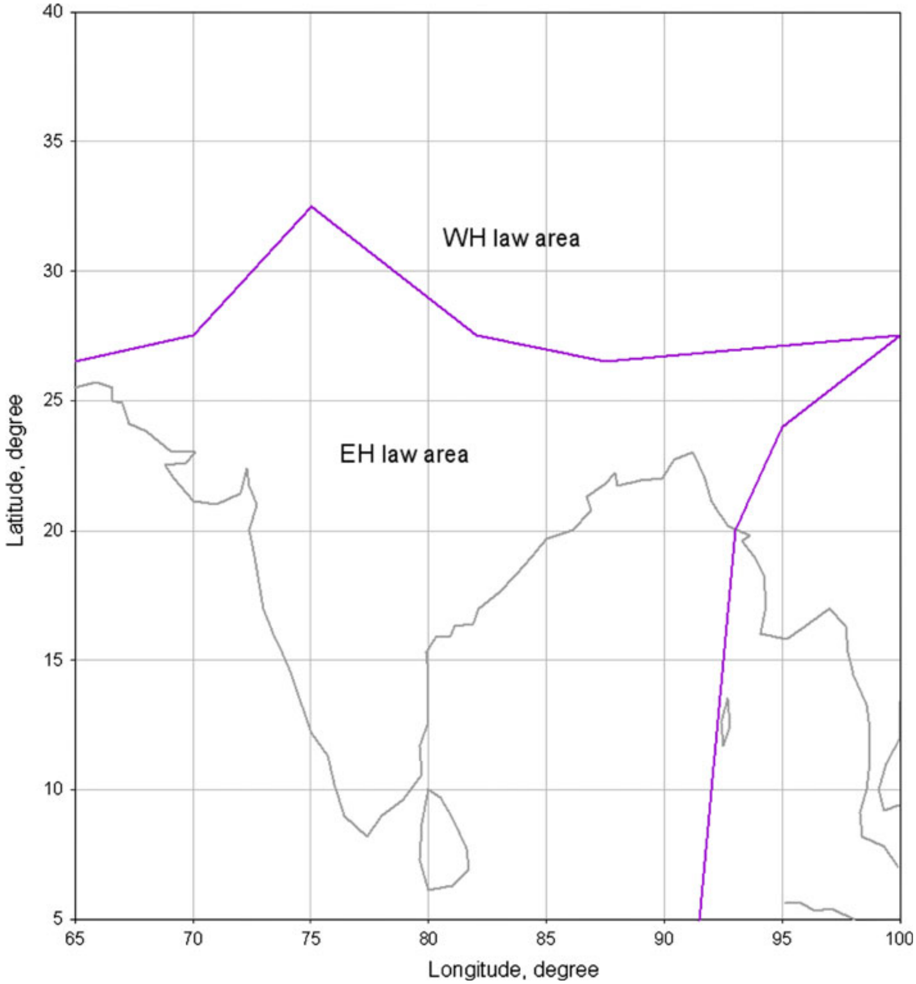

Fig. 2 WH and EH attenuation laws applied in the study area

For small magnitudes, we use the following forms of (14):

$$\lg(A_{\max}) = 0.54M - 1.5 \cdot \lg(D + 10) + 1.25, \quad M < 5 \tag{15}$$

which was derived for the whole world in (Steinberg et al. 1993).

Thus, the sequence (1) is composed of values computed in accordance with the formula (14). As regression formula (14) gives its own error due to error of statistical fitting, the general error ε is composed of two parts: own error and error due to incomplete adequateness of chosen class of functions in (14). We suppose that this general error has a zero mean and is distributed uniformly. We must also keep in mind that a "real" relation of the type (14) must not be stationary and be dependent not only on soil and rock conditions, but on precipitation intensity to the moment of earthquake also. We choose a value of δ for standard deviation of lg ($A_{\max}$) be equal to 0.5 in our calculations as an approximately

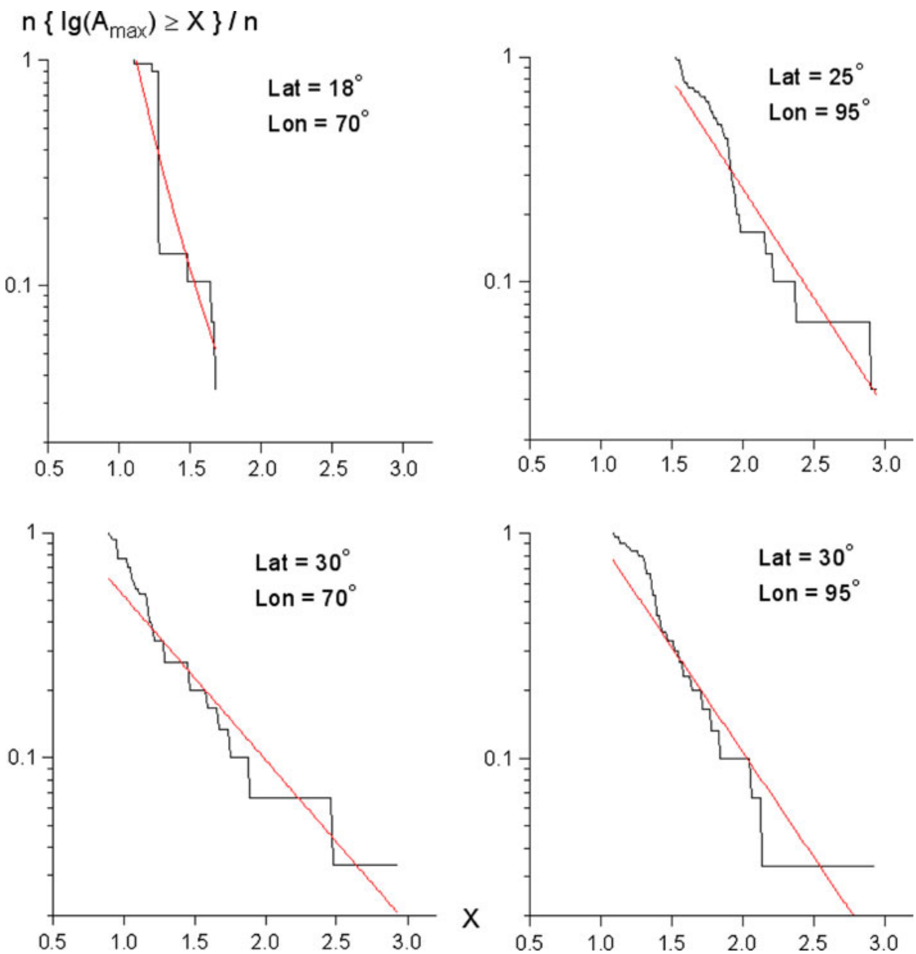

Fig. 3 Empirical tail probability functions for lg(A_{max}) values within 4 nodes of the grid

doubled value of standard deviation of the regression formula (15), in order to take into account influence of these factors of uncertainty.

Then, for satisfying the assumption of Poissonian character of the events flow (1), we must remove aftershocks from the processed seismic catalogs. We could not leave only usual mainshock because an event-aftershock with less value of magnitude, which has an epicenter closer to the considered site, could generate larger peak acceleration than usual mainshock. That is why the aftershocks removing procedure (Gardner and Knopoff 1974) was modified in the following way: all events were usually divided into mainshocks and aftershocks. Afterward, among each mainshock–aftershocks sequence only one event was left—those which generates the largest value of peak using formula (14).

We have estimated the parameter ρ—maximum possible value of lg (A_{max}) and quantile with probability $\alpha = 0.90$ for future time interval of the length $T = 100$ years in nodes of regular grid of the size 106 $\times$ 106 nodes with steps 1/3 degrees by latitude and longitude within rectangular $5^\circ \leq Lat \leq 40^\circ$; $65^\circ \leq Lon \leq 100^\circ$. The estimates were performed by the following way: for each node of the grid, a sequence of lg (A_{max}) was computed using

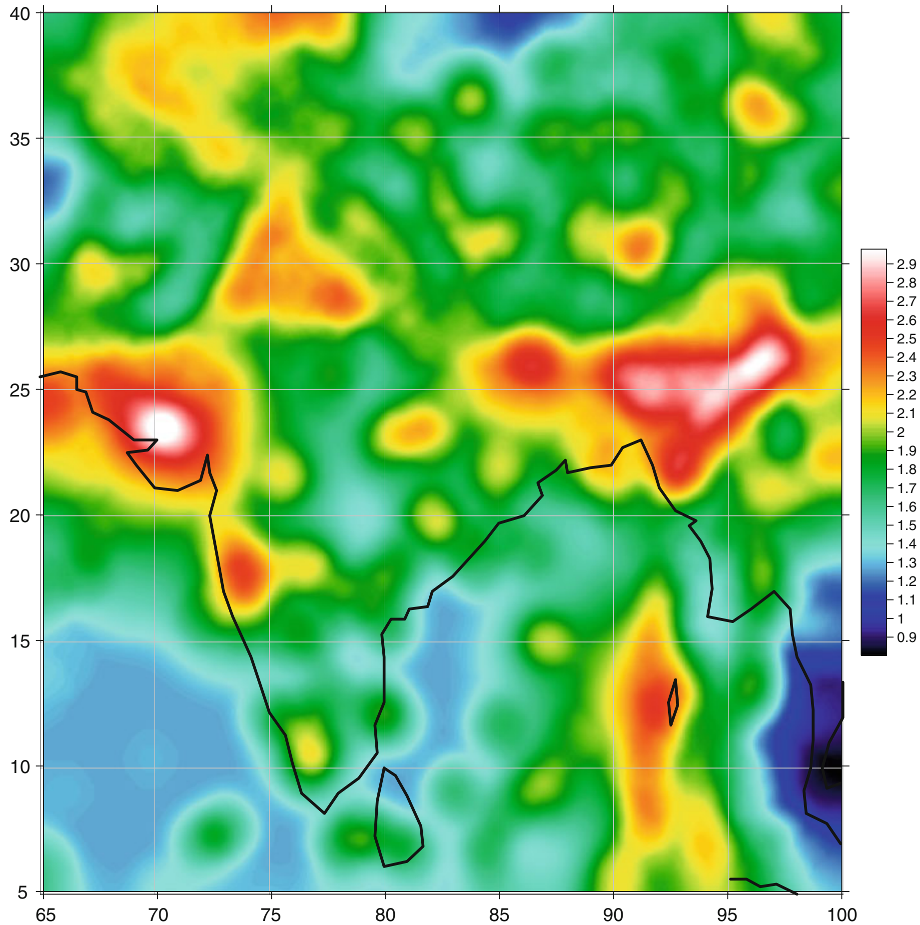

Fig. 4 Map of maximum lg(A_{max}) in cm/sec^2, calculated according to attenuation law and catalog

seismic catalog of India that includes historical earthquakes. The next step was removing aftershocks (as it was described above) in order to provide random character of time moments sequence. After that, the only 30 “main-shocks” events that have the maximum values of lg (A_{max}) were taken for the analysis. Thus, for each node of the grid, we have the same value of $n = 30$ in the formula (1) but different values of R_0 and $R_\tau = \max_{1 \le i \le n} R_i$. The a priori boundary value for ρ was taken as $\rho_{max} = R_\tau + 0.5$.

The Fig. 3 presents graphics of empirical tail probability function for these $n = 30$ events for 4 nodes of the grid. The red lines are the best fit exponential law curves.

Thus, after performing estimates in each node of the grid, we can plot the following maps:

- the map of maximum estimated values R_τ (Fig. 4);
- the map of estimates for maximum possible values ρ of lg (A_{max}) (Fig. 5);
- the map of standard deviation for ρ-estimates (Fig. 6);

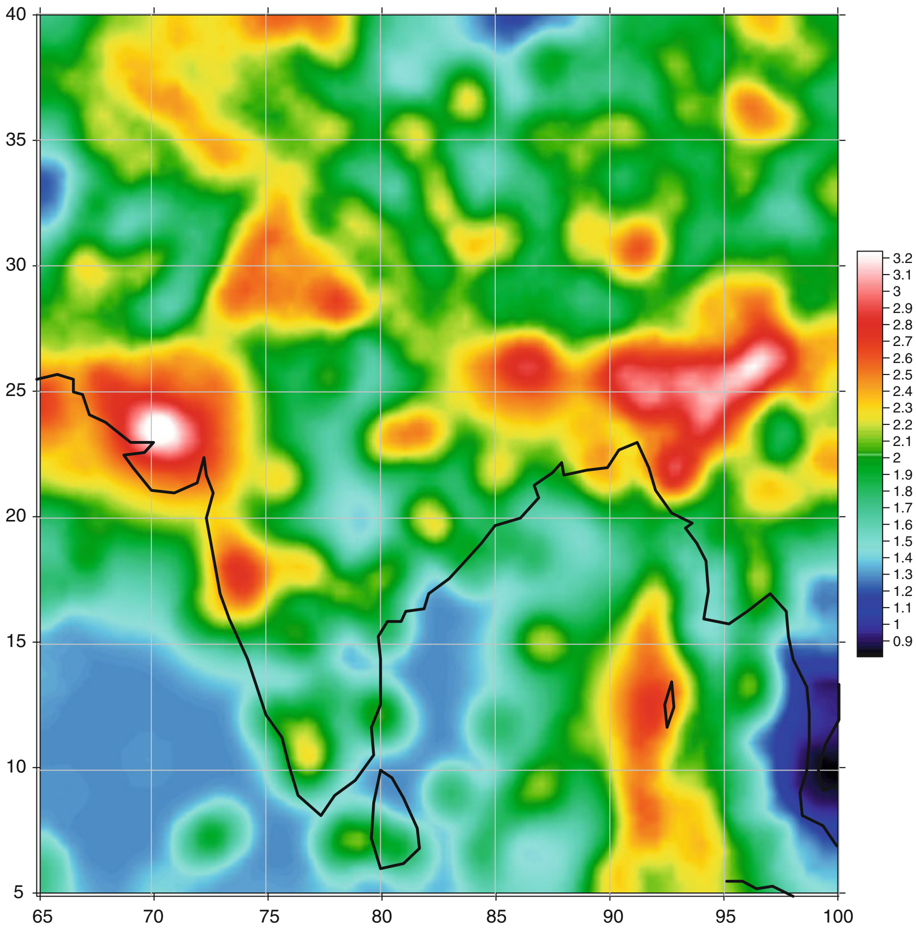

Fig. 5 Map of estimates of maximum possible values ρ (for $\lg(A_{max})$ in cm/sec^2)

- the map of 90% quintile of distribution of maximum values of lg (A_{max}) on the future time interval of the length $T = 100$ years (Fig. 7);
- the map of standard deviations for 90% quintile of distribution of maximum values of lg (A_{max}) on the future time interval of the length $T = 100$ years (Fig. 8).

For reducing the errors, these maps were plotted after smoothing the correspondent grid values by Gaussian kernel functions with radius 1 degree using 128 nearest neighbors values (Hardle 1989).

4 Discussion and conclusion

The earthquakes in the Indian subcontinent are considered as the most dreaded natural hazard as they occur without warning, sometimes in unexpected areas, resulting in great

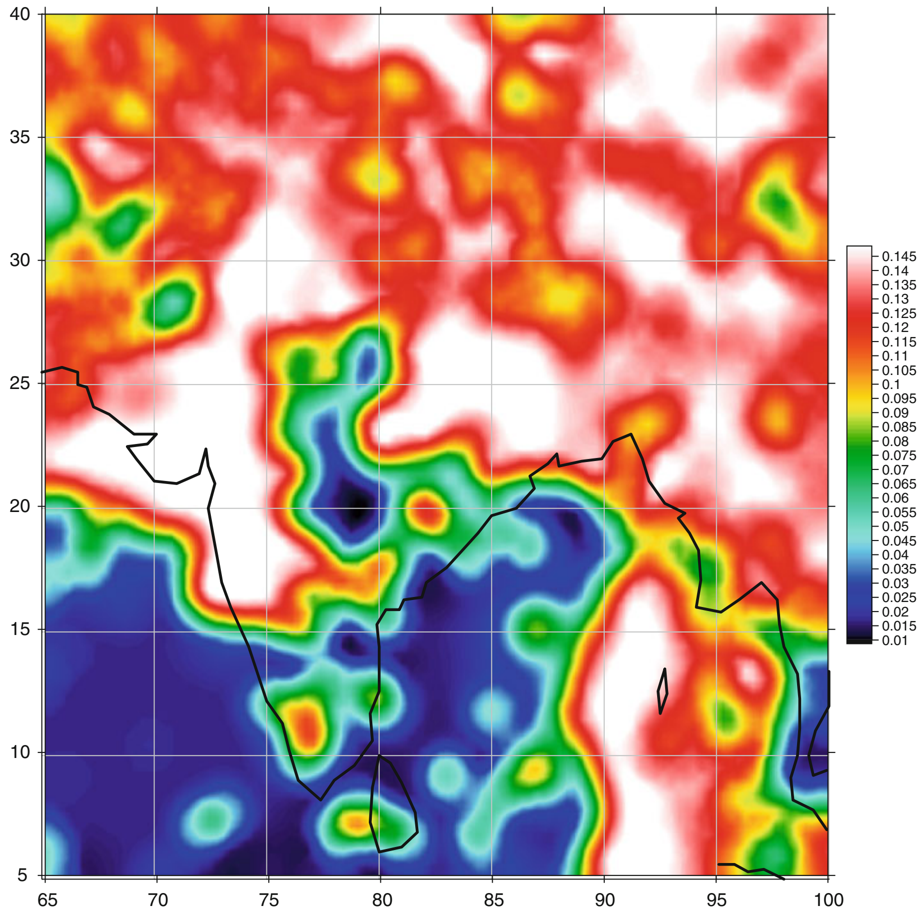

Fig. 6 Map of standard deviations of estimates of maximum possible values ρ (for lg($A_{\max}$) in cm/sec^2)

destruction and loss of lives. A vertical approach to mitigate the destructive impact of the earthquakes in seismically vulnerable regions is to estimate their hazard potential and take appropriate remedial measures. There are several approach to assess the seismic hazard at regional/national level, most commonly used the probability of occurrence of earthquake in time and space, probability of exceeding a specific ground motion and deterministic seismic hazard assessment by simulation of ground motion using source, path and site effect. In the present study, we have estimated the probability of excess of peak ground acceleration using a simplified Bayesian approach. The inputs are based on seismic catalog of the past earthquakes in the region and the proper attenuation law of peak ground acceleration with hypocentral distance and magnitude.

The probabilistic seismic hazard map of India and adjacent areas have been prepared first by Khattri et al. (1984) and then by Bhatia et al. (1999) in terms of peak ground acceleration for 10 percent probability of excess over 50 years time. Parvez et al. (2003) have published the first ever deterministic seismic hazard map of India and adjacent areas

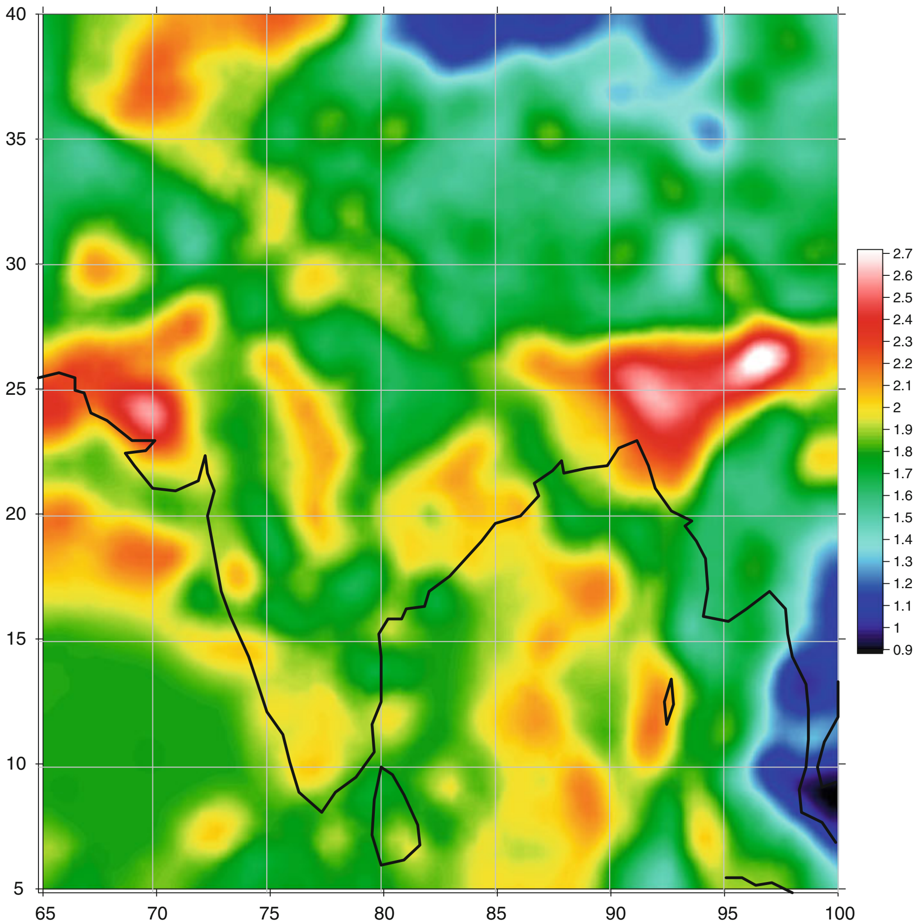

Fig. 7 Map of 90% quintile of distribution of maximum values of $\lg(A_{\max})$ on the future time interval of the length $T = 100$ years

by simulation of ground motion time histories complete with all phases from the knowledge of the seismic source and of the propagation of seismic waves associated with the given earthquake scenarios. So far, no report is available on the study of seismic hazard using Bayesian approach for the Indian region; however, such study has been successfully carried out for California, Balkans and Japan (Pisarenko and Lyubushin 1999), Circum-Pacific Belt (Tsapanos et al. 2001) and territory of Greece (Lyubushin et al. 2002). The results of our study have been mapped in Figs. 4, 5 and 7. The map of standard deviation estimates of maximum possible value of ρ is shown in Fig. 6. The peak ground acceleration is high in the part of northeast India, Kachhach, Andaman and Hindukush region and that varies from 0.5–0.8 g for future time interval length of $T = 100$ years.

We compared our result of the present study with the existing probabilistic seismic hazard of India (Khattri et al. 1984; Bhatia et al. 1999). Khattri et al. (1984) have considered the attenuation law of eastern United State after they found that the intensity attenuation law of the Indian region and the Eastern United State was similar, whereas

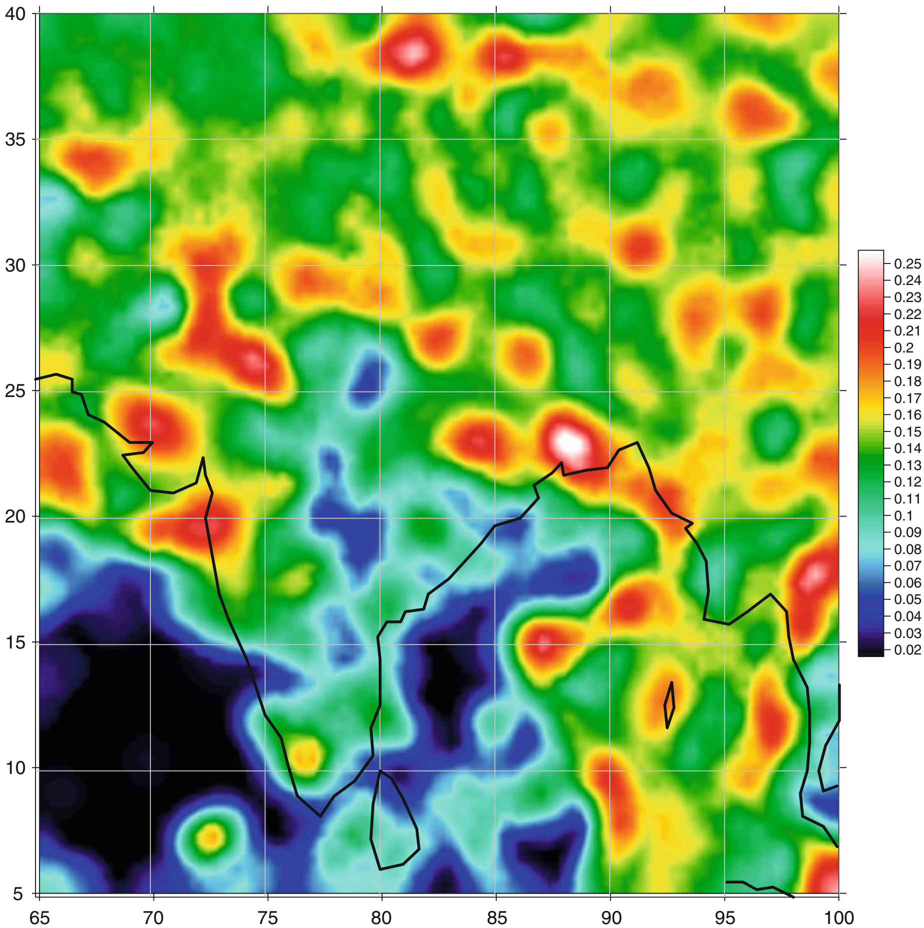

Fig. 8 Map of standard deviations for 90% quintile of distribution of maximum values of $\lg(A_{\max})$ on the future time interval of the length $T = 100$ years

Bhatia et al. (1999) have used the attenuation law of western United State without any justification. In the present study, we have used the attenuation law of derived by Parvez et al. (2001, 2002) using the systematic analysis of Indian strong-motion data. While comparing, we found that our results compare very well with PGA values of Khattri et al. (1984) particularly in the seismogenic belts of Kirthat, Hindukush, northeast India and Andaman region (Fig. 4). However, the PGA values of Bhatia et al. (1999) underestimate the hazard compared to our study. This has been observed after the Bhuj earthquake of January 26, 2001, and Pakistan earthquake of October 8, 2005, that the ground motion predicted in GSHAP by Bhatia et al. (1999) underestimates many folds. The reason of underestimating the hazard values by Bhatia et al. (1999) is the choice of attenuation law that is not suitable for Indian region (Parvez et al. 2003). Our results of this study also compares well with the simulated ground motion of Parvez et al. (2003) in terms of seismic zones of high potential hazard.

The proposed method in this study for estimating probabilistic characteristics of maximal values of seismic peak ground acceleration on a given future time interval for a given site is rather simple in use and needs only those information that is in seismic catalogs and used attenuation laws. We do not need previously estimate maximal magnitudes. This method could be useful for "express" estimating in elaborating a detailed maps of seismic hazard using not only seismic information but geological and paleoseismical as well. For consideration of the time-dependent seismic hazard, the main tool is the regression law between macroseismic intensity and the mean return period for large intensity values. The last step seems to be an indirect using of the primary seismological information, because the definition of return period includes estimating of function of distribution of intensity. The necessity of fitting some law for connection between return period and intensity is one more intermediate step in the method. Each intermediate step brings some uncertainty to the final result. From this point of view, the method applied in this paper seems to be much more straightforward. It does not need any intermediate steps between the "source"—(catalog + attenuation law) and the "target"—the estimates of maximum peak ground acceleration and its quantiles. Of course, the quality of the method should be estimated by its practical usefulness, and there is a lot of work to test and compare different approaches for seismic hazard assessment.

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