ISET Journal of Earthquake Technology, Paper No. 413, Vol. 38, No. 2-4, June-Dec. 2001, pp. 93-102

ESTIMATION OF SEISMIC HAZARD PARAMETERS IN THE HIMALAYAS AND ITS VICINITY FROM MIXED DATA FILES

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ABSTRACT

The seismic hazard parameter estimation using Maximum Likelihood Method (MLM) has been made in the Himalayas and adjoining regions on the basis of a procedure which utilizes mixed data containing incomplete files of large historical events (extreme part of the catalogue) and complete files of the most recent earthquakes (complete part of the catalogue) with the same threshold magnitude. The entire set of earthquake catalogues used covers the period from 1720-1990. The maximum regional magnitude, $M_{\max}$, the activity rate of seismic events, λ, the mean return period, R, of earthquakes above a certain lower magnitude, $M \geq m$, as well as the parameter b of magnitude-frequency relationship have been determined for six seismic zones having different seismotectonic environments. Large differences of the b parameters and hazard level from seismic zone I to VI reflect the high seismotectonic complexity and crustal heterogeneity, thus suggesting that the locations of important projects like hydroelectric power plants and town development should preferably be in the zones of lower hazard level.

KEYWORDS: Seismic Hazard, Himalayas, Seismicity, Return Periods, Maximum Likehood

INTRODUCTION

The natural hazards are inevitable...natural disasters are not. Earthquakes are among the most unavoidable natural hazards. One of the most frightening and destructive phenomena of nature is a severe earthquake and its terrible aftereffects. Numerous attempts to understand and predict this natural phenomenon have yielded partial successes, but most of the time, nature maintains its superiority over present day science by striking in unexpected areas at the most unexpected times of day. The key point of seismic hazard assessment is the determination of seismogenesis zones and structures within the territory studied. It is carried out by the complex analysis of the seismological, geological, geophysical and geodetic information available. But the seismological aspect, being the most important one, is required to be considered in more detail.

Most probabilistic seismic hazard assessment procedures require the determination of seismic source zones, and a knowledge of their hazard parameters such as activity rate and level of completeness, Gutenberg-Richter (G-R) parameter b, and maximum possible magnitude $M_{\max}$. These parameters are then used to assess seismic hazard. As such, information is not readily available for large part of the Indian subcontinent, and most Indian seismic catalogues are highly uncertain and incomplete. Most of the available earthquake catalogues usually contain two types of information: macroseismic observations of major seismic events that occurred over a period of few hundred years, and complete instrumental data for relatively short periods of time, say the last fifty years at the most. Classical methods which are generally used for the estimation of seismic hazard parameters (e.g., Weichert, 1980; Dong et al., 1984) are not suitable for this type of data, because of the incompleteness of the macroseismic part of a catalogue or because of difficulties in estimating its growing incompleteness in earlier times.

In the last two decades, increasing attention has been paid to obtain realistic assessment of seismic hazard (Kiremidjian and Shah, 1975; Mortgat and Shah, 1979; McCann, 1981; Wesnousky, 1986). Seismic hazard studies of different tectonic regions have been carried out by various workers (Bath, 1983; Markopoulos and Burton, 1985; Papazachos, 1988; Papadopoulos and Voidomatis, 1987; Papadopoulos and Kijko, 1991, for the Aegean region; Kijko and Sellevoll, 1989, 1992, for western Norway coastal region; Khattri et al., 1984; Rao and Rao, 1979; Gupta and Srivastava, 1990; Shanker and Singh, 1995; Shanker and Sharma, 1997, 1998, for territory of Indian subcontinent).

Shanker and Sharma (1998) have estimated seismic hazard parameters for the same region using only the complete parts of the database (1900-1990). In the present article, we use the method suggested by Kijko and Sellevoll (1989) to estimate seismic hazard parameters in the six seismotectonic zones identified by Shanker and Sharma (1998) and containing incomplete files of large historical earthquakes (extreme part of catalogue) and complete files of most recent earthquakes (complete part of the catalogue) of the Himalayan belt.

SEISMIC SOURCE ZONES

Seismic zonation means a relatively small part of the lithosphere which includes the rupture zones of the largest main shocks of this part of the lithosphere as well as the rupture zones of smaller main shocks. The characteristic property of a seismogenic region is the interaction among its faults during the important seismic excitation (redistribution of stress, etc.). Therefore, zonation in the present case is the procedure of defining the boundaries of a seismogenic region (Shanker and Sharma, 1998).

To check the effect of zonation on the main feature of the hazard determination procedure, different divisions were made in areas with complex seismicity patterns and tectonics. It was observed that although the accurate definition of seismogenic regions is important, it probably indicates that seismogenic regions, where interactions between faults occur, have not always very sharp boundaries. It is possible even for a distant fault to take part in the interaction, but this probability decreases with increasing distance (e.g., Harris, 1998).

The division of the studied area into seismotectonic segments, i.e., into seismotectonically homogeneous parts of the seismic zones, is one of the basic requirements for the application of the estimation procedure for seismic hazard parameters. The Himalayan region (20°-36° N and 69°-100° E) is seismically very active and highly complicated from seismotectonic point of view, and for this reason, the whole Himalayan seismic area has been divided into six active zones based on seismotectonics, seismicity distribution and topographic variations. These six seismic zones (Shanker and Sharma, 1998) along the major tectonic features of the area (Rectangles I, II, III, IV, V and VI in Figure 1) are:

Seismic zone I	Hindukush-Pamirs (HKP) (25°-36° N and 69°-75° E)
Seismic zone II	Kashmir-Himachal Pradesh (KHP) (25°-36° N and 75°-80° E)
Seismic zone III	India-Western Nepal Border (IWNB) (25°-32° N and 80°-84° E)
Seismic zone IV	Nepal-India-Sikkim Border (NISB) (20°-30° N and 84°-89° E)
Seismic zone V	North-East India (NEI) (20°-30° N and 89°-94° E)
Seismic zone VI	Burma-Andaman-Nicobar (BAN) (20°-30° N and 94°-99° E)

EARTHQUAKE DATABASE

In the present analysis, the earthquake catalogue (1720-1990) has been used. Data for the time interval of 1720-1986 has been taken from Chandra (1992) while data after that has been taken from the National Geophysical Data Center, Boulder, Colorado, U.S.A. The plots of epicenters with magnitude $M \geq 3.0$ are shown in Figure 1.

METHODOLOGY

Generally, the available earthquake catalogues contain two types of information: one is macroseismic observations of major seismic events that occurred over a period of a few hundred years, and other is complete instrumental data for relatively short periods of time (Figure 2). The methods which are generally used for the estimation of seismic activity parameters (parameter b in G-R equation, earthquake activity rate λ, and $M_{\max}$) are not suitable for this type of data due to incompleteness of the macroseismic (extreme) part of the catalogue.

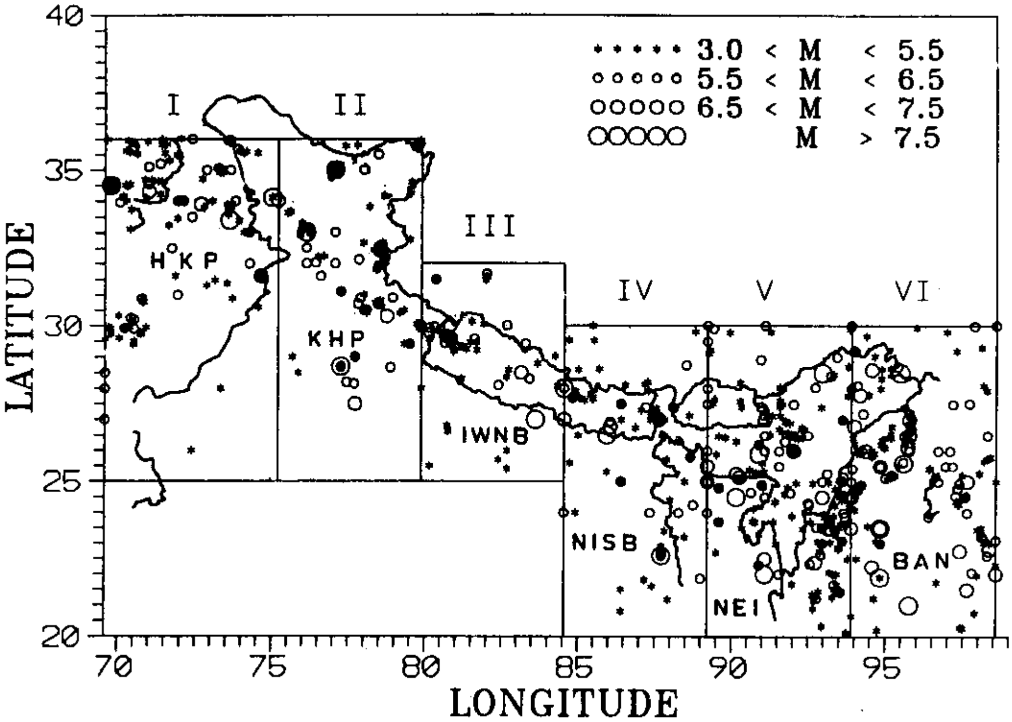

Fig. 1 Seismicity map of the Himalayas and its vicinity for the period 1720-1990 (the identified seismic zones for the analysis are shown by rectangles denoted by I, II, III.....VI (after Shanker and Sharma, 1998))

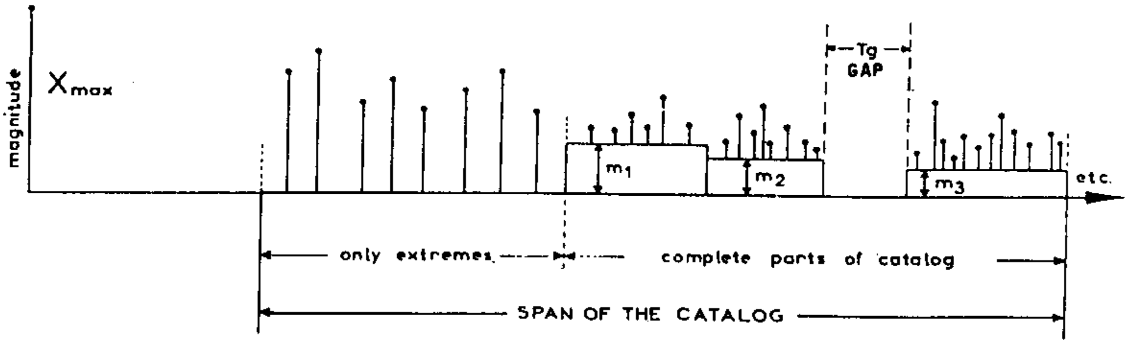

Fig. 2 Illustration of data used for seismic hazard parameter estimation (after Kijko and Sellevoll, 1987) taking into account extreme as well as complete data files (this approach also accepts gaps (T_g: period for missing earthquake data))

One of the suitable methods for analyzing the macroseismic part of the catalogue is extreme distribution, extended to allow for varying time intervals from which maximum magnitudes are selected. This method of incorporating the incomplete part of the catalogue into the analysis is very far from being optimum, as a great deal of information contained in small shocks is wasted. Another method for estimating the seismic activity parameter is to reject the macroseismic observations that are incomplete and to use any standard method for the data from the other complete part of the catalogue. It is obvious that this procedure is also highly ineffective, as the quantitative assessment of recurrence of strong seismic events based on observations over a short period of time is burdened with large error (Knopoff and Kagan, 1977; Dong et al., 1984). Kijko and Sellevoll (1987, 1989) have developed an approach utilizing both the information on strong events contained in the macroseismic part of the catalogue as well as that contained in the complete catalogue which contains complete data above a certain magnitude threshold. This method assumes the Poissonian model of earthquake occurrence and the doubly truncated Gutenberg-Richter distribution.

In this paper, we use this approach to estimate seismic hazard parameters in six major seismotectonic zones (seismic zones) of Himalayas and its vicinity (Figure 1) in which mixed data files are being used. Such a study is of importance for two main reasons: (i) we evaluate hazard parameters utilising as much as possible seismological information not only from the instrumental period, but also from several hundreds of years of the historic era; in other words, we use historical seismological information not used so far in Himalayan hazard determination, (ii) the application of this approach in a region of high seismotectonic complexity and high seismicity is a good methodological test offering a suitable basis for seismotectonic discussion.

Table 1: Input Data Used for Seismic Hazard Analysis

Seismic Zone	Number of Events Extreme (N_e)	 Complete (N_c)	Standard Deviation	Max. Obs. Magnitude
I	7	107	0.37	7.7
II	9	68	0.66	8.6
III	5	52	0.55	8.7
IV	12	46	0.66	8.4
V	8	166	0.59	8.7
VI	3	157	0.75	8.7

ESTIMATION OF SEISMIC HAZARD PARAMETERS

A well-known technique (Kijko and Sellevoll, 1989) for the estimation of seismic hazard parameters for the mixed data files has been used. The method accepts mixed data, one containing only the largest earthquakes (extreme part) and other containing data sets complete to different threshold of magnitude (complete part). A computer program based on this method and written by the above authors is also used for the analysis. According to the requirement of this computer program, the whole span of database has been broken into two parts: one extreme part (1720-1900) and other complete part (1900-1990), as illustrated in Figure 2. It was assumed that in order to estimate the seismic hazard in the present study for each zone, the maximum possible magnitude $M_{\max}$ is determined with standard error as 0.10 and threshold magnitude $M = 5.0$. Table 1 summarises the input data used for the seismic hazard evaluation in the six seismic zones of the Himalayan belt. The selection of extreme part of the catalogue is demonstrated in Figure 3. The inset in the histogram of the extreme and complete part shows the extreme magnitude selected from a 10 year time period, constituting the extreme data file for seismic hazard estimation.

RESULTS AND DISCUSSION

Results of the hazard analysis are summarised in Table 2. Zone I, Hindukush-Pamir (HKP) is limited by 25°-36° N and 69°-75° E, and has a V-shaped lithosphere as inferred by seismicity. The depth range of earthquakes in this region is 5 to 250 km. The largest earthquake of Richter magnitude 7.7 occurred in 1885. The seismicity distribution is along Herat fault, north of Kabul, Chaman fault and mountain ranges in the Pamir Knot. The focal mechanism indicates thrust faulting and stress to be active at different depths. The seismic activity of the region is non-linear and follows the Poisson distribution (Shanker and Singh, 1995). The extreme part of the catalogue starts at 1720/01/01 and ends at 1889/12/03. The complete part of the catalogue starts at 1900/01/01 and ends at 1990/12/03 with threshold magnitude 5.0. The $M_{\max}$ values for all the six zones could not be estimated using the present technique. The $M_{\max}$ values are, therefore, taken as $M_{\max} = M_{\max\text{-obs}} + 0.5$, which is the default value taken by the computer program since the program is not able to assess $M_{\max}$. Analysis for Zone I gives $\beta = 1.98 \pm 0.14$, $\lambda = 16.25 \pm 3.33$, $M_{\max} = 8.2 \pm 0.86$ and $b = 0.84 \pm 0.06$, where the minimum data in the set i.e. $M_{\min} = 3.3$. For magnitude 6.0, the return period $R_{6.0}$ is computed as 13.1 years, as given in Table 2. For the above computations the data contributions to the parameters are 36.2% and 6.2% for the extreme part and 63.8% and 93.8% for the complete part of the catalogue for β and λ, respectively.

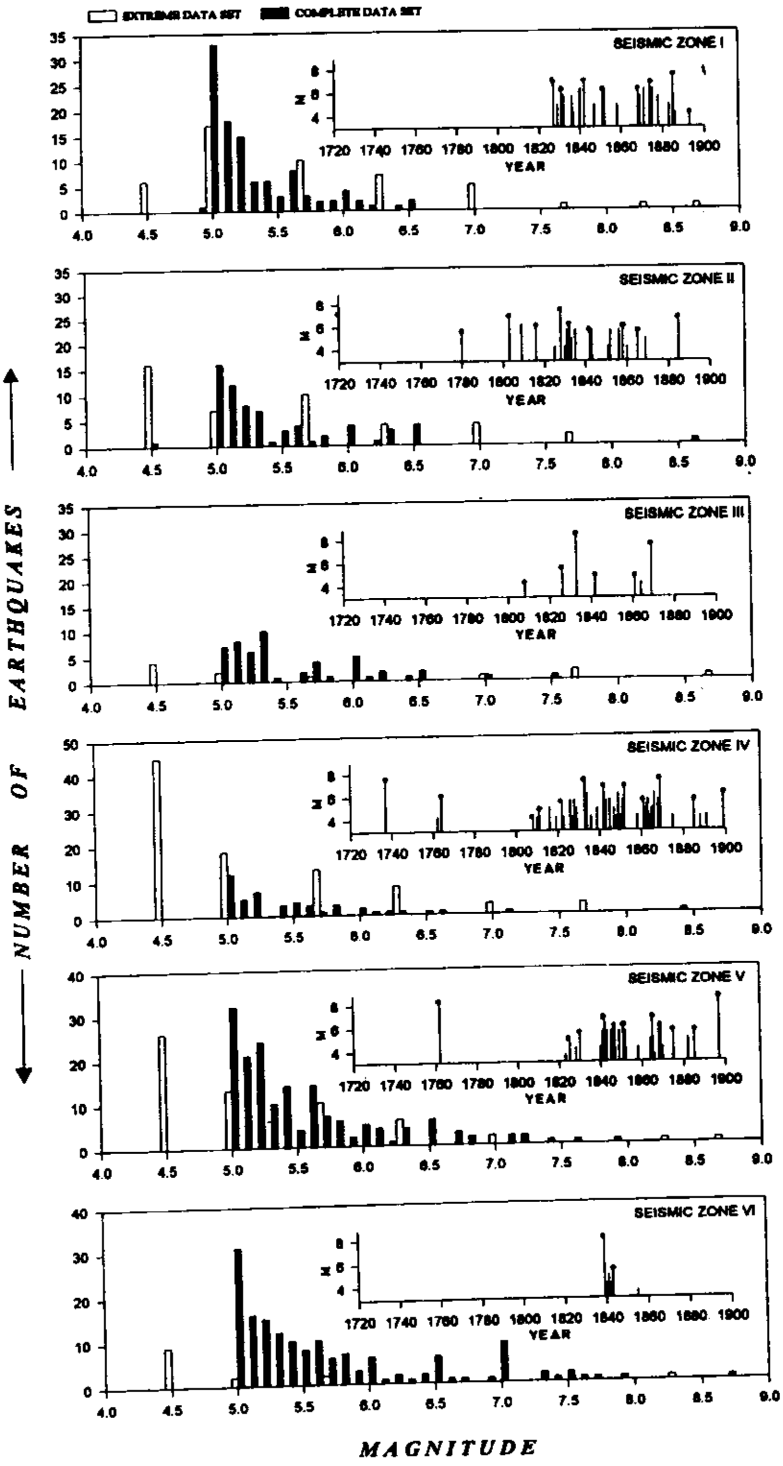

Fig. 3 Frequency distribution histograms for the extreme (1720-1900) and complete (1900-1990) parts of the whole data set for the six seismic zones (the extreme parts are selected (marked as ↑) from the period 1720-1900 with 10 year time interval as shown in the insets via magnitude versus time plots)

Table 2: Seismic Hazard Parameters

Seismic Zone	λ	β	b-value	M_{max}	$R_{6.0}$ Years
I	16.25±3.33	1.98±0.14	0.84±0.06	8.2±0.86	13.1
II	2.35±0.29	1.83±0.16	0.77±0.07	9.1±2.10	16.4
III	1.18±0.26	1.15±0.16	0.49±0.07	9.2±0.74	19.2
IV	1.77±0.41	1.29±0.17	0.55±0.07	8.9±0.76	18.9
V	6.70±0.61	2.16±0.12	0.92±0.05	9.2±3.8	11.2
VI	3.91±0.31	1.78±0.11	0.75±0.05	9.2±1.47	9.0

Figure with (±) shows 90% confidence level

Seismic zone II, Kashmir-Himachal Pradesh (KHP) which extended from 25°-36° N and 75°-80° E is seismically very active. The earthquakes are shallow in nature. The largest earthquake of magnitude 8.6 was Kangra earthquake of 1905, which killed over 20,000 people. Major Srinager, 1885 earthquake took a toll of 6000 lives. The prominent faults in this region are the MBT, Indus suture zone (ISZ) and the Kaurik faults. The seismicity and return period of this region have been discussed by Shanker and Singh (1997) in detail by using Gumbel's models based on the extreme value theory. In this zone, the number of events in the extreme part is 9 and in the complete part is 68 (Figure 3). The values of hazard parameter for this zone are β = 1.83±0.16, λ= 2.35±0.29, M_{max} = 9.1±2.10, b = 0.77±0.07, where M_{min} = 4.0. The data contribution to the parameters for β is 49.6% and 50.4%, and for λ, it is 11.8% and 88.2% for extreme and complete parts, respectively. These values agree well with previous analysis (Shanker and Sharma, 1998).

In seismic zone III, i.e., India-Western-Nepal Border (IWNB), the earthquakes are shallow to a depth of 23 km. The largest earthquake in this region occurred in 1833. Uttarkashi earthquake 1991 of magnitude 7 killed 768 people. The seismic activity is different along the Main Central Thrust (MCT). Other main thrusts present in the region are Almora and Vaikrita thrust and tear faults like Yamuna tear fault. The value of hazard parameters are β = 1.15±0.16, λ = 1.18±0.26, M_{max} = 9.2±0.74 and b = 0.49±0.07, where M_{min} = 3.30. Here, the data contribution by the complete part and the extreme part are 54.2% and 45.8% for β and 91.1% and 8.9% for λ, respectively.

Nepal-India-Sikkim Border (NISB), i.e. Zone IV, is characterised by scattered seismic activity associated with MCT and MBT and some tear faults. The largest earthquake of January 15, 1934 had a magnitude of 8.4. The recent earthquake of August 22, 1988 (M = 6.8), though smaller in magnitude than the great Bihar-Nepal earthquake of 1934, shows almost similar meizoseismal pattern. For this seismic zone, the hazard parameters have been computed as β = 1.29±0.17, λ= 1.77±0.41, M_{max} = 8.9±0.76, while M_{min} = 3.30 and b = 0.55±0.07. The data contributions by the complete and the extreme parts are 44.5% and 55.5% for β and 79.6% and 20.4% for λ respectively.

The seismic zone V, North-East India (NEI) is seismically very active. Earthquakes are shallow to intermediate depths (up to 200 km). The focal depths increase towards Burmese arc at the eastern margin of the Indian plate. The largest earthquake of magnitude 8.7 which occurred on 12 June 1897 was most disastrous in the history of earthquakes. Another earthquake of magnitude 8.5 occurred on 15 August, 1950 in the eastern syntaxial bend close to India-Tibet border. The hazard parameters for this region are β = 2.16 ± 0.12, λ = 6.70±0.61, M_{max}= 9.2±3.8, where M_{min} = 4.0 and b = 0.92±0.05. These values agree well with the values obtained only by the complete part of the data files (Shanker and Sharma, 1997). The data contribution by the complete and the extreme parts are 46.0% and 54.0% for β and 95.4% and 4.6% for λ, respectively.

In Burma-Andaman-Nicobar (BAN) i.e., seismic zone VI, the earthquakes have occurred from a shallow depth of 5 to 230 km. The largest earthquake in this region has been reported to be of magnitude 8.7 which occurred in 1950. The focal mechanism of many earthquakes in this region shows predominance of strike-slip movement. The calculated hazard values are β = 1.78±0.11,

$\lambda = 3.91 \pm 0.31$; $M_{\max} = 9.2 \pm 1.47$ where $M_{\min} = 4.0$ and $b = 0.75 \pm 0.05$. The data contributions by the complete and the extreme parts are 53.4% and 46.6% for β and 98.2% and 1.8% for λ, respectively.

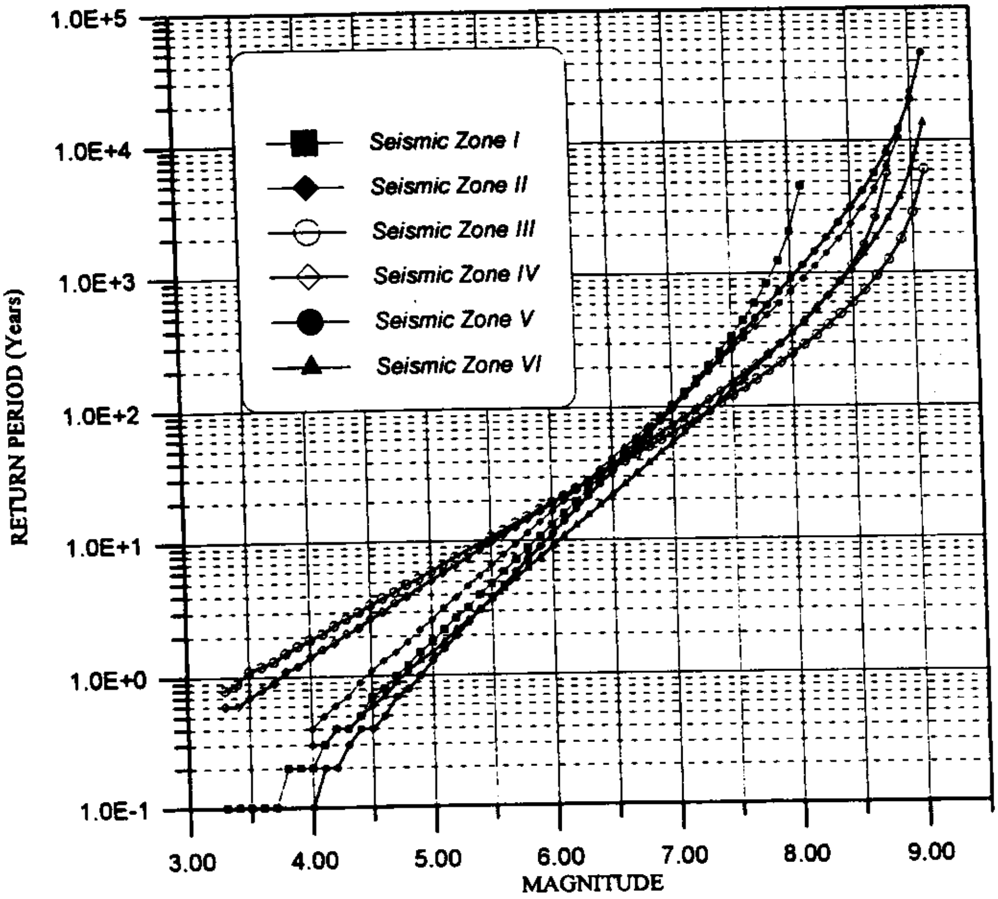

Fig. 4 Return periods estimated using mixed data (1720-1990) for the six seismic zones

Seismic interpretation of Table 2 indicates that β and b-values decrease from Zones I to VI but Zone V (NEI) has the highest value of β and consequently high b-value showing the activity of the zone. The low b-values in Zones III and IV may be attributed to the lesser number of events of lower magnitudes in the complete set of catalogue as is also evident from Figure 3. The parameter λ is highest in Zone I and lowest in Zone III, and hence, we get lowest return period for Zone I and greatest return period for Zone III. From Figure 4, it is clear that Zones II, III and IV show greater return periods $(M \geq 6.0)$ than Zones I, V and VI, implying that strong events occur more frequently in Zones I, V and VI as compared to the rest of the zones. Frequency distribution curve (Figure 3) also supports this view point. Considering the return period for $M = 6.0, 6.5, 7.0$, one may conclude that Zone VI is most active in the whole region. Probability of occurrence plats for 50, 100 and 1000 year return periods (Figure 5) imply that probability of occurrence of earthquakes decreases with magnitude in Zones I to VI.

In general, seismic hazard is sharply higher in Zones I, II and V. Zones III and IV show relatively low hazard than other zones, and Zone VI is the most hazardous zone than the other zones in the whole Himalayan belt. The distribution of hazard potential in several zones is informative and useful from engineering point of view; so, the hazardous zone may be avoided for engineering constructions or proper risk evaluation be done before going for constructions in such a zone.

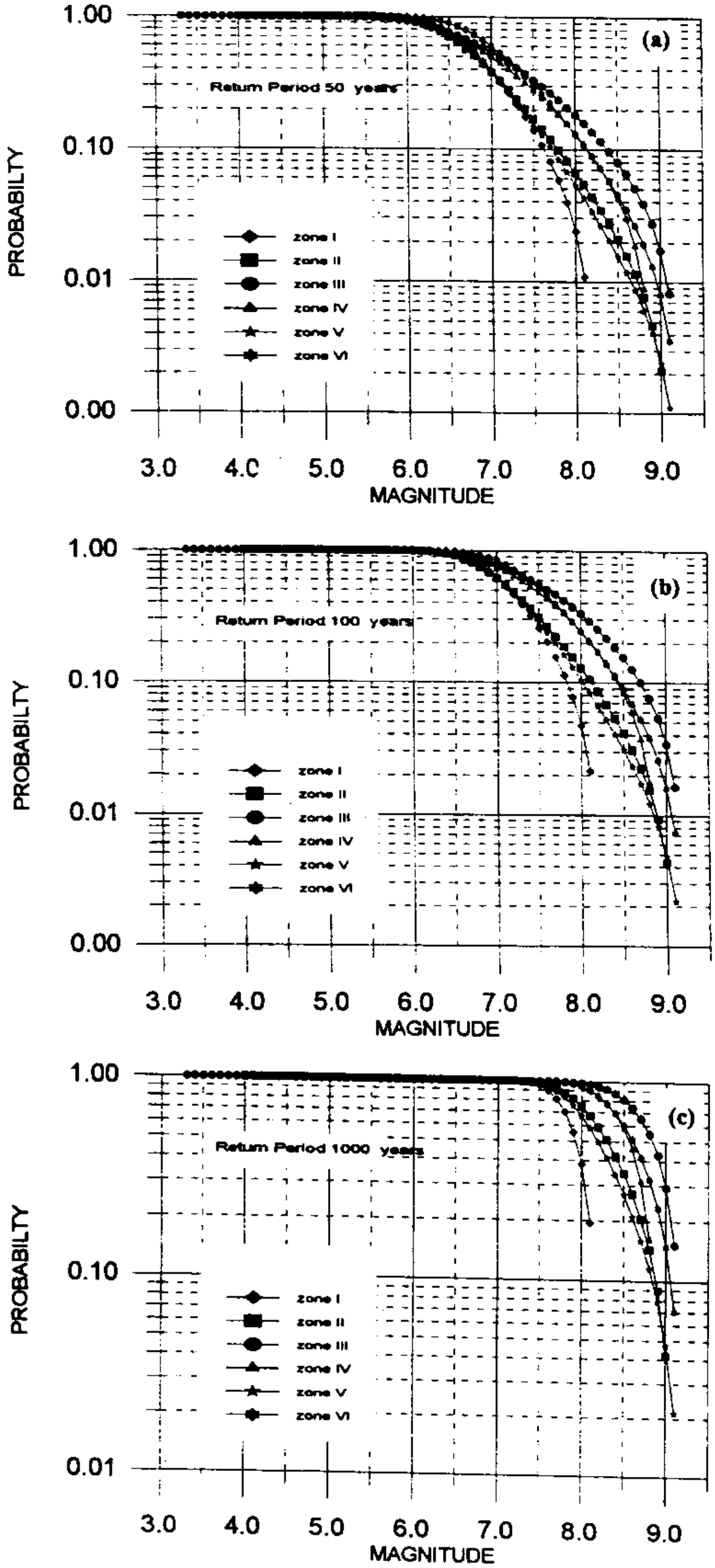

Fig. 5 Probability–magnitude diagrams for six seismic zones for return periods (a) 50 years, (b) 100 years and (c) 1000 years

SUMMARY AND CONCLUSIONS

The reliability of the results for seismic hazard estimation in a given region depends on the methodology and input information used. For the sake of simplicity, we have applied a MLM for mixed catalogue covering about 270-years long data. As a consequence, the hazard of each seismic zone (I-VI) is independently determined. In conclusion, the hazard level is sharply high in Zones NEI and BAN. Zones KHP, IWNB and NISB show intermediate hazard. The same can also be concluded from b -value distribution.

The variation of seismic hazard from zone to zone may be used as a characteristic parameter in the application of micro-seismic zonation in young mountainous areas. The major earthquakes $(M \geq 7.5)$ are likely to occur at those points along thrust and plate boundaries where excessive accumulation of strains/stresses have occurred. However, the stress accumulation will be restricted to local weak zones only along the thrust and junction of three lineaments. Thus, there is a possibility of adjoining areas having much lower seismic risk. Such areas of low seismic risk within the zone of high tectonic activity may be demarcated as those areas where major earthquakes have not occurred in the past two hundred years. It appears that major earthquakes will continue to occur repeatedly only in the zone of strain accumulation and stress concentration. Thus, the zones of lower earthquake risk may be demarcated reliably on the basis of seismic history.

The important projects like hydroelectric project and town planning should preferably be located in the areas of lower seismic risk. It is time to generate confidence and interest among geophysicists and geoscientists to develop computer modeling of three-dimensional non-linear geodynamic analysis and seismic migration technique. Apart from its importance in seismicity and earthquake prediction studies, b is an indicator of the mechanical properties of the seismogenic materials, such as stress concentration, crack density and degree of heterogeneity. The hazard parameters λ, β, b -value in each seismic zone represent the seismic potential of each zone. Thus, attention should be focused on these parameters for future engineering or other practical purposes.

Seismological investigations suggest that stress concentration and major earthquakes are likely to occur where three plate boundaries are meeting, such as NE-Himalayas and Kashmir. It is true that major earthquakes have been occurring in these zones. As such, many areas of lesser earthquake risk may exist in Himalayas in between Assam and Jammu as only two plates are interacting in the normal direction. Thus, attention should be focused on micro-seismic zonation.

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