

Seismic Hazards Assessment in the Eastern Himalayas Region

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Abstract: Spatial distribution of seismicity and seismic characteristics (fractal dimension, b-value, energy release, reoccurrence period) are assessed for the Himalayan Region (27° – 30°N and 85° – 97°E). The database consists of relocated earthquakes $M \geq 3.8$ selected for the period 1964-2017 from the International Seismological Centre (ISC) catalogues (Engdahl, van der Hilst, and Buland (EHB) 2007). The *Gutenberg - Richter* frequency-magnitude relation (b-value) is calculated by the Maximum Likelihood Method (MLM) and by Least Square Method. The fractal dimension is estimated using the correlation integral method. The entire event set was also used for estimating radiated energy in the region. Four probabilistic models namely, *Weibul*, *Gamma*, *Lognormal* and *Exponential* have been used to estimate the probability of the occurrence of moderate earthquakes ($M \geq 5.5$ and $M \geq 6.5$) during a specified interval of time using the Maximum Likelihood Estimates (MLE) for estimating the model parameters. The highly stressed zones in the entire region are indicated by low b-values, low fractal dimension and low radiated energy. The vulnerable zones (Arunachal Himalayas, Mishami thrust zone) have been identified by these maps which are further corroborated with the probabilistic models to assess the seismic hazards in the Himalaya region. These areas are indicative of future probable earthquakes regions.

Keywords: Eastern Himalayas, b-value, Fractal Dimension, Radiated Energy, Return Periods

1. Introduction

The Eastern Himalayas fall in zone V in the seismic zonation map of India [4]. The area under study in Himalaya lies between 27° - 30° N and 85° – 97° E. To analyse the statistical characteristics of seismicity and seismogenic faults, a comprehensive study of the *b-value*, *fractal dimension* (D) and *radiated energy* (E) is made in the study area.

The b-value in the frequency-magnitude relation which characterizes the distribution of earthquakes over the observed range of magnitudes. The power law relation between the frequency of occurrence and magnitude of earthquakes is introduced by Gutenberg and Richter in the year 1944 [11]:

$$\log_{10}N=a-bM$$

where N is the cumulative number of earthquakes having

magnitude larger than M, 'a' is a constant, and 'b' is the slope of the log-linear relation. This relationship has been found to be applicable over a wide range of earthquake sizes both globally and locally [35]. The variability of b-value in different regions may be related to structural heterogeneity and stress distribution in space [22, 29, 5].

The earthquake phenomenon possess fractal structure with respect to time, space and magnitude and therefore earthquakes are represented by self similar mathematical construct, the 'fractal', and the scaling parameter is called the fractal dimension D [20]. The fractal dimension characterizes the degree to which the fractal fills up the surrounding space. The fracture characteristic of earthquake can be predicted by knowing the value of D. It was illustrated [34] that possible values of fractal dimension are bound in a range between 0 and 2, which is dependent on the dimension of the embedding space. Interpretation of such limit values is that a set with $D \sim 0$ has all events clustered into one point; at the other end of the scale, $D \sim 2$ indicates that the events are

randomly or homogeneously distributed over a two-dimensional embedding space.

The energy released during an earthquake is an important parameter to quantify an earthquake. Many researchers have attempted to use the observed seismograms for the estimation of seismic energy [10, 12, 13, 2, 33, 6, 31, 19, 21]. Cumulative energy released during an earthquake was originally estimated in 1951 [3]. The relation between the magnitude m (body wave magnitude, m_b) and the radiated energy E [13] can be expressed as

$$\log E = 5.8 + 2.4 m$$

where E is in ergs.

Seismic hazard assessment

The term seismic hazard is used to denote the probability of occurrence of an earthquake with magnitude larger than or equal to a particular value in a region within the defined time interval. It has been observed that in some seismic regions large earthquakes occur at fairly regular intervals. Such a series of earthquakes is often represented by a renewal process, in which the time interval T between successive strong events has a certain distribution $w(T)$. The systematic evaluation of the reoccurrence period of an earthquake is very important for evaluation of the seismic risk and of great importance to the effort of earthquake prediction [36, 26].

2. Objective

The present study is aimed to;

- 1) Evaluate seismic parameters like b-value, fractal

dimension and energy release, in the Eastern Himalayas.

2) To make a quantitative assessment of seismic hazards using various probability models such as (i) Lognormal distribution (ii) Gamma distribution (iii) Weibull distribution and (iv) Exponential distribution. The probability of occurrence of moderate or large earthquakes with magnitude > 5.5 during a specified interval of time is estimated on the basis of these probabilistic models.

3. Tectonic Set up of Eastern Himalayas

The conceptual tectonic model of the Himalaya [30, 18] indicate major tectonics structures/faults following the ~2500 km long Himalayan trend. These faults are geologically mapped; from north to south these are the Trans Himadri Fault (THF), the Main Central Thrust (MCT), the Main Boundary Thrust (MBT) and the Himalayan Frontal Fault (HFF) [8, 23, 37, 25, 28, 27] (Figure 1). Further north, the Indus Suture Thrust (IST) represents the junction of the two colliding continents. It was suggested [27] that the HFF is the present day surface expression of shortening between the Himalaya and the Indian plate: a shortening rate of 6-16 mm/yr is estimated. It was argued [24] that the HFF is the potential zone for large earthquakes in the Himalaya. Large earthquakes of magnitude 7.0 and above, or intensity VIII and greater that caused fatalities in the Himalaya and surrounding regions are shown in Figure 2. The great ($M > 8.0$) and the most destructive earthquakes are shown by larger symbols and the years of occurrence are annotated.

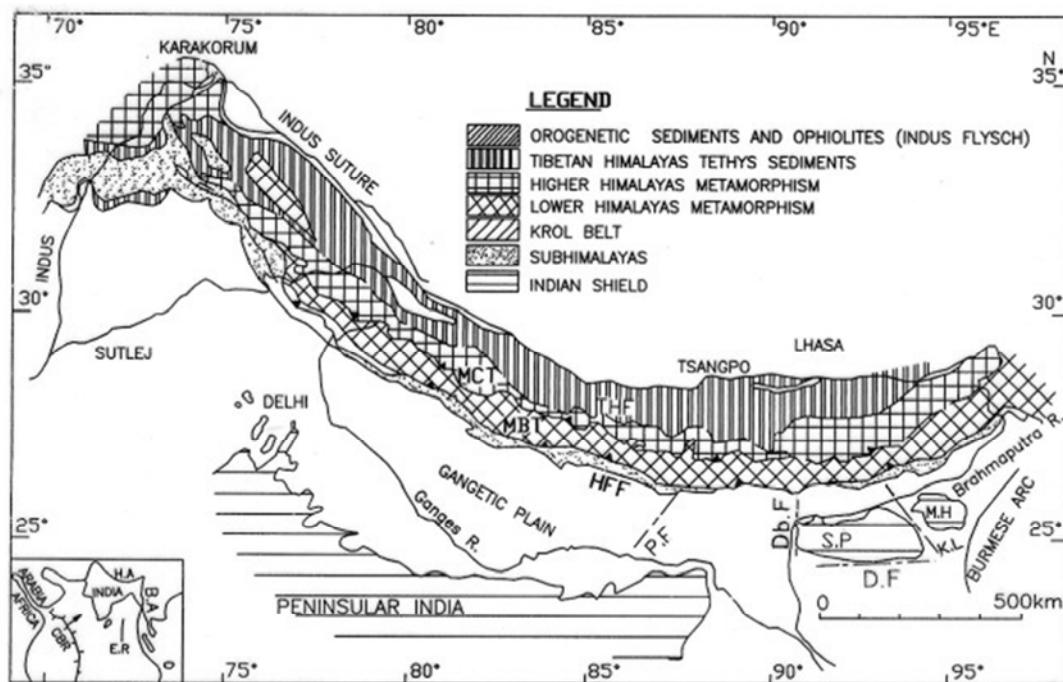


Figure 1. Himalayan arc with the major tectonic features. HFF: Himalayan Frontal Fault, MBT: Main Boundary Thrust, MCT: Main Central Thrust, THF: Trans Himadri Fault, PF: Patna Fault, Db.F: Dhubri Fault, SP: Shillong Plateau, MH: Mikir Hills, KL: Kopili Lineament, DF: Dauki Fault, Inset: sketch map showing north-northeastward motion of the Indian plate, HA: Himalayan Arc, BA: Burmese Arc, CBR: Carlsberg Ridge, ER: East Ridge [17].

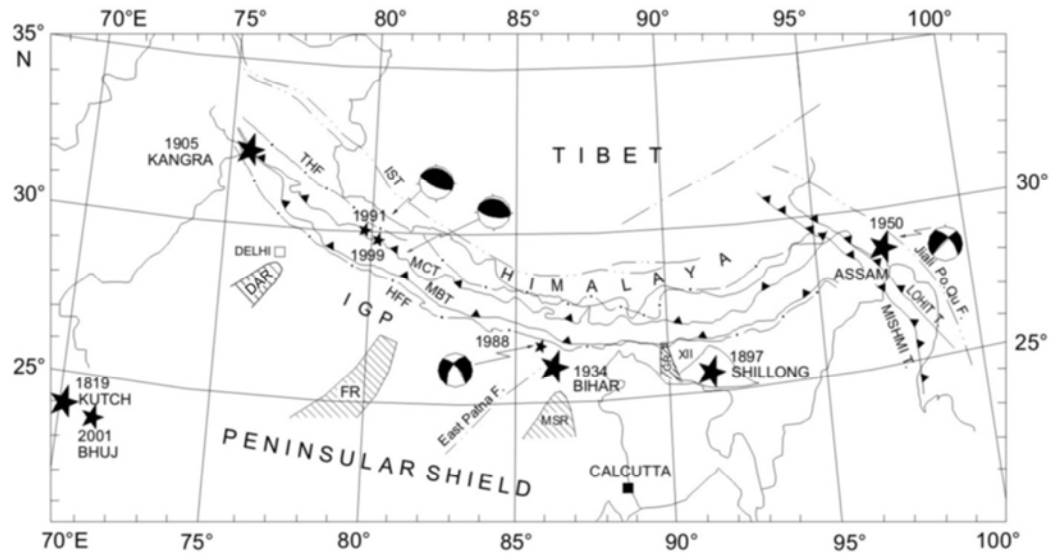


Figure 2. Tectonic map of the Eastern Himalaya and the foredeep region with the transverse basement ridges; DAR: Delhi-Aravalli Ridge, FR: Faizabad Ridge, MSR: Munger Saharsa Ridge, GR: Goalpara Ridge [17]).

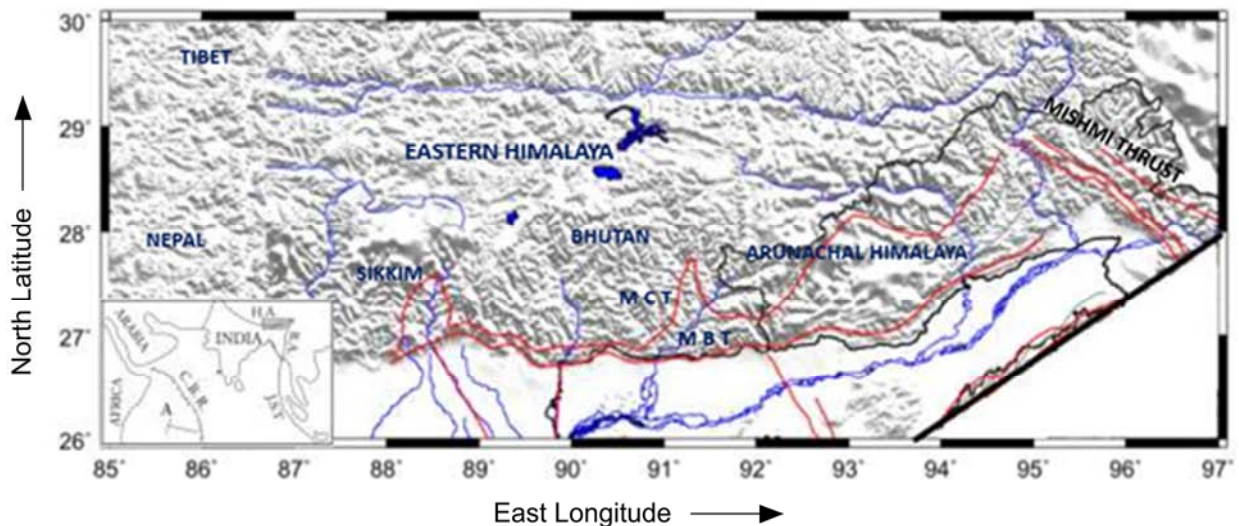


Figure 3. Tectonic Map of Eastern Himalayas.

The tectonics of the Eastern Himalayan mountains is dominated by extensive thrust sheets which have moved from north towards south or south-east. Some of the prominent lineaments viz. Yamuna lineament cuts across the whole Himalaya fold belts and extends from Ganga - Brahmaputra delta to Tibet. The important arcuate lineaments take a NE - SW to NNE - SSW trend in the Subansiri and Siang district of Arunachal Pradesh and terminate against the Siang fracture zone. This Eastern Himalaya zone is a part of the Eurasian seismic belt that extends from the Alpine to the East Indies (Figure 3).

The Eastern Himalaya comprising Sikkim Himalaya and Arunachal Himalaya. Situated at the junction of the E-W trending Himalayan belt, NW-SE trending Mishmi Tectonic Block and N-S trending Indo-Burma folded belt and proximal to the plate boundaries defined by Indian, Eurasian and Burmese plates. The eastern Himalayas is geodynamically very complex

and seismotectonically very active and is classified as zone IV in the seismic zonation map of India [4]. West of Sikkim Himalayas is bounded by the Nepal Himalayas and by Bhutan Himalayas to the east. Continued subduction of the Indian plate below the Tibetan landmass in the north and northeast and below the Burmese Plate in the east have resulted in the evolution of a series of E - W to NE - SW trending thrust systems in the Himalayas, namely MCT, MBT, MFT and their sympathetic splays and NW - SE trending Mishmi Thrust, Tiding suture, Lohit Thrust etc. in the northeast forming Siang Window and providing the "tectonic corridor" between the Himalayan orogenic belt and Indo-Myanmar Mobile belt. These faults are the source region of active seismicity and hence need to be studied in a comprehensive way. The potential of experiencing a great earthquake in such sections rises proportionally with the time elapsed since the last great earthquake as a consequence of slow plate motions due to which

strains develop over decades or centuries. Evidences of historical to recent earthquakes have been documented in the geological, geomorphological as well as in geophysical platform and repetition of such an occurrence cannot be ruled out. Large crustal and intraplate earthquakes ($M=6$ to 8.7) have occurred in the North Eastern Region. Significant earthquakes recorded from Sikkim region includes the 7.7 MW earthquake of 1883 occurring West of Sikkim, the 1934 Bihar–Nepal earthquake of 8.3 MW that occurred to the west of Sikkim causing widespread damage around the region and the 6.6 MW of 1988. Furthermore, in the recent past, the instrumentally recorded (both national and international) events indicates that seismicity level of this region has increased sufficiently as evidenced by occurrence of Sikkim Earthquake (Mw 6.9) on 18th September,

2011 and Nepal earthquake (Mw 7.9) on 25th April, 2015.

4. Data Source

Since the inception of the WWSSN (World Wide Seismograph Station Network) in 1964 and its up gradation to the GDSN (Global Digital Seismic Network) in 1980s, globally the earthquakes $M \geq 4$ are more or less located uniformly. These data are published in seismological catalogues of the USGS [15] and ISC [16]. The database in this study consists of about 1700 events in the Himalayas recorded during 1964 – 2017 and taken from the International Seismological Centre (ISC) catalogues. The epicentre map are shown in Figure 4.

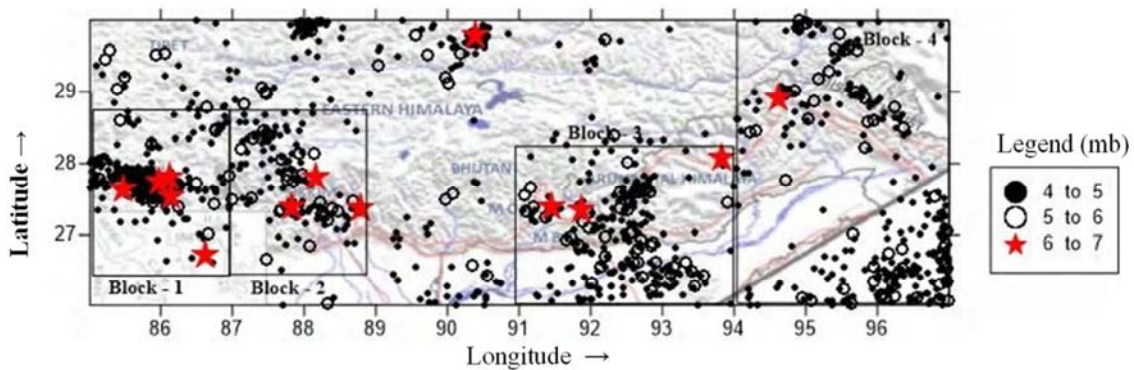


Figure 4. Epicenter Map of Earthquakes located in the region falling between Himalayan Region ($27^{\circ} - 30^{\circ}$ N and $85^{\circ} - 97^{\circ}$ E) for the period from 1964-2017.

5. Methodology

The selected earthquake data in the Eastern Himalaya ($27^{\circ} - 30^{\circ}$ N, $85^{\circ} - 97^{\circ}$ E) are analysed. An empirical relation has been used to convert M_s to m_b to make uniform data sets. For the estimation of seismicity parameters (b-value and fractal dimension) and its mapping, the selected regions under study were divided into grids. The b-value from the Gutenberg-Richter frequency-magnitude relation is calculated by the commonly used least square-fit method and by MLM. The Fractal Dimension (D) was estimated using the Correlation Integral method using the epicenter data in each grid. The total set of events was used for estimating Energy released in this area.

5.1. Estimate of b-value

For estimating the seismic b-value the following methods were used:

(a) Maximum Likelihood Method

In this study b-value is calculated by the maximum likelihood method because it is reported to be more appropriate way to compute a better estimation of b-value since it is inversely proportional to the mean magnitude [35, 1]:

$$b = \frac{\log_{10} e}{M - M_0}$$

where M is the average magnitude of events exceeding a threshold magnitude M_0 for complete reporting of earthquake magnitudes and $\log_{10} e = 0.4343$. In this study, earthquake data set with magnitude $M_0 \geq 3.8$ is chosen (Figure 5). A stable estimation of the b-value by this method requires at least 50 events [35].

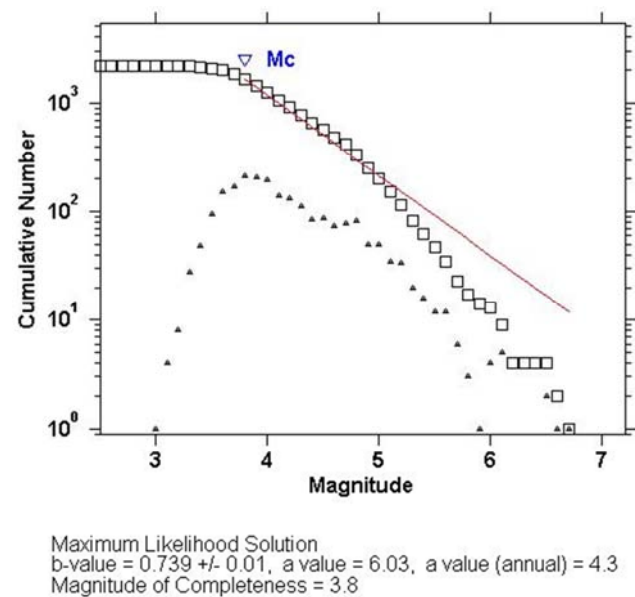


Figure 5. Graph indicating the magnitude of completeness of the data set.

(b) The Least Square-fit Method

The basic and commonly used method to estimate b-value and the parameter a-value [11] using least-square algorithm (Figure 6a):

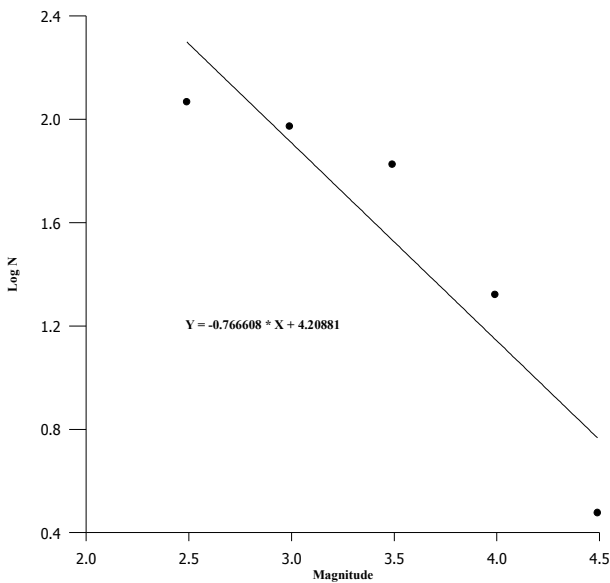
$$\log_{10} N = a - bM$$

5.2. b-value Error Estimate

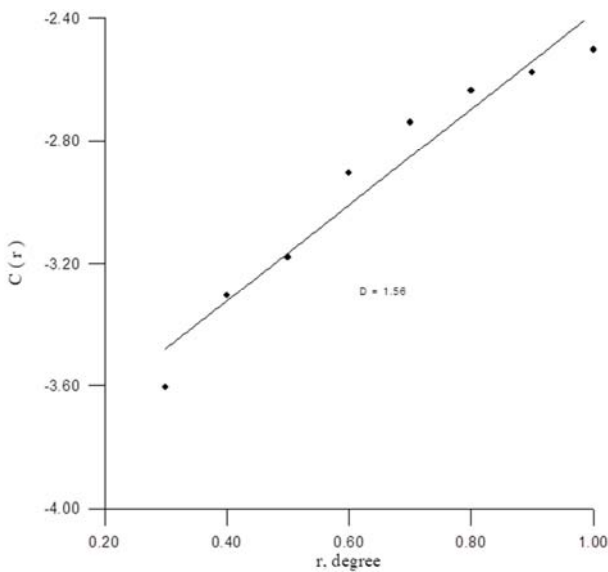
An estimate of the standard deviation δb of the b-value is obtained using the equation [1]

$$\delta b = b / \sqrt{n}$$

where 'n' is number of earthquakes in a set. The estimated δb for the b-values calculated in this study ranges from 0.0027 to 0.0104.



(a)



(b)

Figure 6. (a) Graph indicating b-value estimation by least square fit method. (b) Graph indicating the estimation of fractal dimension using correlation

integral method.

5.3. Fractal Dimension

The fractal dimension of the spatial distribution of seismicity is calculated from the correlation integral given by [9] (Figure 6b):

$$D_{wr} = \lim_{r \rightarrow 0} \log (C_r) / \log r$$

where (C_r) is the correlation function. The correlation function measures the spacing or clustering of a set of points, which in this case is earthquake epicenters, and is given by the relation:

$$C(r) = \frac{2}{(N-1)} N(R < r)$$

where $N_{(R < r)}$ is the number of pairs (X_i, X_j) with a smaller distance than r . If the epicenter distribution has a fractal structure, the following relation is obtained:

$$C(r) \sim r^D$$

where D is a fractal dimension, more strictly, the correlation dimension [9]. Using this relation the fractal dimension of spatial distribution of the earthquakes will be calculated by plotting $C(r)$ against r on a double logarithmic coordinate, the fractal dimension D can be obtained from the slope of the graph. The distance r between two events, (θ_1, ϕ_1) and (θ_2, ϕ_2) , will be calculated by using a spherical triangle [14] as:

$$r = \cos^{-1} (\cos \theta_1 \cos \theta_2 + \sin \theta_1 \sin \theta_2 \cos (\phi_1 - \phi_2))$$

The slope can be obtained by fitting a least-square line in the scaling region.

5.4. Energy Release

The relation between the magnitude m (body magnitude) and the radiated energy E [13] can be set up with less theoretical difficulty and a minimum of observational inaccuracy, takes the form:

$$\log E = 5.8 + 2.4 m$$

where E is in ergs.

5.5. Mapping: b-value, Fractal Dimension and Energy Release

The total set of events of the Himalayan regions were separately analysed for estimating b-value, fractal dimension and energy release. On the basis of epicentral map the entire Eastern Himalayan region was divided into 04 blocks (Figure 7). The blocks are Block -1: Nepal Himalayas, Block-2: Sikkim Himalayas, Block -3 Arunachal Himalayas and Block 4: Mishmi thrust. Each block is further gridded at 2° spacing with an overlapping of 1° . Each grid is overlapped both in X and Y direction. The number of events varies from 47 to 191 in each grid. A stable estimation of the b-value requires at

least 50 events [35]. It was suggested [32] that, the minimum number of points or events required for a reliable for fractal dimension calculation is $N_{min} > 42$, which meets the

condition for reliable calculations. The average b value, average fractal dimension and average energy released was calculated for each block and is presented as Table 1.

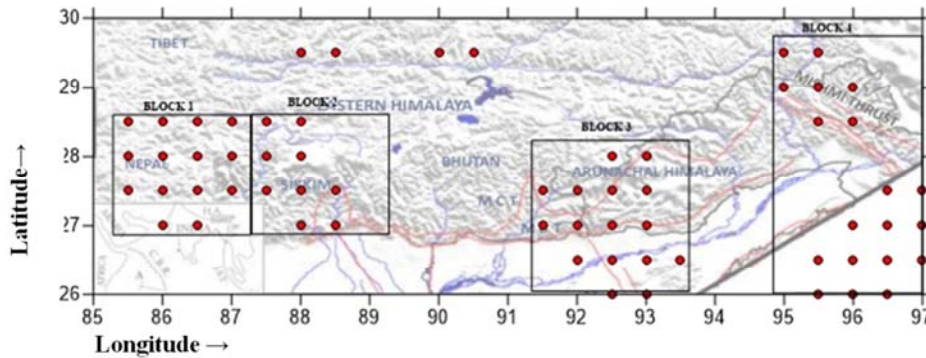


Figure 7. Map indication the Grid points for estimating the statistical Parameters.

Table 1. b-values (by MLM & LSF), fractal dimension & amount of energy released for different blocks.

Block	b-Value MLM	b-Value LSF	Fractal Dimension	Energy Release
Block -1	0.89	0.92	1.02	41.19×10^{20} Ergs
Block -2	0.81	0.84	1.05	10.1×10^{20} Ergs
Block -3	0.69	0.73	0.70	1.02×10^{20} Ergs
Block -4	0.64	0.70	0.82	0.50×10^{20} Ergs

5.6. Seismic Hazard Assessment

(a) Lognormal Model:

The probability distribution function $w(T)$ is given by

$$w(T) = \frac{1}{\sqrt{2\pi}\sigma T} \exp\left\{-\frac{(\ln T - m)^2}{2\sigma^2}\right\}, m > 0, \sigma > 0,$$

$$\phi(t) = \Phi\left(\frac{\ln t - m}{\sigma}\right)$$

$$\rho(\tau/t) = 1 - \{1 - \Phi\left(\frac{\ln(t+\tau) - m}{\sigma}\right)\} / \{1 - \Phi\left(\frac{\ln t - m}{\sigma}\right)\}$$

where m and σ are the model parameters and $\phi(t)$ is the cumulative probability of the next earthquake that will occur at a time later than t , and t is the time measured in years from the last earthquake and $\rho(\tau/t)$ is the conditional probability that the next earthquake will occur during the time interval between t and τ .

$\Phi(x)$ represents the error integral given as;

$$\Phi(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^x \exp^{-u^2/2} du$$

(b) Gamma Model:

$$w(T) = \frac{k}{\Gamma(l)} (kT)^{l-1} e^{-kT}$$

$$\phi(t) = \Gamma(l, kt) / \Gamma(l)$$

$$\rho(\tau/t) = 1 - \frac{\Gamma(l, k(t+\tau))}{\Gamma(l, kt)}$$

where $k > 0$, and $l > 0$ are the model parameters and other notations are the same as above. $\Gamma(k, x)$ represents the incomplete gamma function of the second kind, i.e.,

$$\Gamma(k, x) = \int_x^{\infty} e^{-u} u^{k-1} du.$$

(c) Weibull Model:

$$w(T) = \alpha\beta T^{\beta-1} \exp(-\alpha T^{\beta}), \alpha > 0, \beta > 0$$

$$\phi(t) = \exp(-\alpha t^{\beta}),$$

$$\rho(\tau/t) = 1 - \exp[-\alpha\{(t+\tau)^{\beta} - t^{\beta}\}]$$

where α and β are the model parameters and other notations are the same as above.

(d) Exponential Model:

$$w(T) = a \exp\left\{\frac{a}{b}(1 - e^{bT}) + bT\right\}, a > 0, b > 0$$

$$\phi(t) = \exp\left\{\frac{a}{b}(1 - e^{bt})\right\},$$

$$\rho(\tau/t) = 1 - \exp\left\{\frac{a}{b}(e^{bt} - e^{b(t+\tau)})\right\}$$

where a and b are the model parameters and other notations are the same as above ([36, 26]).

6. Results and Discussion

6.1. b-value

There is an observed variation of b-value in the entire area of study. The general relation which fits best for this region can be represented by the equation:

$$\log N(M) = 6.03 - 0.739M$$

It is observed that the b values obtained by least square fit method are higher than the b-values obtained by maximum likelihood method.

Table 1 indicates Low b values in the Block 3 (~ 0.69 , Arunachal Block) and Block 4 (~ 0.64 , Mishmi thrust area). A comparatively higher b is obtained in Block 1, Nepal Himalayas (~ 0.89), Block 2 Sikkim Himalayas (~ 0.81).

6.2. Fractal Dimension

The spatial variation of fractal dimension (D) map range between 0.35 and 1.37 indicates that the faults are spatially distributed in the entire region, and the whole region is seismically active. Seismically active faults are generally found with fractal dimension 0.5-1.5 (Hirata, 1989). Broadly the whole region is identified as a zone with $D \sim 1.7$, parallel to the MBT/MCT along the Himalayan trend. This implies a highly active zone along the Eastern Himalaya. As indicated in Table 1 low fractal Dimension values are obtained in the Block 3 (~ 0.70 , Arunachal Block) and Block 4 (~ 0.82 , Mishmi thrust area). A comparatively higher b is obtained in Block 1, Nepal Himalayas (~ 1.02), Block 2 Sikkim Himalayas (~ 1.05).

6.3. Energy Release

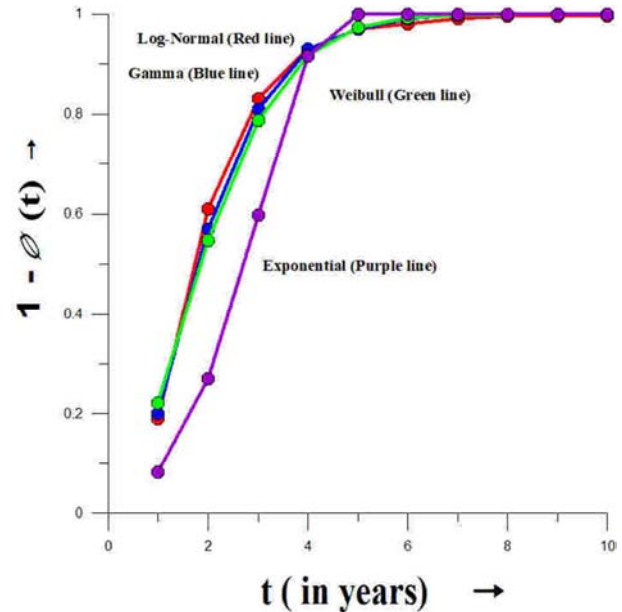
Table 1 indicated the amount of energy released in different blocks. In the Block 3, (Arunachal) and Block 4 (Mishmi thrust) Energy released is low ($\sim 1.02 \times 10^{20}$ ergs and $\sim 0.50 \times 10^{20}$ ergs. respectively). High energy release values are obtained in Block 1, Nepal (41.19×10^{20} ergs.), Block 2, Sikkim (10.1×10^{20} ergs.). Low energy released in the Arunachal and Mishmi thrust region may be indicative of higher stress concentration for future release of the energy.

6.4. Seismic Hazard Assessment

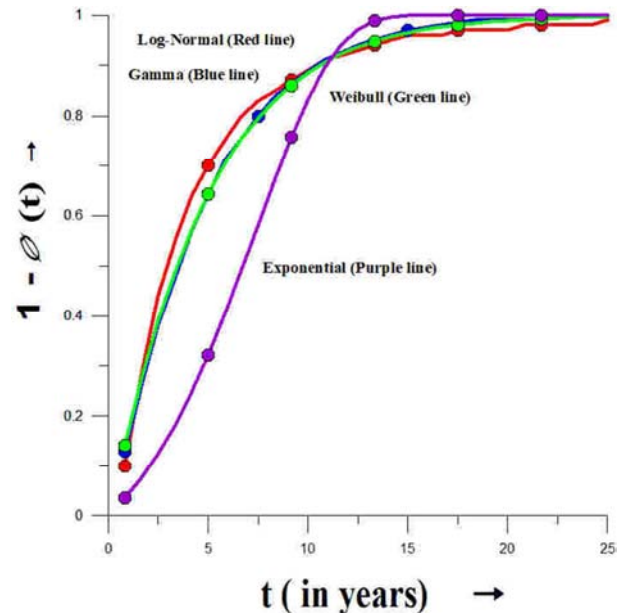
The probability of occurrence of an earthquake $M > 5.5$ and $M > 6.5$ during a specified interval of time has been estimated on the basis of four probabilistic models namely, Exponential, Weibull, Gamma and lognormal distribution. The model parameters have been estimated by the method of Maximum Likelihood Estimates (MLE). The cumulative distribution of the observed time intervals for the occurrence of at least one earthquake using the Gamma, Weibull, Lognormal and Exponential models is shown in the Figure 8 (a, b). The probability of occurrence of at least one earthquake of Magnitude more than 5.5 and at least one earthquake of Magnitude more than 6.5 in Eastern Himalayas using the Gamma, Weibull, Lognormal and Exponential models are given in Table 2 and Table 3 respectively.

Table 2. Probability of occurrence of at least one earthquake with $\text{mag} \geq 5.5$ by the four probabilistic models.

t	Log-NL	Gamma	Weibull	Exponential
1	0.19	0.20	0.22	0.08
2	0.61	0.57	0.55	0.27
3	0.83	0.81	0.79	0.60
4	0.93	0.93	0.92	0.92
5	0.97	0.97	0.97	1.00
6	0.98	0.99	0.99	1.00
7	0.99	1.00	1.00	1.00
8	1.00		1.00	1.00



(a)



(b)

Figure 8. (a) Cumulative distribution of T_i and the curves of $1-\Phi(t)$ using the four models (Lognormal, Gamma, Weibull and Exponential) for the Eastern Himalaya for earthquakes of Magnitude $M > 5.5$. (b) Cumulative distribution of T_i and the curves of $1-\Phi(t)$ using the four models (Lognormal, Gamma, Weibull and Exponential) for the Eastern Himalaya for earthquakes of Magnitude $M > 6.5$.

Table 3. Probability of occurrence of at least one earthquake with $\text{mag} \geq 6.5$ by the four probabilistic models.

Probability of occurrence of at least one earthquake with $\text{mag} \geq 6.5$				
t	Log-NL	Gamma	Weibull	Exponential
1	0.1	0.13	0.14	0.03
2	0.28	0.26	0.27	0.08
3	0.44	0.38	0.39	0.13
4	0.55		0.49	0.18
5	0.64	0.57	0.57	0.25
6	0.7		0.64	0.32

Probability of occurrence of at least one earthquake with $\text{mag} \geq 6.5$				
t	Log-NL	Gamma	Weibull	Exponential
7	0.75	0.71	0.7	0.4
8	0.8		0.75	0.49
9	0.83	0.8	0.8	0.58
10	0.85	0.84	0.83	0.67
11	0.87		0.86	0.76
12	0.89		0.89	0.83
13	0.91	0.91	0.91	0.89
14	0.92		0.92	0.94
15	0.93	0.94	0.94	0.97
16	0.94	0.95	0.95	0.99
17	0.95		0.96	1
18	0.96	0.97	0.96	1
19	0.96		0.97	1
20	0.96	0.98	0.98	1
21	0.97		0.98	1
22	0.97	0.99	0.98	1
23	0.97		0.99	1
24	0.97		0.99	1
25	0.98	0.99	0.99	1
26	0.98		0.99	1
27	0.98		0.99	1
28	0.98		1	1
29	0.98		1	1
30	0.99		1	1

7. Conclusion

The results of b-value, fractal dimension (D), energy release and probability of strong earthquakes/seismic hazards in the region corroborate and demarcate pockets with probability strong earthquakes/seismic hazards in the region. The zones of impending strong/large earthquakes are identified.

The average b-value in the Eastern Himalaya is 0.77, Fractal dimension 0.88 and Energy release is 13.2025×10^{20} Ergs (Table 1). Thus the entire region is associated with low b-value, low fractal dimension and low energy release. Low b-value indicates greater stress, low fractal Dimension indicates close clustering of earthquakes and low energy release indicates stress is accumulated.

The zones, block 3 and 4, show lower b – value (0.64-0.69) indicating higher stresses, and lower fractal dimensions (0.7-0.8) indicating greater clustering of epicenters. These zones are also associated with the lower energy release. The probability of a medium to strong earthquake (M 5.5 – 6.5) in these zones is 90-95% in four years from 2017 i. e probable year of occurrence of such event is in 2021. The probability of a stronger to large earthquake (M 6.6 -7.0) in these zones is 90-95%, in 14 years from 2015, i. e probable year of occurrence of such event is in 2029.

It is, however, an overwhelming information and experience to note that while the authors are in the process of revising this manuscript, an earthquake M 6.0-6.5 occurred in the zone/ block 3 on April 27, 2021. Thus, occurrence of this event in this zone in 2021 is fairly well estimated in our present study, and it proves that our earthquake forecast model works fairly well in this region. The zone 3 is also vulnerable for an impending stronger or large earthquake M 6.6-7.0 in the year 2029 or so. We suggest that our results may be taken into account for seismic risk assessment and disaster management

for the impending stronger or larger event in 2029, i.e. within another eight years so from now. The estimated earthquake (s) forecast for the zone 4 is equally significant.

8. Scope for Future Work

Probabilistic hazard can be assessed by many other probabilistic model like Poisson, Rayleigh, Pareto distribution etc. and by correlating each other for appropriate models. Multifractal analysis is a good tool for investigating statistical properties of seismic catalogues that could not be identified with standard techniques. Moreover, a continuous monitoring of the seismic parameters like b-value, fractal dimension, radiated energy (both in space and time) would provide a more comprehensive evaluation of earthquake occurrences.

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