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Return Period Analysis Of Earthquakes Of Northeast India And Its Adjoining Region

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ABSTRACT: *The study region has been divided into six tectonic blocks and the temporal variation together with the return period of earthquakes has been analysed. The spatial variation of 'b' value and its correlation with the fractal dimension of the crust of the region is investigated. The number of earthquakes reported in the period 1964 – 1978 is less, after that there is a gradual increase. The Naga Hill region and the Eastern Himalayas shows a dip in seismic activity in the period from 1994 – 1998. Seismic activity in the other three regions viz. Surma Valley, Shillong Plateau and Brahmaputra Valley does not vary much. Arakan Yoma region is found to be highly seismic from the study of temporal variation and return period. The estimated return periods of earthquakes differ from the observed ones. The estimated fractal dimensions in this study suggest that the faults are spatially distributed in the whole region. The trend of fractal dimension contours is similar to that of the b –value contours showing high value contours along the Arakan – Yoma and Indo – Burma region followed by the Kopili Lineament and the Shillong Plateau. The fractal dimension D value of the region has been found to be on the average 2.89 times of b – value.*

KEYWORDS: *b-value, correlation coefficient, Fractal Dimension, Return Period, Temporal Variation.*

I. INTRODUCTION

The relation between geological characteristics and occurrence of earthquakes has been studied since the very beginning of twentieth century. The temporal variation of seismicity is taken as an indicator of the trend of seismic activity in the region. It can be used to understand the physical mechanism of earthquakes and is a tool of earthquake prediction by indicating possible return periods of earthquakes having different magnitudes. The rate of seismic activity in a region is not uniform; rather it drops off drastically after a few years of the occurrence of a major earthquake and follows a low activity period. The study of seismic activity in a probabilistic manner for a long period of time is useful in the long range forecasting of earthquakes. The method used for long range forecasting is based on the periodicity of large earthquakes (if any) and accumulation of tectonic strain. Generally long – range forecasting of earthquakes have two objectives [1]. Firstly, since no exact estimate of time of occurrence of future earthquakes can be possible, the results are more useful to identify regions where observations can be intensified for medium and short term forecasts. Secondly, considering higher probability of future earthquakes, earthquake risk for engineering designs can be estimated. A return period also known as a recurrence interval is an estimate of the likelihood of an event, such as an earthquake.

It is a statistical measurement typically based on historic data denoting the average recurrence interval over an extended period of time, and is usually used for risk analysis. The method used for long range forecasting is based on the periodicity of large earthquakes (if any) and accumulation of tectonic strain. To find out the periodicity or recurrence rate, various expectancy studies have been made with the application of standard statistical methods used by different seismologists of the world [2]. The magnitude – frequency relation of Gutenberg and Richter [3] has been applied by a number of workers [4], [5],[6],[7]. Yadav et. al.[8] also computed the return period of earthquakes and the magnitude of largest most probable annual earthquake for different tectonic blocks of the region. They found that the most probable largest annual earthquakes are close to 4.6, 5.1, 5.2, 5.5 and 5.8 in the four seismic zones, namely, the Shillong Plateau Zone, the Eastern Syntaxis Zone, the Himalayan Thrusts Zone, the Arakan-Yoma subduction zone and the whole region, respectively. Mittal et. al [9] used Gumbel's extreme value method to estimate the return period of earthquakes of Chandigarh. Earlier different models were proposed for the recurrence of earthquake generation in the past. After long debates and discussions a Regional Time and Magnitude – Predictable

Seismicity Model have been accepted and applied successfully in different seismically active regions to estimate the magnitude and the time of occurrence of forthcoming earthquakes. These models have put forward to Central Himalaya and its vicinity[10] Eastern Anatolia[11]; Taiwan [12]; Hindukush Pamir Himalaya[13]; North-East India[14]. The term seismotectonics was used by Sieberg [15] and Hobbs[16] at the beginning of the twentieth century and was applied to the characteristics of the occurrence of earthquakes in relation to regional tectonics and general geodynamic conditions. The study of seismotectonics basically includes the integration of earthquake data with other information available from tectonics, geophysics and geology of a particular region. Thingbaijam et .al [17] together with J.Angelier and S. Baruah [18] made an extensive study of seismicity and seismo – tectonics of the region. In this study, a seismo – tectonic analysis of the region has been carried out considering the seismic parameters like return period of earthquakes and variation of b-value. Moreover, the earthquake phenomenon possesses fractal structure with respect to space, time and magnitude. The two-point spatial correlation function for earthquake epicentres displays a power law structure [19]. The earthquakes are represented by self-similar mathematical construct, the 'fractal', and the scaling parameter is known as the fractal dimension, 'D' [20].The fault zones where earthquakes occur are quite complex and fractal dimension gives vital information about the stability of a region. A change in fractal dimension corresponds to the dynamic evolution of the states of the system. It is scale-invariant and has introduced an efficient statistical parameter to quantify the dimensional distribution of seismicity and with that the proportion of randomness and clusterization. [19],[21],[22]. The moment of the earthquake relates to its magnitude and hence, the fractal dimension of regional or world wide seismic activity is simply twice time of the b – value.[23] Here, an attempt is made to analyse the possible correlation between b-value and fractal dimension of the region.

II. STUDY REGION AND DATASOURCE:

Northeastern India and its adjoining region lying between latitude (22^0 N – 30^0 N) and longitude (89^0 E – 98^0 E) display tectonically distinct geological domains occurring in intimate spatial association. Rocks representing the entire span from Archean to Recent, occur in this very small region. Eocene (Disang) sediments of trench facies occur in juxtaposition with those of platform facies (Jaintia) of stable shelf condition; Neogene Siwalik foredeep molasse in front of the Himalaya and Tipam molasse of Upper Assam basin in front of the Indo – Myanmar mobile belt occur in close proximity and are separated by the Brahmaputra alluvium. Proteozoic to early Paleozonic intrusive granites are common in Meghalaya Plateau, while Tertiary granites are found in the upper reaches of the Eastern Himalaya. Upper Jurassic Cretaceous and multi – phase effusion of volcanic are exposed in the Meghalaya Plateau, while the Abor volcanic of Upper Palaezoic to Eocene age from the Eastern Himalaya indicates episodic and protracted volcanisms. Upper Cretaceous mantle derivatives (carbonites and ultramafics) in the Meghalaya Plateau and Mikir Hills, and the admixture of continental and marine Gondwana rocks in a narrow belt along the foothills of the Eastern Himalaya, represent early stage of rift – drift tectonism during disintegration of East Gondwanaland, which was eventually followed by convergent tectonism at the two (i.e. northern and eastern) leading edges of the Indian shield. Northeastern India and its adjoining region thus has the geological features that characterize both convergent tectonism in the north and subduction tectonism in the east including fossil rift settings that preceded plate convergence. The relief of most of the hills in the study region varies from 130 meters to 1610 meters above mean sea level. Now, based on the distribution of epicentres, fault plane solutions and geotectonic features, northeastern region can be divided into six seismotectonic zones.(fig. 1)[24]

The zones are:

[1] The Eastern Himalayan collision belt including the trans – Himalayan Tethyan zone, the Tsangpo Suture zone (with ophiolites) and the Andean type grano – diorite margin to the north.
[2] The Naga Hills region which comprises of Diorite – grandiorite complex of the Mishmi block with frontal folded and thrusted metamorphic belt.
[3] The Indo – Myanmar mobile belt and the Arakan – Yoma.
[4] The Shillong Plateau with platform sediments to the south and the east and the Mikir hills.
[5] Brahmaputra Valley with cover of alluvium and Tertiary sub – crop elements.
[6] Surma Valley covering almost whole of West Bengal and Bangladesh with Cretaceous to Recent sediments.

The comprehensive data file prepared by using earthquake catalogues of ISC and USGS that are available for the study region has been used for this analysis for the period 1964 – 2012 (31^{st} July). The epicentral plot of all seismic events (> 4.0 mb) considered for this analysis is given in the fig.2.

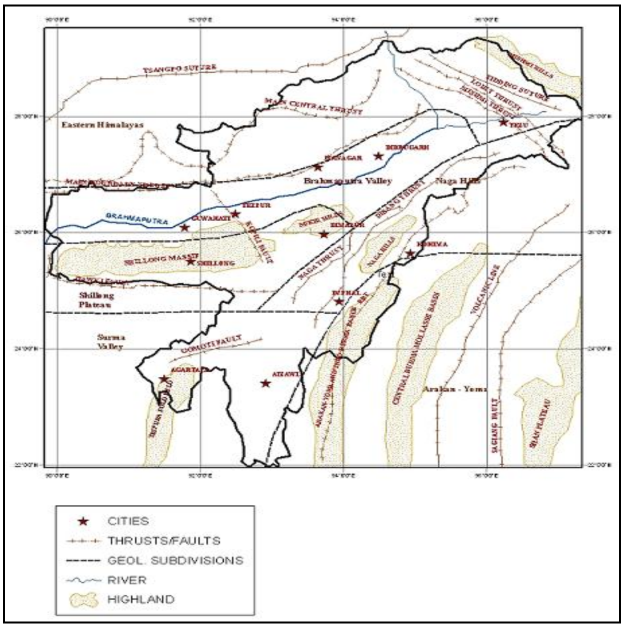

Figure 1: The map of the study region with the geo-tectonic subdivisions or zones.

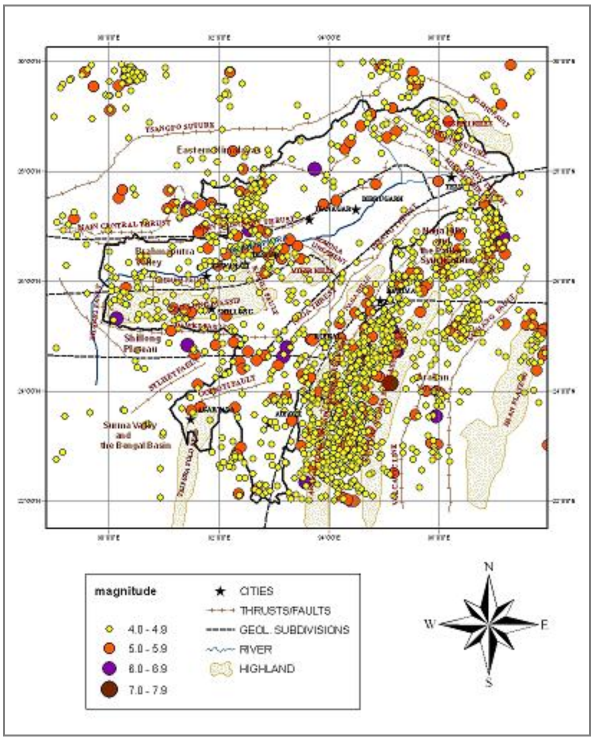

Figure 2: Epicentral plot of the earthquake events of the study region

III. METHODOLOGY

3.1 TEMPORAL VARIATION OF EARTHQUAKES:

Geologically, the study area comprises oldest to youngest rock types: Precambrian gneissic complex, the Shillong group, older and younger alluvium. The topography of this region reveals a criss-cross pattern of faults cutting the ancient rocks of the basement. The geological features of the region characterize both convergent and subduction tectonism including the fossil rift setting that preceded plate convergence. Hence, it has been observed that the seismic activity in the study region is not uniform. Therefore, temporal variation of earthquakes or the number of earthquakes occurring every five year or each year in every block which is termed as pentad and annual variation has been investigated.

3.2 CORRELATION OF THE NUMBER OF EARTHQUAKES:

The number of earthquakes of each tectonic block varies in the study region. An investigation has been made to find a relationship among the variation by calculating the correlation coefficient between the number of earthquakes of each tectonic block. This will give an insight on whether there is some similarity of the nature of stress accumulation at nearby tectonic blocks. The correlation coefficient is determined statistically using the relation:

$$r = \frac{n\sum xy - (\sum x)(\sum y)}{\sqrt{n(\sum x^2) - (\sum x)^2}\sqrt{n(\sum y^2) - (\sum y)^2}} \quad \ldots\ldots\ldots\ldots (1)$$

3.3 RETURN PERIOD ANALYSIS:

3.3.1 Least Square Method and Maximum Likelihood Method:

For return period analysis, it has been generally accepted that the occurrence of earthquakes is not a random process. But, because of the impossibility of predicting earthquake deterministically, only the observational data have been treated as the samples in probability spaces so far. Statistical models based on probability are found to be capable of predicting the future earthquakes sequences in a region probabilistically. The most commonly used model makes use of the assumptions [2] that –

(i) The number of earthquakes in a year is a Poisson's random variable.

(ii) The earthquake magnitude is a random variable distributed with cumulative distribution function.

$$F(m) = 1 - e^{-\beta M}, \quad M \geq 0 \quad \text{------------------} \quad (2)$$

This model is generally known as the 'Large-Earthquake model' and is especially useful when one has access only to a list of the largest earthquakes in a region, and affords predictions of mean return periods and the expected number of earthquakes exceeding a given magnitude [25].

The number of earthquakes in a region is found to decrease exponentially with their magnitude. This relationship is usually expressed by the so-called 'magnitude-frequency' relationship [3] and it is of the form,

$$\text{Log } N(M)\, dM = (a - bM)\, dM$$

where M is the magnitude of the shocks. On integrating the above equation, it is found as,

$$\text{Log } N(M) = a - bM \quad \text{--------------------} \quad (3)$$

Where N(M) is the number of earthquakes of magnitude M or greater, and 'a' and 'b' are two constants. The constant 'a' is the measure of the number of events above magnitude '0', while 'b' is a measure of the seismic severity. The magnitude – frequency relation can be normalized so as to yield the frequency distribution of magnitude in a region. Thus, it is observed,

$$a = \text{Log } N(0)$$

when M = 0 and normalization is achieved by dividing through N(0) .

$$log[1 - F(M)] = \frac{log N(M)}{N(0)} - b \quad \text{-----------------} \quad (4)$$

which yields,

$$1 - F(M) = 10^{-\beta M} = e^{-\beta M}, M \geq 0 \quad \text{------------} \quad (5)$$

where $\beta =$ b/log N(M) and F(M) is the cumulative probability distribution function of earthquake magnitude.

If enough data is available for any given region, a plot of M against log N(M) can be made and equation (2) can be fitted to the observed data by the method of least squares. Decrease of the constant 'a' in 'b' over a period of time indicates an increase in the proportion of large shocks or by a relative decrease in the frequency of a small shock. Variation of b value depends upon stress conditions of the rock mass generating the earthquakes. However, as discussed by [26] for this type of problem, the method of least squares is inadequate; since the assumptions – (a) there is no uncertainty in 'M" and (b) log N(M) is normally distributed with uniform variance for all magnitude interval cannot be justified. This result gives too much weight to the relatively few large shocks and too little to the many small events. Therefore, a statistically proper estimate of 'b' is given by the method of maximum likelihood. Several authors [27], [28], [29] have preferred maximum likelihood method as a best method.

For a sample of N earthquakes having magnitude ranging from M_{max} to M_{min}, the maximum likelihood estimates of 'b' is given by,

$$b = \frac{\bar{M} - M_{min}}{M_{max} - M_{min}} = \frac{1}{b\ln(M_{max} - M_{min})} - \frac{1}{e^b \ln(M_{max} - M_{min}) - 1} \quad \text{-----------} \quad (6)$$

where, $\bar{M}$ is the average magnitude of the sample. When M_{max} is more than two units of magnitude greater than M_{min} the above equation can be approximated by the equation derived by Utsu [30] and Aki[31],

$$b = \frac{log e}{\bar{M} - M_{min}} \quad \text{--------------------} \quad (7)$$

where, $\bar{M} = \sum \frac{M_i}{N}$

where , $\bar{M}$ and M_{min} represent the average and the minimum magnitude in a given sample. Using the values of 'a' and 'b', the number of earthquakes, N(M) having magnitude greater than or equal to M has been computed out and their respective return period is estimated.

3.3.2 Extreme Value Theory :

Gumbel postulated that if the earthquake magnitude is unlimited, if the number of earthquakes per year decreases with their increase in size, and if the individual events are unrelated, then the probability P that the size of the largest magnitude $M^{/}$ in any year will be less than M, is:

$$P(M^{/} < M) = \exp\{- \exp(- a (M – u))\} \text{ ---------------- (8)}$$

This may be converted to more convenient form

$$M = u – (1/\alpha)\ln(- \ln P) \qquad \text{-------------------------- (9)}$$

Here u and α are constants which can be evaluated by least square method. Equation (9) represents Gumbel's Type I distribution.

On the other hand if it is believed that there is an upper bound on magnitude, M_{max} for any specific region, then

$$P(M^{/} < M) = \exp[- \{(M_{max} – M)/(M_{max} – u)\}^{k}] \text{ ------- (10)}$$

where k and u are constants. This is known as Weibull's Type III distribution. M_{max} is taken according to highest magnitude earthquake observed on land. To evaluate the constants k and u, eq. (10) is converted to

$$\ln(M_{max} – M) = (1/k) \ln(-\ln P) + \ln(M_{max} – u) \text{ ---------- (11)}$$

and the least square method is applied by taking –ln(-lnP) and $\ln(M_{max} – M)$ as variables.

To evaluate the constants in eq. (9) and eq. (11) the largest observed yearly earthquake magnitudes M_1, M_2, ……, M_N in a sample of N consecutive years are arranged in the order of increasing size. Then the values of P are estimated by using Gumbel's plotting rule P = n/(N + 1) and Knopoff's and Kagan's [27] plotting rule P = (n – 0.5)/N, where n varies from 1 to N.

Finally the return period of extremes may be obtained for values equal to or exceeding M as:

$$T(M) = 1/(1 – P) \text{ ------------------- (12)}$$

3.4 CORRELATION BETWEEN b – VALUE AND FRACTAL DIMENSION:

3.4.1 Determination of fractal dimension:

At the outset, the data was gridded at 1^0 interval with an overlapping of 0.5^0. The events in each grid were used as a data set for analysis. These grids were interactively created, and seismically inactive area was excluded. In this study, the fractal dimension, the *D* values, are estimated using the correlation dimension. The correlation dimension, [32] measures the spacing of a set of points, which in this case are the earthquake epicentres. The correlation integral technique gives the correlation dimension; it is preferred to the box-counting algorithm, which gives a fractal 'capacity dimension' because of its greater reliability and sensitivity to small changes in clustering properties. The correlation integral given by:

$$D = \lim_{r\to 0} {\log C(r)}/{\log (r)} \qquad \text{------------------- (13)}$$

where C(r) is the correlation function. The correlation function measures the spacing or clustering of a set of points and is given by the relation:

$$C(r) = \frac{2}{N(N-1)}\, N(R < r) \qquad \text{-------------------- (14)}$$

where $N (R < r)$ is the number of pairs (Xi, Xj) with a smaller distance than *r*[32].

3.4.2 Determination of b – value:

The b-value is calculated by the maximum likelihood method using the eq. 7 given by Aki, which is based on theoretical considerations and is the most accepted method of b-value estimate.

IV. RESULTS AND OBSERVATIONS

4.1 TEMPORAL VARIATION OF EARTHQUAKES:

4.1.1 Pentad Variation:

The number of earthquakes (M ≥ 4.0 mb) that occurred in each block during a period of 5 year duration starting from 1964 to 2012 (31st July) are computed out and the variation patterns of the pentad values are shown in Fig. 3.

From the fig. 3 it is observed that the number of earthquakes reported in the period 1964 – 1978 is less due to non-availability of sensitive instruments to detect earthquakes of small magnitude. After that there is a gradual increase in the number. Seismic activity is very high in the Arakan Yoma region compared to other regions. This is followed by the Eastern Himalayas. The Naga Hill region and the Eastern Himalayas shows a dip in seismic activity in the period from 1994 – 1998. Seismic activity in the other three regions viz. Surma Valley, Shillong Plateau and Brahmaputra Valley does not vary much.

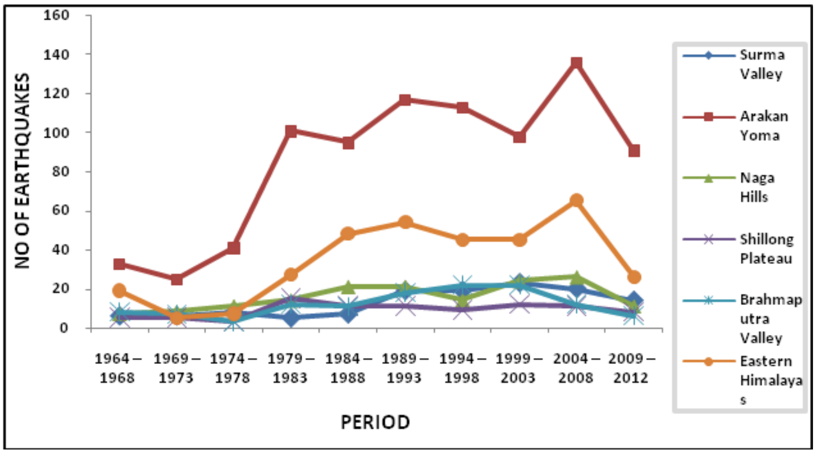

Figure 3: Pentad variation of earthquakes

The activity of the Shillong Plateau is almost same from 1984 onwards. While the seismic activity of Brahmaputra Valley and Surma Valley bears a lot of similarity as they both belong to the Indo – Gangetic and Brahmaputra basin. The activity decreases after 2008 for all the region as the study period is only till 31st July, 2012. This variation in seismic activity indicates that there are differences in the generation of stress field in different section of the study region.

4.1.2 Annual Variation:

The number of earthquakes (≥ 4.0 mb) occurred in each year in all the six tectonic blocks during the period 1964 to 2012(31st July) is represented in Fig. 4. It is observed that up to 1977 the series may be considered as incomplete due to poor reporting of small magnitude earthquakes and therefore it should be omitted from discussion of trend. After, 1977 only Arakan - Yoma region and Eastern Himalayas show proper reporting of earthquakes.

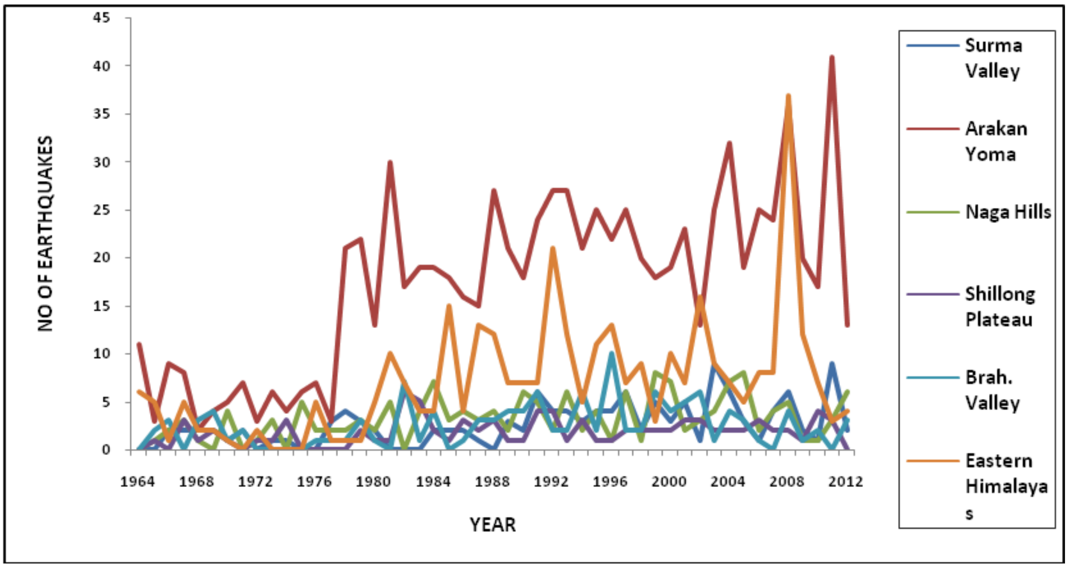

Figure 4: Annual variation of earthquakes

In other regions , the series can be considered to be complete from 1984 onwards. All the series are fluctuating and no similarity is seen among them. However, there can be identified a low seismic activity period from 1997 to 2001 in the Arakan – Yoma and Eastern Himalayas.

But in Naga Hills low seismic activity was observed from 1999 to 2005. Maximum no of earthquakes occurred in 2011 at the Arakan-Yoma region and Surma Valley, in Brahmaputra Valley it is 1996 while it is 2008 at the Eastern Himalayas. The seismic activity of Shillong Plateau region has been observed to be uniform throughout the period.

4.2 Correlation coefficient among the number of earthquakes:

The correlation of the number of earthquakes between the six tectonic blocks of the northeast India and its adjoining region has been analysed by determining the correlation coefficient using eq. 1.

Table 1. Corrrelation Co – efficient

Block	Eastern Himalayas	Naga Hills	Arakan Yoma	Surma Valley	Shillong Plateau	Brahma Valley
Eastern Himalayas	1	--------	------------	----------	----------	----------
Naga Hills	0.1391	1	-------------	-----------	----------	----------
Arakan Yoma	0.4521	0.5044	1	-----------	----------	---------
Surma Valley	0.2317	0.3380	0.2247	1	----------	----------
Shillong Plateau	0.0091	0.1093	0.3447	0.0939	1	----------
Brahma Valley	0.237	0.1109	0.1865	0.1965	0.2784	1

Analysis of correlation among the number of earthquakes of the six regions from the above table shows that the correlation is maximum between Arakan- Yoma region and the Naga Hills (0.5044) and is minimum between Shillong Plateau region and the Eastern Himalayas (0.0091). The Arakan – Yoma region also bears a correlation with the Eastern Himalayas but its value is less than that with the Naga Hills. This indicates that there might be similarity between the Arakan – Yoma region and the Naga hill region in the process of strain accumulation or release compared to other regions. While the dissimilarity is highest between Shillong Plateau and the Eastern Himalayas.

4.3 RETURN PERIOD ANALYSIS:

4.3.1 Least Square Method and Maximum Likelihood Method:

Using the magnitude – frequency relationship obtained by methods of Least Squares and Maximum Likelihood, the number of earthquakes for each magnitude class has been estimated for each tectonic block together with the whole region and return period has been calculated and compared with the observed ones which is represented in Table 2.

Table. 2 Return Period Of Earthquakes Having Different Magnitudes

Blocks/Regions	Magnitude(mb)	Observed No. of earthquakes	Average Return period in years		
			Observed	Maximum Likelihood Method	Least Square
Eastern Himalayas	4.45	287	0.17	0.05	0.13
	5.45	51	0.93	0.52	1.39
	6.45	3	15.86	5.51	14.82
Naga Hills	4.45	134	0.36	0.10	0.28
	5.45	22	2.16	1.30	3.51
	6.45	1	47.58	16.50	44.40
Arakan Yoma	4.45	730	0.07	0.02	0.056
	5.45	112	0.42	0.21	0.562
	6.45	7	6.80	2.07	5.55
	7.45	1	47.58	20.41	54.94
Surma Valley	4.45	109	0.44	0.13	0.36

	5.45	17	2.80	1.50	4.05
	6.45	1	47.58	17.06	45.91
Shillong Plateau	4.45	76	0.63	0.23	0.61
	5.45	11	4.33	1.23	3.31
	6.45	3	15.86	6.73	18.02
Brahmaputra Valley	4.45	98	0.49	0.13	0.34
	5.45	22	2.16	1.42	3.81
	6.45	1	47.58	15.63	42.11
Whole Study Region	4.45	1434	0.03	0.01	0.02
	5.45	235	0.20	0.11	0.30
	6.45	16	2.97	1.35	3.62
	7.45	1	47.58	16.37	43.25

From Table 2. it is seen that the values of return period obtained by least square method is comparable to the observed values. The return period of earthquakes of all the magnitudes is minimum in the Arakan Yoma region. This implies that the probability of occurrence of earthquake is maximum in this region implying its seismically active nature as the region lies in the subduction zone of the Indian Plate under the Burmese Plate. For magnitudes 4.45 mb the return period is maximum at Shillong Plateau. This indicates that the probability of occurrence of earthquake of magnitude 4.5 mb is minimum at Shillong Plateau. For, 5.45 mb and 6.45 mb the return period is maximum at Surma Valley, this indicates the stability of the region as this is a zone of folded sediments. After 1964, there is only one seismic event greater than 7.0 mb in this region.

TABLE.3 Expected largest earthquake of magnitude for various return period

BLOCK	RETURN PERIOD (YRS)	LEAST SQUARE (mb)	MAXIMUM LIKELIHOOD (mb)
EASTERN HIMALAYAS	25	7.33	7.14
	50	7.63	7.43
	75	7.80	7.60
	100	7.92	7.73
NAGA HILLS	25	6.27	6.66
	50	6.55	6.94
	75	6.71	7.10
	100	6.82	7.21
ARAKAN – YOMA	25	6.79	7.22
	50	7.48	7.91
	75	7.89	8.32
	100	8.18	8.61
SURMA VALLEY	25	6.25	6.66
	50	6.54	6.94
	75	6.70	7.11
	100	6.82	7.23
SHILLONG PLATEAU	25	6.69	7.28
	50	7.10	7.68
	75	7.34	7.92
	100	7.51	8.09
BRAHMAPUTRA VALLEY	25	6.28	6.70
	50	6.57	6.98
	75	6.74	7.15
	100	6.86	7.27

WHOLE AREA	25	7.27	7.67
	50	7.55	7.95
	75	7.71	8.11
	100	7.83	8.22

Using the same magnitude frequency relationship the maximum expected value for earthquakes having return period 25 yrs, 50 yrs, 75 yrs and 100 yrs respectively for each tectonic block and the region as a whole has been estimated which is shown in Table 3.

It has been observed that for a return period of 25 yrs and 50yrs the value of estimated magnitude of an earthquake is maximum at Eastern Himalayas which is 7.33 mb and 7.68mb respectively. In case of return period 75yrs and 100yrs the value of estimated magnitude of an earthquake has been found to be maximum at Arakan Yoma region which is 7.89 mb and 8.18 mb respectively.

4.3.2 Extreme value method:

Table 4. Computation of return period in years by extreme value method

Blocks/Regions	Mag. (mb)	Plotting Rule P = N/(N+1) (Gumbel)				Plotting Rule P = (N – 0.5)/N (Knopoff and Kagan)			
		TYPE I		TYPE III		TYPE I		TYPE III	
		P	T	P	T	P	T	P	T
Eastern Himalayas	4.45	0.0278	1.02	0.05	1.05	0.01	1.01	0.035	1.03
	5.45	0.8168	5.45	0.803	5.09	0.83	6.04	0.819	5.54
	6.45	0.9886	87.96	0.985	66.67	0.98	90.9	0.9871	77.51
Naga Hills	4.45	0.2448	1.32	0.25	1.33	0.22	1.29	0.23	1.3
	5.45	0.863	7.33	0.854	6.86	0.88	8.4	0.871	7.787
	6.45	0.984	66.08	0.9873	78.74	0.98	50	0.9865	74.07
Arakan Yoma	4.45	0.0082	1.00	0.003	1.03	0.00	1	0.023	1.02
	5.45	0.6302	2.70	0.592	2.45	0.64	2.78	0.602	2.51
	6.45	0.9565	23.03	0.961	26.3	0.96	27.81	0.969	32.63
	7.45	0.9921	126.58	0.9912	113.63	0.99	138.89	0.9918	121.95
Surma Valley	4.45	0.193	1.24	0.21	1.27	0.17	1.2	0.19	1.24
	5.45	0.887	8.86	0.88	8.38	0.9	10.42	0.89	9.6
	6.45	0.9851	67.11	0.9869	76.33	0.98	56.49	0.9849	66.23
Shillong Plateau	4.45	0.377	1.6	0.36	1.57	0.36	1.58	0.354	1.54
	5.45	0.883	8.61	0.87	8.32	0.90	10.1	0.896	9.68
	6.45	0.984	64.51	0.9881	84.03	0.98	92.26	0.9863	72.99
Brahmaputra Valley	4.45	0.237	1.31	0.239	1.31	0.21	1.277	0.22	1.28
	5.45	0.905	10.58	0.908	10.89	0.92	12.81	0.922	12.86
	6.45	0.9893	93.45	0.9879	82.64	0.98	90.9	0.9891	91.74
Whole Study Region	4.45	0.0000	1	0.0065	1	0.00	1	0.0001	1
	5.45	0.412	1.7	0.3928	1.64	0.40	1.69	0.38	1.62
	6.45	0.941	17.22	0.948	19.23	0.95	20.943	0.9569	23.23
	7.45	0.9921	126.58	0.9916	119.04	0.99	121.95	0.9919	123.45

To apply the extreme value theory, the largest observed earthquakes of all the six blocks and the study region as a whole, are arranged in ascending order. Then, by considering the largest expected earthquake of return period 100 years from table 3. for each of the six blocks and the region as a whole together with both Gumbel and Knopoff and Kagan plotting rules the probability P that the size of the largest magnitude M' in any year will be less than M is determined. Then, a plot of ln(-lnP) vs M (Type – I) and {-ln(-lnp)} vs {ln(M_{max} – M)} (Type – III) is done. From the relations obtained by plotting, the return period is determined and the values are given in Table 4.

Table. 2 and table. 4 shows that the estimated return periods of earthquakes having different magnitudes are less than that of their respective observed return periods in case of least square and maximum likelihood methods and more in the extreme value method. The observed return period of magnitude 4.45 mb, 5.45 mb and 6.45 mb corresponded well more with those determined from Least Square Method than by Maximum Likelihood method. In case of extreme value Type I and Type III distribution , the values obtained from the plotting rule of Gumbell supported well the observed ones. For the region as a whole, from the estimated return values of earthquakes by least square and maximum likelihood method, it is seen that there is a high probability of occurrence of earthquake greater than 6 mb but less than 7.0 mb in the study region.

4.4 Fractal dimension and b – value mapping:

The b-value varies from region to region and is also dependent upon the used period of time, but is generally in the range of from 0.8 to 1.2. The variability of b-values in different regions may be related to structural heterogeneity and stress distribution in space. The b-value represents a statistical measurement of the relative abundance of large and small earthquakes in the group. A higher b-value means that a smaller fraction of the total earthquakes occur at the higher magnitudes, whereas a lower b-value implies a larger fraction occur at higher magnitudes. The higher levels of motion at a site are dominated by occurrences of the larger earthquakes. If b is large, large earthquakes are relatively rare. The variation of b-value before and after a major earthquake has been taken as an earthquake precursor [33], [34]. The b-value is also correlated to geotectonics [35],[36]. An understanding of physical basis of b-value would be significant to the studies on earthquake generation process and earthquake prediction. The fault zones where earthquakes occur are quite complex. Map and field observations [37], [38]. and laboratory observations [39], [40] showed fractal distribution of fault surface. The fractal dimension, describes quantitatively the scale invariance of a structure or provides a measure of the relative importance of large versus small objects [41]. The correlation between b-value and fractal dimension (D) is described by b = D /3 and by b = D/2 [41],[42]. From a probabilitic synthesis, the relation of the two parameters was speculated to be b = D/2.[43] However, from the analysis of the actual earthquake data in the Tohoku area, a negative correlation (D = 2.3 - 0.73) between the two parameters was reported[44]. The ranges of D values and b-values are from 1.3 to 1.8 and from 0.7 to 1.2, respectively. It is obvious that more studies are needed to explore the relation between the two parameters. The Gutenberg–Richter relation for frequency vs magnitude is a power law involving magnitude. Similarly, the after shock decay follows another power law involving time. The fractal dimension of the spatial distribution of hypocentres may be related to the heterogeneity of the fractured material. Here, an attempt has been made to map the spatial distribution of D and b-value in northeast India and also to study the possible correlation between b-value and fractal dimension.

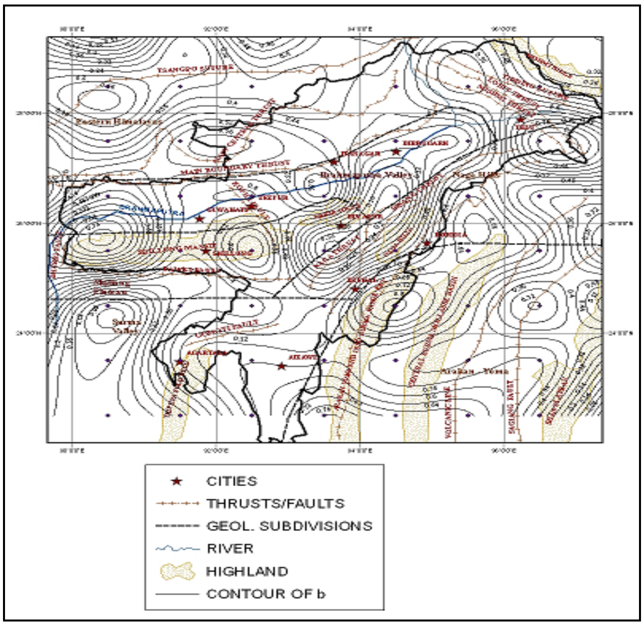

Figure 5: Contour map of b – value.

The study region has been gridded into 1^0 interval and the b – value has been determined by considering the events in each grid. The centers of each grid has been plotted and contoured with respect to b – value which is depicted in fig.5. The b – value map clearly represent the spatial variation of earthquake frequency in the region. From the map, higher b – value contours are seen in the Arakan – Yoma region with the value decreasing gradually in the South – East direction towards the Shan plateau. This may be due to the subduction tectonics of the Indian plate under the Burmese Plate.

The higher b - values in the Indo-Burma ranges indicate clustering of epicentres in 2D space, due to greater stress concentration and heterogeneous nature of the crustal surface. The greater stress concentration may be due to bending of the subducting Indian plate as well as external forces due to overriding Burmese plate in this zone; maximum interplay between the two plates causes more external forces for the higher b values. The b –value at the Shillong Plateau is more than that along the Kopili Lineament but it is slightly lower than that along the Indo – Burma ranges. This indicates higher seismic activity at the Shillong Plateau. The activity along the Kopili fault in the Assam valley is due to transverse tectonics that extend to the Bhutan Himalaya. The recent 2009 Bhutan Himalaya earthquake 6.3 Mw is explained by transverse tectonics of the ~400 km long Kopili fault. The intraplate earthquakes of Shillong plateau is explained by pop – up tectonic. The Kopili fault zone, approximately 300 km long and 30 km wide, separate the Shillong plateau and Mikir massif by strike slip movement and it is identified as the most active fault in the Assam valley area . Seismotectonic analysis indicated the probability of large earthquake in this zone in near future [45], [46]. This Kopili fault was responsible for 1869 Cachar earthquake as well as the 1943 event (M > 7). The 200 km long EW Dauki fault defining the southern margin of the Shillong plateau had been active since Cretaceous to the Recent. At present this fault seems to be dormant. The NW–SE trend b – value along the Kopili Fault extends from the Mikir Hills to Arunanachal Himalaya across the MBT. The Surma valley region comprising of the Bengal Basin shows lower b-contour values which indicates low seismic activity and is attributed to thicker sediments and locking of the Indian plate below the basin. Along the Tripura Fold Belt and Gomti Fault the contours of b show medium value which is attributed to less seismic activity. The region along the Tidding Suture, Mishmi Thrust and Lohit Thrust also shows high b – values but lower than the Indo – Burma range but comparable with Kopili Lineament. As these are made up of diorite and granodiorite complex with a frontal belt of high grade schists and migmatites, and inner belt of low grade schist with crystalline limestone and serpentinite lenses. The b – value gradually decreases along the North – East direction. The contours of b – value along the MBT and MCT indicates seismic activity lower to the Indo – Burma range but comparable to Kopili Lineament. From the contour map of b another small region of high seismic activity observed in the North – West beyond the Tsangpo Suture. High b – value indicates material heterogeneity in the areas mentioned and presence of a number of randomly oriented faults and fractures in the region. Contour map of b – value also indicated crustal homogeneity of Brahmaputra valley and also the presence of Assam gap.

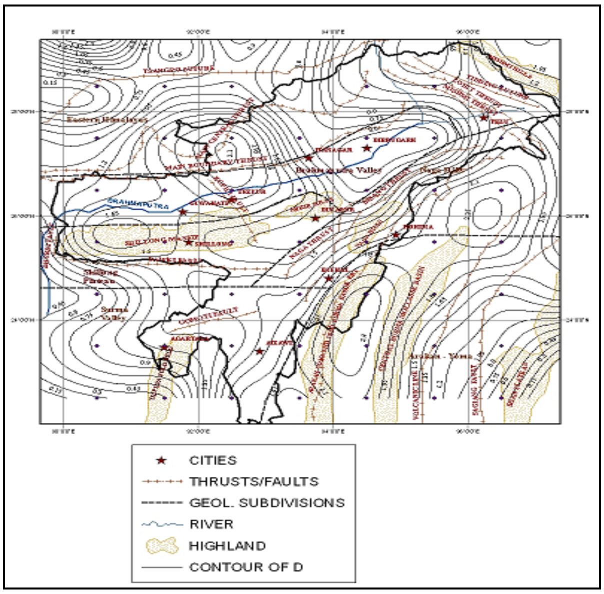

Figure 6: Contour map of fractal dimension, D

The fractal dimension D has been estimated by considering the number of events within each grid of (1^0 x 1^0) and is contoured by plotting the centers of each grid which is shown in fig. 6. The estimated fractal dimensions in this study suggest that the faults are spatially distributed in the whole region, and the whole region is seismically active.

The trend of fractal dimension contours is similar to that of the b – value contours showing high value contours along the Arakan – Yoma and Indo – Burma region followed by the Kopili Lineament and the Shilong

Plateau. Pal [47] also found the ascending order of the fractal dimension contours (both for the earthquakes and the drainage parametres) towards Shillong plateau, Indo Burma range and Indo Tibetan range indicate the clustering of epicentres in the two-dimensional space may be due to greater stress concentration. The higher D values in the Indo-Burma ranges (~ 2.4) indicate the clustering of epicentres , as such the region is seismically active and the stress bearing capacity of the rocks is less indicating heterogeneous nature of the crustal surface of the region in other words the region consists of a diffused set of faults, collectively referred to as Eastern Boundary Thrusts, trending NS and demarcated on the east by the Shan Sagaing fault. It is parallel to Indo - Burma plate boundary and Shan Boundary Fault (SHF).The fractal dimension contours show a higher trend in the NW–SE direction along the Kopili lineament. The D - values in the Kopili Lineament (1.2 – 1.8) indicate less material heterogeneity, possibly due to the deep-rooted Kopili Fault. The contour of D lies between (1.05 – 1.65) in the Shillong Plateau region along the Dauki Fault. The Dauki Fault was believed to be active during the late quaternary time by the geomorphic features of the Shillong Plateau, the gravity anomaly data, and uplifted tertiary and quaternary deposits on the southern foothills of the Shillong Plateau. The contours of D show a lower value in the Bengal basin as it is a delta region and there is rich deposit of sediments and also due to the absence of major active fault in the region. In the Lohit and Mishmi thrust region the value of D indicates the presence of a number of line source of earthquakes. Lower contour of D values found in the Brahmaputra valley indicates that a huge amount of strain is accumulating in the region which may be a source of future seismic event of high magnitude as there is the movement of the Indian Plate beneath the valley unlike the Surma Valley region consisting of the Bengal Basin. Bhattacharya, Majumdar & Kayal [48] studied fractal dimension of this seismically active zone by correlation integral method with 2 degree and 1 degree gridded spacing. They estimated the fractal dimension value as 0.80 to 1.90 and 1.05 to 1.75 which is comparable to the D – value estimated for this region. The fractal dimension D value of the region has been found to be on the average 2.89 times of b – value.

V. CONCLUSION

The investigation of temporal variation of seismic events of the region under study indicates that number of earthquakes reported in the period 1964 – 1978 is less due to non-availability of sensitive instruments to detect earthquakes of small magnitude. After that there is a gradual increase in the number. Seismic activity is very high in the Arakan Yoma region compared to other regions. From annual variation of earthquakes a low seismic activity period from 1997 to 2001 in the Arakan – Yoma, Naga Hills and Eastern Himalayan regions has been identified. From the analysis of correlation of the number of seismic events in different blocks it has been observed that the correlation is maximum between Arakan- Yoma region and the Naga Hills (0.5044) and is minimum between Shillong Plateau region and the Eastern Himalayas (0.0091). The Arakan – Yoma region also bears a correlation with the Eastern Himalayas but its value is less than that with the Naga Hills. This indicates that there might be similarity between the Arakan – Yoma region and the Naga hill region in the process of strain accumulation or release compared to other regions. While the dissimilarity is highest between Shillong Plateau and the Eastern Himalayas.

The return period of earthquakes of all magnitude is minimum in the Arakan Yoma block, followed by Eastern Himalayas. Thus Arakan Yoma block is seismically very active. The return period of earthquakes of magnitude lying between (6.0 – 7.0) mb for the different tectonic zones have been found to be on the average 50yrs while for seismic events greater than 7.0 mb the return period is more than 75 yrs. It may be seen that while the study region as a whole is highly seismic, there are pockets of very high seismicity with other small areas of comparatively less activity. The b-value and the fractal dimension mapping in NE India have identified the seismogenic structures along the Kopili Fault and the Indo-Burma ranges. The higher D values along the Kopili Fault are due to the heterogeneous transverse structure. This observation suggests a higher risk zone along this fault. The higher D values in the Indo-Burma ranges are due to greater stress concentration. The contour map also suggested high deposition of sediments in the Bengal Basin region which is attributed to low seismic activity of the region. The contour map also suggests a region of comparatively less seismic activity which is the Brahmaputra Valley. Since seismic activity in this region is less inspite of the presence of the Kopili Fault, the probability of occurrence of a seismic event of high magnitude cannot be ruled out. Contour map of fractal dimension gives a vivid picture of seismicity of the study region which is comparable with the b – value contour map.

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