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SEISMICITY IN THE NW HIMALAYA, INDIA: FRACTAL DIMENSION, B-VALUE MAPPING AND TEMPORAL VARIATIONS FOR HAZARD EVALUATION

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Abstract- In the NW Himalayan region, India Wadia institute of Himalayan Geology is operating a Seismic array comprises a dense coverage of modern seismometers and producing high-quality seismic data.In the last century earthquakes of varying intensities have hit the region and similar threats remain imminent. We have analyzed 1300 Earthquakes from the northwest Himalayan region and the adjoining regions fall in the intense Himalayan seismic zone. All the events are precisely located. The seismicity is characterized by the *b*-value of the Gutenberg-Richter relation and the fractal dimension *D*. The contour of b value mapping of the region lying between 28.5^{o}-33.5^{o}N and 75.5^{o}-81.5^{o}E indicate the inconsistency of b value in the NW Himalayan region. Fractal correlation dimension D varies from 0.18 to 0.75, which shows that this region has low D value. The average value of D in the region is very low which indicates strong heterogeneity in this part.Temporal variation of b-value in Chamoli and its adjoining region 78˚E to 81˚E in longitude and 29˚N to 32˚N for the data set 1975 - 2005 shown that within the vicinity of forthcoming large earthquakes there is decrease in b and then a return to normal. The 1991 Uttarkashi and 1999 Chamoli earthquake show the same phenomenon.

Keywords- NW Himalayan, seismicity, b-value, Fractal Dimension, Temporal variation of b value, Hazard evaluation.

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Introduction

NW Himalayan region, India is tectonically very active; it is important to understand the frequency-magnitude relation and fractal dimension of the earthquakes distribution for assessing the Seismic risk in this region. In the last 105 years, the main earthquakes occurred in the NW Himalaya are: the Kangra earthquake of 1905 (Ms=8.0), the Kinnaur earthquake of 1975 (M=6.8), Dharchula earthquake of 1980 (Mw=6.5), Uttarkashi earthquake of 1991 (Mb=6.6), Chamoli earthquake of 1999 (Mb=6.8) and the Kashmir earthquake of 2005 (Mw=7.6), which resulted in tremendous loss of life and property. The earthquakes occurrence possesses non-linear relation with respect to space and size. Fractal dimension and b-value are determined from 1300 well-located earthquakes, recorded at 10-19 WIHG seismic stations in NW Himalaya during 2004-2010 and at USGS stations during1995-2003.

Since the Indian plate is colliding with the Eurasian plate at geologic convergence rates of 3.0-5.0 cm/yr. About 1.5-2.0 cm/yr of that relative plate motion is presently accommodated across the Himalaya [1-3]. A large amount of internal stress is continuously being built-up in this region. In the past 100 years four great earthquakes have ruptured and released strain various parts of the plate boundary. The intervening section of the plate continues to accumulate strain energy, making them potential sites for the future great earthquakes. With the growth of populated centers and high storage dams with their associated power plants in the region, the risk due to seismicity has increased manifolds in the recent years. In view of these facts we have studied the b-value and fractal dimension of seismicity in this highly seismically prone region to obtain a realistic hazard evaluation of North-Western Himalaya and adjoining regions.

Tectonic setup of the study area

Himalayan mountain belt setup is broadened about 2400 km long in east-west direction with variable width of 230 to 320 km [4-6]. It is formed due to the convergent movement of two blocks of the earth's lithosphere. The Indian and Asian continental blocks collided some 50 m.y. ago [7-10] resulting lithospheric deformation and modification of the seismotectonic model of the region with the span of time. The seismotectonic investigations have been done by many scientists [11-15] for the Himalaya; we have well documented information of great (M≥8.0) seismic events since 1897. To understand the ongoing deformation pattern of Himalaya, Seeber et al. [14] proposed a steady state tectonic model in 1981, while Ni and Barazangi formulated an evolutionary model in 1984. These models have highlighted the seismogenic discontinuities as MFT, MBT, and MCT, a plane of detachment (MBT and MCT coincide with this plane at depth). In this study we have concentrated on the NW Himalayan region (Fig.1)

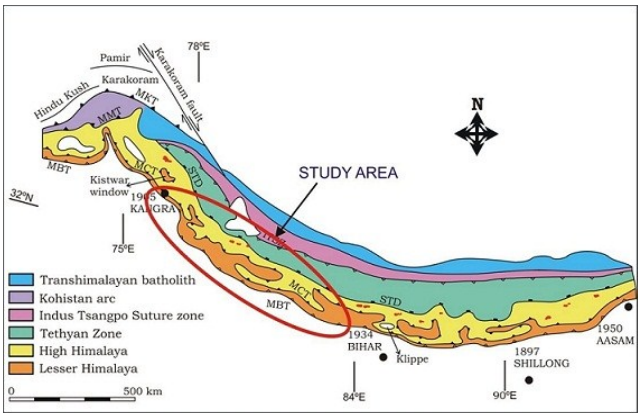

Fig. 1- Broad scale geology of the NW Himalaya. MBT, MCT and STD are the abbreviation for Main Boundary Thrust, Main Central Thrust and South Tibetan Detachment respectively.

About the Fractal Dimension

The main attraction of fractal geometry stems from its ability to describe the irregular or fragmented shape of natural features as well as other complex objects that traditional Euclidean geometry fails to analyze. This concept enables a simple, geometrical interpretation and is frequently encountered in a variety of fields, such as geophysics, biology or fluid mechanics.

Fractal properties of seismicity, a stochastic self-similar structure in time and space distribution of earthquakes, can be measured by fractal dimensions e.g. [16-18].The fractal dimension provides a measure of the degree of fractal clustering of points (as epicenters of earthquake) in the space and help in Quantitative measurement of the degree of heterogeneity of seismic activity in fault systems of a region [19] and tracing the secondary or hidden structures [20, 21]. The variability of the fractal dimension in different zones may be related to geological heterogeneity [22]. 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. Possible values of fractal dimension are bound to 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 $D \rightarrow 0$ has all events clustered into one point, and at the other end of the scale, $D \rightarrow 2$ indicates that the events are randomly or homogeneously distributed over a two-dimensional embedding space [23].The low value of D sometimes indicates the presence of fluid in the sub-surface. The presence of fluid may contribute to reduce the effective stresses [24].The value of D began to decrease before occurrence of a large earthquake. So it may be precursor of an earthquake [25].

About the b-value Analysis

One of the basic seismological parameters used to describe an ensemble of earthquakes is the b-value in the Gutenberg-Richter frequency-magnitude relation. Scholz [26] suggested that the state of stress, rather than the heterogeneity of the material constituting the rocks, plays the most important role in the b-value. It characterizes the distribution of earthquakes over the observed range of magnitudes. It is an important parameter in seismology for its association with several geotectonic features of an area [26, 27]. Mogi [27] showed that the b-value is influenced by the degree of heterogeneity and crack density in the medium. The b-value tells about the material properties of the source region, it is sensitive to stresses and stress drops [28]. High and low stresses causes earthquake with low and high b values. Large material heterogeneity corresponds to higher b-values.

WIHG array Data

Data is recorded at Wadia Institute of Himalayan Geology (WIHG) regional seismic network consisting 30 seismographs (27 broadbands and 3 short periods) (Fig.2) deployed in the NW Himalaya to address seismotectonics, and the evolution of stress pattern of the region. These are Taurus Portable Seismographs with Trillium 240 broadband low noise seismometers have a response flat to velocity from 240 seconds to 35 Hz; RefTek 3-component Data logger with CMG-40T a short-period seismometer (1 sec), and broadband seismometer (30 s to 100hz).

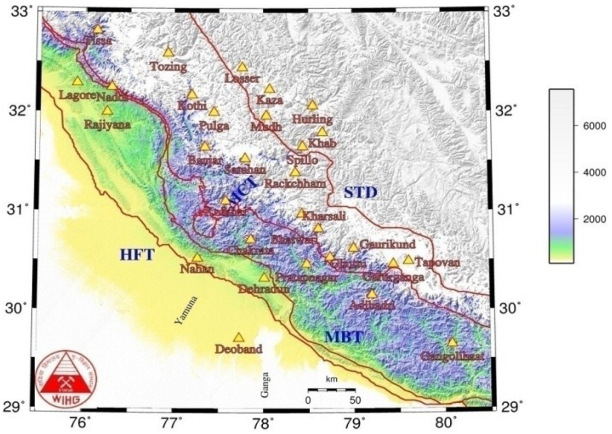

Fig. 2- Deployment of Broad-band and short period seismographs in the NW Himalaya is shown by triangles

About the earthquakes Data used in this analysis

The earthquakes data used in this study are recorded at 10-19 WIHG stations (2004-2010) and from USGS catalogue (1995-2003). Out of total 5544 earthquakes data of all magnitude recorded in the NW Himalayan region, in the longitude 74°-82° and latitude 28°-32° range, the best 1300 earthquakes of magnitude ≥3 has been selected (Fig.3). The area is gridded at 1°x 1° spacing with an overlapping of 0.5°x 0.5°. To get reliable values of D and b values we have considered only those grids which contain more than 40 earthquakes. We have divided the region into 47 grids for the calculations.

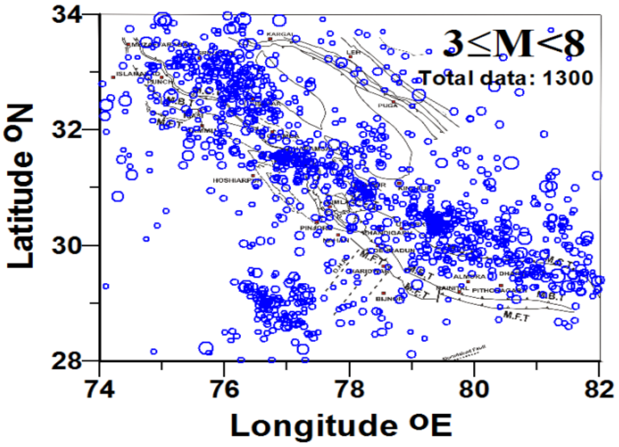

Fig. 3- Epicentral Plot (Epicenters are shown with the circles)

Data Selection Criteria

Data is selected on the basis of the parameters like uniform magnitudes, time span, sub catalogs, completeness and de-clustering. It is important that reported magnitudes are homogeneous throughout the whole catalogue.Time span of the catalogue must be at least comparable and possibly larger than the return period of the largest expected event. Depending upon the type of the study, it may be to generate sub-catalogues corresponding to geographic sub-regions with different specific characteristics. Each sub-catalogue is treated separately. To guarantee the completeness of the data, analysis will comprise only events with magnitudes equal to or greater than the M_c: Magnitude M_c is determined from the G-R diagrams. Here data with magnitudes ≥ 3 is consider for the study. To avoid dependent data, the catalogue has to be de-clustered by deleting all the fore shocks and aftershocks. Obviously, this step is usually relevant merely for global/ regional catalogues comprising large events with long aftershock/ foreshock series. To de-cluster the distribution of events in time has been studied in order to understand the correlation of aftershocks generation. Aftershocks are not Poissonian and are temporarily correlated with each other as it is well known that they follow the main shock, occur in a narrow region around it having smaller magnitudes and the aftershock activity decays over time from the time of main shock occurrence. Omori's law [29] is used to study the frequency of occurrence of aftershocks n(t) at time t after the mainshock and removed them from the data set.

Methodology

Fractal dimension is denoted by D and is estimated using the correlation dimension. The correlation dimension is the measure of the spacing of a set of points, which in this case are the earthquake epicenters.

The fractal dimension of epicenters is determined using the generalized correlation integral C(r) given by [30]

$$C(r) = 1/N^2 \lim_{N\to\infty} \sum_{i=1}^{N} \sum_{j=1}^{N} H(r-|x_i-x_j|), \qquad (1)$$

Where, r is the radius of a sphere of investigation and N is the number of points in the grid, x are the co-ordinates of the epicentres and H is the Heaviside step function $H(x)=0$ for $x\leq 0$, $H(x)=1$ for $x\sim 0$. This equation can be simplified as

$$C(r) = 2^*N(R<r)/N\,(N-1), \qquad (2)$$

Where, Correlation function C(r) is defined for the data set of epicentral distribution $\{X_i\}^{N}_{i=1}$, which measures the spacing or clustering of a set of points. N is the total number of aftershocks. N(R<r) is the number of pairs with a smaller separation than r.

The fractal dimension is given by

$$D = \lim_{r\to 0} \ \log(Cr)/\log r, \qquad (3)$$

Where, Cr is the correlation function.

The correlation coefficient is related to the standard correlation function as given by [9] $C(r) \sim r^{D2}$,

Where, D_2 is a fractal dimension. The distance (r) between two events (θ1, φ1) and (θ2, φ2) is calculated by the formula

$$R = \cos^{-1}[\cos\theta 1\cos\theta 2 + \sin\theta 1\sin\theta 2\cos(\varphi 1-\varphi 2)], \qquad (4)$$

Where θ1, θ2 are the latitudes and φ1, φ2 are the longitudes of the event1 event2, respectively. D is estimated as the slope of log C (r) versus log(r) using the least square method where θ1, θ2 are the latitudes and φ1, φ2 are the longitudes of the event1 & event2, respectively. D is estimated as the slope of log C (r) versus log(r) using the least square method.

b- value is estimated using following methods

Earthquake size distribution follows Gutenberg -Richter law [31]:

$$LOG\ N = a - bM, \qquad (5)$$

Where, N is the number of earthquake with magnitude less than M, *a* & *b* are parameters of correlation.

Maximum likelihood estimation for the b-value is claimed to be a better estimation as given by Aki [32]:

$$b = \log_{10} e / M_{AV} - M_0, \qquad (6)$$

Where, M_{AV} *is the average magnitude and* M_0 *is the threshold magnitude.*

Error estimation of b value

Using the empirical formula of Pickering [33] based on a Monte Carlo simulation of the sampling effect on the exponent of a power -law distribution. The formula is as follows:

$$\sigma = k\,(b/N)^{1/2} \text{ for } b<1, \qquad (7)$$

Where, σ is the standard deviation of the b-value estimate, N is the sample size, and k is a factor depending on a scale range of the analysis. This estimate is depends on carefully selecting the value of k. That is why the error estimates of b value has also carryout using the usual Aki's [32] method.

Results and discussion

The changes in b value and fractal dimension D of hypocenter distribution in the NW Himalaya and adjoining regions has analyzed in this study. The resulting Characteristics found by this analysis are shown in Fig. 4 & 5 and their interpretation is as follows: The contour of b value mapping of the region lying between 28.5°-33.5°N and 75.5-81.5°E indicate that b value is inconsistent in the NW Himalayan region.

The b- value maps clearly depict the variations of the earthquake frequency in the region. Low b value observed around the Chamoli region (30.5°N, 79.5°E).

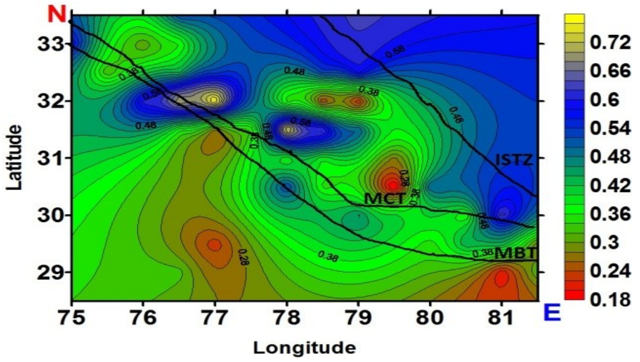

Fig. 4- b value contour map for total 1300 earthquakes (M≥3.0)

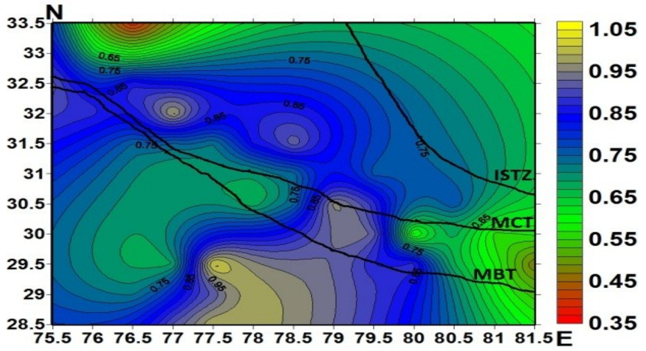

Fig. 5- D value contour map for total 1300 earthquakes (M≥3.0)

The low value of b in this zone indicates the presence of fluid in the sub-surface as suggested by Monsalve et al. [24]. We have also observed low D value around this region. The low value of D in this zone indicates the presence of fluid in the sub-surface as suggested by Monsalve [24]. The presence of fluid in this zone may contribute to reducing the effective stresses and show relatively lower value of D as observed by Barton [34] in Long Valley, California, and Singh [35] in Koyna region. The Low fractal value around the chamoli region strength the evidence of presence of fluid filed rock matrix in the upper crust of this region. Mukhopadhyay and Kayal, [36] studied the aftershocks of Chamoli earthquake (1999) and their tomographic interpretations they obtained low-velocity zone (high V_P/V_S ratio) that extends from the surface down to 15 km depth, and explained this anomaly as may be due to fluid-filled fractured rock matrix. The liquid-filled source area might have contributed to the nucleation of the mainshock. Delineation of such characteristic seismic images may be useful for seismic hazard/risk evaluation in active tectonic zones. Apart from this possibility an increase in applied shear stress [26] or an increase in effective stress [37] decreases the b-value. The high stress in the area could be due to crustal deformation in study region. A lower value of b infers that the region is under higher applied shear stress. Low *b* implies shorter recurrence time. Patches with low *b* may be interpreted as possible asperities (stress concentrations) reflecting variations in frictional properties along the fault, which may control the recurrence of the next large event.

In the present analysis, the calculated value of Fractal correlation dimension D varies from 0.18 to 0.75, which shows that this region has low D value. The average value of D in the region is very low (0.38). The obtained value of D is low along the passage of MCT and north of the MCT trend indicates strong heterogeneity in this part (Fig. 5).

The low D value is observed in the NE-SW trending zone in the western Himalaya. Arora and Singh [38] have also reported a conductive zone in this region using magnetotelluric survey. We found a positive correlation between b and D values (Fig.6).

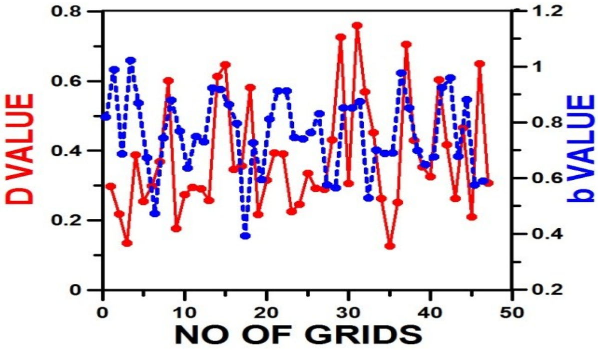

Fig.6- Plot shows the correlation between D and b value with time

The average spatial correlation in this region is 0.7, which indicates the events are not randomly distributed, but more or less clustered. The b value ranges from 0.35-1.05 using MLM. The b value is estimated 0.66 using LSM. The error estimate of b- value lying under reasonable limits 0.02-0.07. However, this estimate is depends on carefully selecting the value of k, which is a factor depending on a scale range of the analysis. The error estimates using the usual method [32] varies between 0.06 to 0.11. This estimate is little higher than the previous estimates, but looks more reasonable in view of the present giant data set.

b~1, from both the methods suggests that the area is seismically active. A sharp rise in the b value is observed in the north of the MCT along the MCT trend indicates strong heterogeneity in this part.

From the slop of the plot C(r) and it is found that fractal dimension D is 0.78 (D<1), which shows that the faults are distributed in a line and is indicative of more clustered events in the region. Similar results have been obtained in the eastern Himalaya and southern Tibet region by Chandrani et al., [35].

Temporal variation of b-value in Uttarkashi & Chamoli and its adjoining region 78˚E to 81˚E in longitude and 29˚N to 32˚N for the data set 1975-2005 indicates that within the vicinity of forthcoming large earthquakes there is decrease in b and then a return to normal. The 1991 Uttarkashi and 1999 Chamoli earthquake show the same phenomenon.

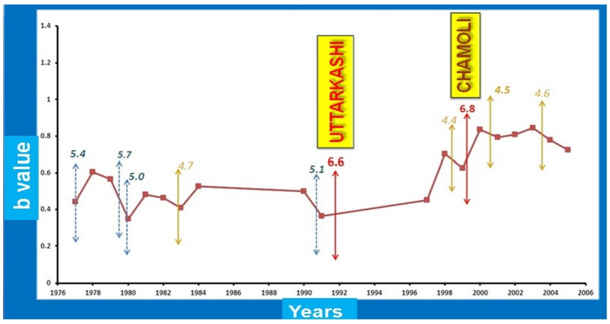

Fig. 7- Temporal variation of b-value in Uttarkashi & Chamoli and its adjoining region

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