Evaluation of Seismic Hazard Parameters for Bangalore Region in South India

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Abstract

In this paper, seismic hazard parameters are evaluated and presented for Bangalore region following the different methods such as Gutenberg-Richter (G-R) recurrence relation and maximum likelihood procedure and data sets. The seismic data have been collected from various sources for area covering a radius of 350 km around Bangalore. A complete analysis has been carried out using the method as proposed by Stepp[27]. From the analysis it was found that the seismic data is homogenous for the last four decades irrespective of magnitude. The value of seismic hazard parameter "b" was estimated for complete data by using G-R relation. Completed data do not include the maximum reported magnitudes of 5 and above in this region. Hence b value has been evaluated by considering mixed data magnitude range of 3.5 to 6.2 and 4 to 6.2 using Gutenberg–Richter[6] recurrence relation. In addition seismic hazard parameters such as, "b" of the magnitude- frequency relationship, R the mean return period and M_{max} maximum regional magnitude is evaluated based on maximum likelihood procedure. It has been observed that the comparative analysis using complete and mixed data, gives comparable values. The "b" values presented in this paper are higher than the earlier reported values.

Keywords: Seismic Hazard parameters, seismicity, completeness, "*b*" value and recurrence rate.

Introduction

Study of seismicity of an area is mandatory for the purpose of seismic microzonation, ground response analysis and design of important structures. South India, once considered as a stable continent, has recently experienced many earthquakes. Recent seismic hazard studies[4,5,18,23,24,25,28,29] in south India have revealed that south India is becoming seismically active. Bangalore, which is located in south India is densely populated and the fastest growing city in Asia. It is also an economically and industrially important city in India. This region is vulnerable even for moderate earthquakes due to mushrooming of all kinds of buildings erected on encroached areas of tank beds[23]. More than 150 lake beds in Bangalore have been dried up and silted up over a period of time and they have been converted and used for construction in the last 50 years. Non engineering structures constructed on filled up soil are more vulnerable even for moderate earthquakes. Recently, deterministic seismic hazard analysis has been carried out for Bangalore and maximum credible earthquake (MCE), seismogenic sources, synthetic ground motion model were evaluated by Sitharam et al[24] and Sitharam and Anbazhagan[23].

Unlike, deterministic seismic hazard analysis probabilistic analysis allows the uncertainties in the size, location, rate of recurrence and effect of earthquakes to be explicitly considered in the evaluation of seismic hazard. The probabilistic seismic hazard analysis procedures require the "*b*" of the magnitude-frequency relationship, *R* the mean return period, M_{max} maximum regional magnitude etc. As such, information on seismic hazard parameters are not available for a larger part of south India and in particular Bangalore. Generally, the available earthquake catalogues contain two types of information: one, macro seismic observations of major seismic events that occurred over a period of few hundred years and the other complete instrumental data for relatively short periods of time. The methods which are generally used for the estimation of seismic activity parameters are not suitable for this type of data due to incompleteness of the macro seismic part of the catalogue. Classical methods which are generally used for the estimation of seismic hazard parameters[3,15] are not suitable for this type of data. One of the suitable methods for analyzing the macro seismic (older) 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 a small shock is wasted. Another method for estimating the seismic activity parameters is to reject the macro seismic observations that are incomplete and to use any standard method for the data from the other complete part of the catalogue[13,14]. It is to be noted 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 errors.

In this paper seismic hazard parameters are evaluated based on two methods by using complete and mixed data set. Complete analysis of data set has been evaluated based on the method as proposed by Stepp[27]. Seismic hazard parameters were then evaluated based on the competed data and mixed data set using Gutenberg and Richter[6] method. In addition, seismic hazard parameters were evaluated based on the method proposed by Kijko and

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Sellevoll[13,14] using mixed data file. Seismic hazard parameters such as "*b*" of the magnitude-frequency relationship, R the mean return period and M_{max} maximum regional magnitude are evaluated and reported.

Study Area and Geology

Study area having a radius of 350 km around the city center of Bangalore, South India has been selected for the seismicity study as per Regulatory Guide[20] 1.165. Regional, geological and seismological details for the Bangalore city have been collected by using literature review, study of maps and remote sensing data. The study area marked in the map of India is shown in figure 1. This study area having the center point as Bangalore city, (with latitude of 12°58'' N and longitude of 77°36'' E) has a radius of 350 km covering the latitude 9.8° N to 16.2 ° N and longitude of 74.5° E to 80.7° E. It covers major part of the Karnataka, northern part of Tamil Nadu and portion of Kerala and Andhra Pradesh. Geology of the study area is presented as described in the Seismotectonic Atlas of India[22], published by Geological Survey of India. Geological formation of the study area is similar to Indian Peninsula, which is geologically considered as one of the oldest land mass of the earth's crust. Tectonic/Geological map of the study area is shown in figure 2. Most of the study area comprises of Gneissic complex/Gneissic granulite with a major inoculation of greenstone and allied supracrustal belt. The coastline on the eastern and western side of the area has alluvial fill in pericratonic rift.

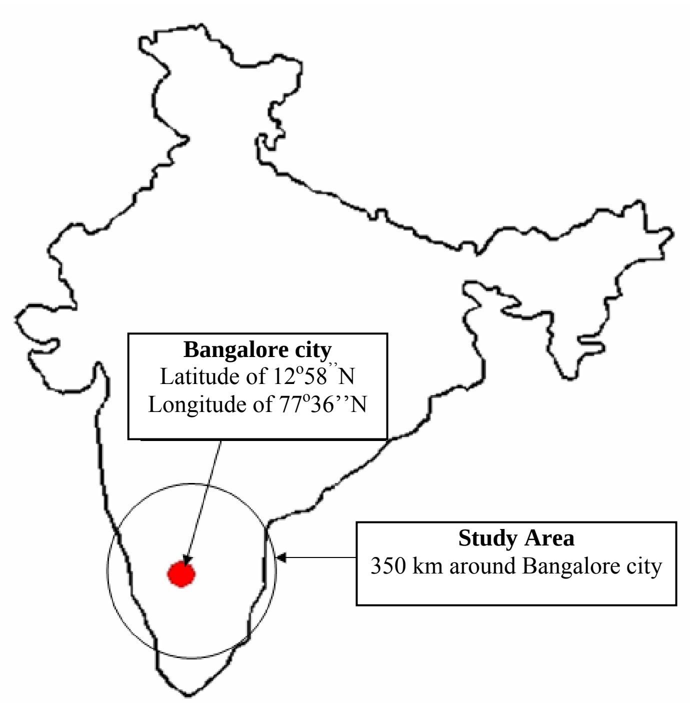

Figure 1: Study area in India map

Seismicity in the Study Area

Seismicity of India and Peninsular India have been addressed by many researches[1,2,9,11,16,19,23,24,30]. As per IS 1893[8] , the study area is upgraded to seismic zone III and zone II from zone II and zone I respectively. Seismic activity in south India is highlighted by Srinivasan and Sreenivas[26] , Valdiya[31], Purnachandra Rao[17] , Ramalingeswara Rao[18], Subrahmanya[28,29] , Ganesha Raj[4], Sridevi Jade[25], Ganesha Raj and Nijagunappa[5], Sitharam et al[24] and Sitharam and Anbazhagan[23]. All the above authors highlighted that the seismic activity of the south India has shown an increasing trend. With these recent updates, a study of seismicity data for its completeness and evaluation of seismic parameters for the Bangalore region has become essential.

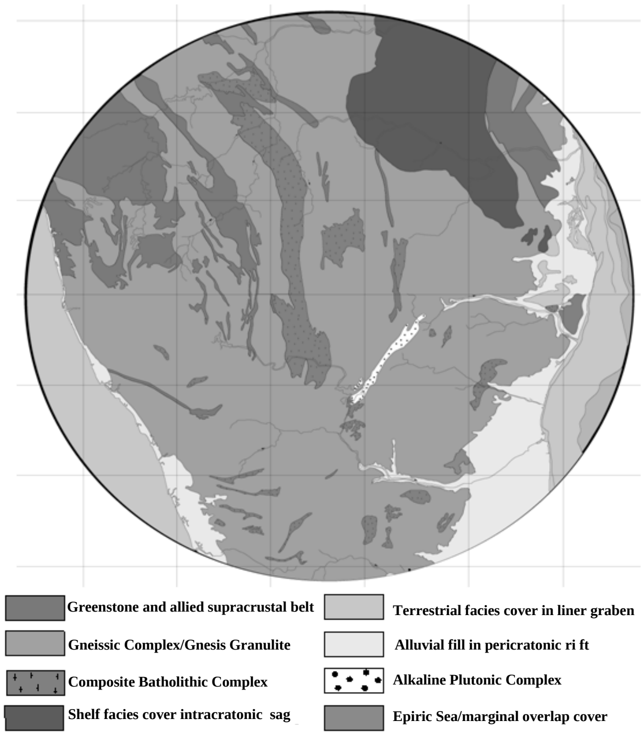

Figure 2: Tectonic/Geologic map of the study area

Seismic data has been collected from various agencies such as United State Geological Survey (USGS), Indian Metrological Department (IMD), NewDelhi; Geological Survey of India (GSI) and Amateur Seismic Centre (ASC), National Geophysical Research Institute (NGRI), Hyderabad; Centre for Earth Science Studies (CESS), Akkulam, Kerala and Gauribindanur (GB) Seismic station. The data contain information about the earthquake size in different scales such as intensity, local magnitude or Richter magnitude and body wave magnitudes. These magnitudes are converted to moment magnitudes (Mw) to achieve the status of the uniform magnitude by using magnitude relations given by Heaton et al[7].

The earthquake events collated are about 1421 with minimum moment magnitude of 1.0 and a maximum of 6.2 and are shown as various symbols with different colors in figure 3. About 1421 earthquakes have been collated and their magnitudes were converted as moment magnitude scale for the purpose of study. The data set contain 394 events which are less than moment magnitude 3, 790 events with moment magnitudes from 3 to 3.9, 212 events from 4 to 4.9, and 22 events from 5 to 5.9 and 3 events which have a moment magnitude more than 6. Maximum earthquake magnitude of about 1421 events reported in the study area is 6.2. The earthquake events collated with latitudes and longitudes are used to prepare the seismicity map of Bangalore region shown in figure 3. Out of 1421 seismic data, about 1340 data are collected from the record of Gauribidanur seismic array (GBA), which is in operation for long time, having geographic coordinates of the array center point, 13^{o}36'15''N, 77^{o}26'10"E. GBA seismic station is about 85 km away from the center of the study area. The GBA has an L-shaped configuration with dimensions of about 22 x 22 km^2 and a station interval of about 2.5 km (Fig. 4). GBA data set is unique and it is the only array data available in the public domain to study seismic properties of the south India. GBA data are widely used for evaluating seismotectonic parameters in south India. Seismic data have been collected in GBA from 1977 to 2006. Other agencies (CESS, NGRI, and IMD) have been established recently and the data for the last 10 years have been collected from these agencies.

Figure 3 shows the distribution of seismic data in the study area. The seismicity is denser in the northern part, southern most part and central part of the study area. There are clusters of earthquakes of moment magnitude (Mw) of 2 to 2.9 found at intersection of 10.8^{o} N and 76.9^{o} E, 12.5^{o} N and 76.5^{o} E, 13.0^{o} N and 76.5^{o} E, 14.3^{o} N and 78.0^{o} E and 14.5^{o} N and 78.6^{o} E. Mw of 3.to 3.9 has frequently occurred at intersection of 15.1^{o} N and 76.8^{o} E, Mw of 4-4.9 is distributed through out the study area and clustered at two locations (13.2^{o} N and 75.1^{o} E and 15.1^{o} N and 76.6^{o} E). The range of 5 to 5.9 is randomly distributed in the study area, frequently reported close to the center of the study area.

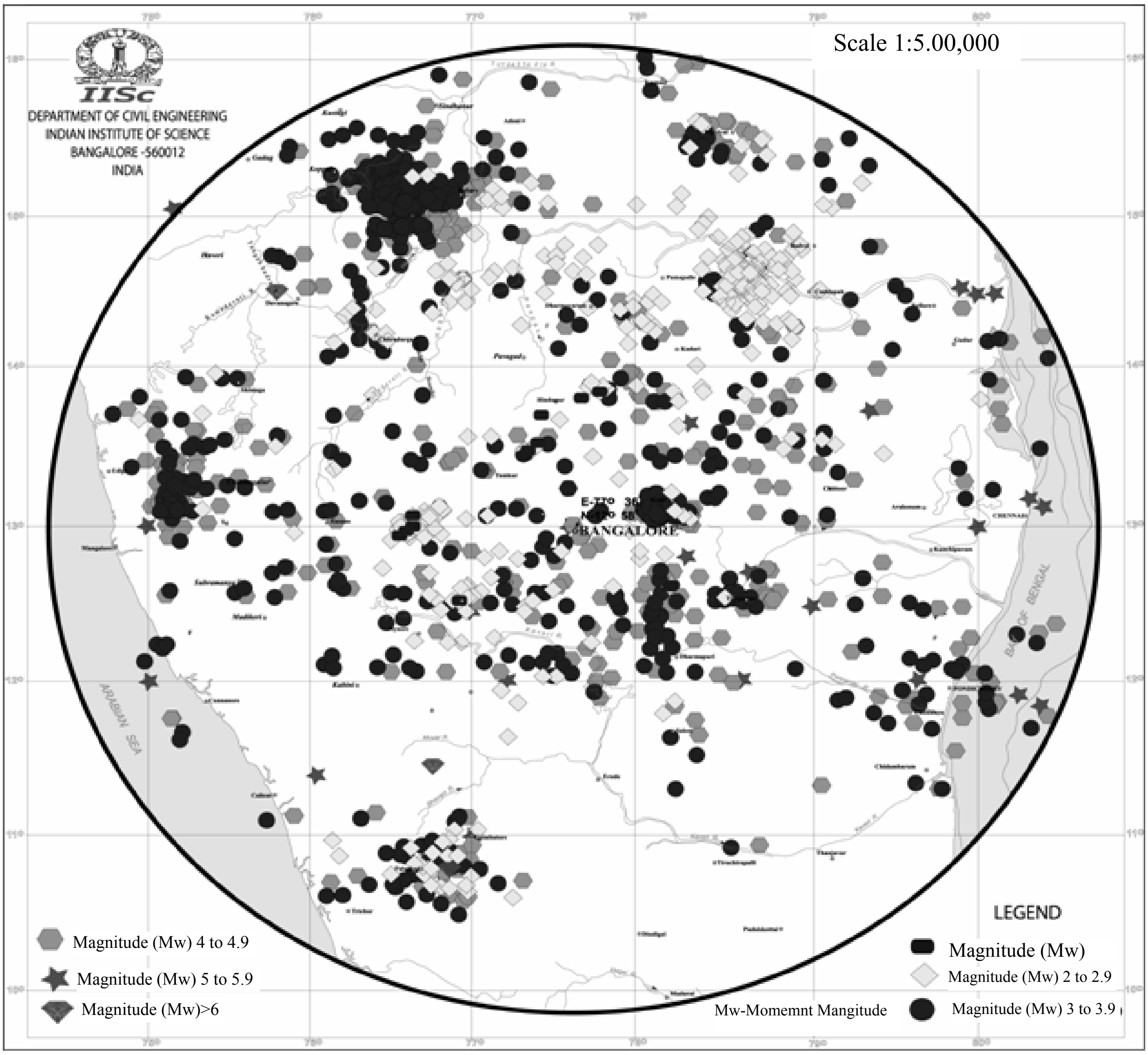

Figure 3: Seismicity map of Study area

Gutenburg-Richter Recurrence Law

Unlike deterministic seismic hazard analysis, the probabilistic analysis allows the uncertainties in the size, location, rate of recurrence and effect of earthquakes to be explicitly considered in the evaluation of seismic hazard. But probabilistic approach needs recurrence relation to quantify the size uncertainty. Uncertainty in size of earthquakes produced by each source zone can be described by various recurrence laws. The regional earthquake recurrence activity is commonly expressed in terms of the Gutenberg-Richter magnitude frequency relationship[6] represented by the following exponential magnitude distribution function:

$$Log_{10} N\left(\geq M \ per\ year\right) = a - b\,M \quad (1)$$

where N is the number of events per year with magnitude greater than or equal to M. The a-value is the rate per unit area per year of M earthquakes and the b-value is the slope of log-linear fit that represents the relative likelihood of larger and smaller earthquakes.

For a certain range and time interval, eq.1 will provide the number of earthquakes, (N) with magnitude, (M) where ‘a’ and ‘b’ are positive, real constants. ‘a’ describes the seismic activity (log number if events with M=0) and ‘b’ is a tectonic parameter describing the relative abundance of large to smaller shocks (typically close to 1).

Important step in the any data analysis is the investigation of available data set to access the nature and degree of completeness. Incompleteness of available data of earthquakes make it difficult to obtain fits of equation 1 that are thought to represent true long term recurrence rate. All most all earthquakes catalogs are biased against small shocks, because of seismographs station density or in the early records population density[27].

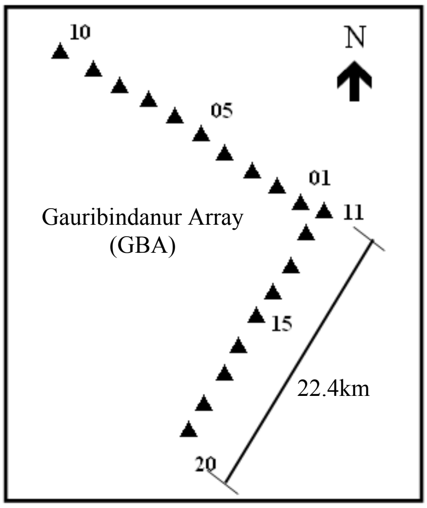

Figure 4: Location of receivers in Gauribindanur array

Analysis of Seismic Data for Bangalore Region

The number of earthquakes per decade was divided in five different magnitude ranges such as 2 < M < 2.9; 3 < M < 3.9; 4 < M < 4.9; M > 5. Table 1 describes the number of earthquakes reported in each decade[27] starting from the year of the available historical record. Figure 5 shows the histogram representing the data listed in table 1 for the whole catalogue from 1807 to 2006. The whole catalog shows that from 1807 to 1976, the data are poorly reported, which may be due to the lack of observations. However, from 1976 to 1996, better recording of the data can be observed. Again, from 1997 to 2006 limited data can be observed and this is attributed to non availability of earthquake data from GBA.

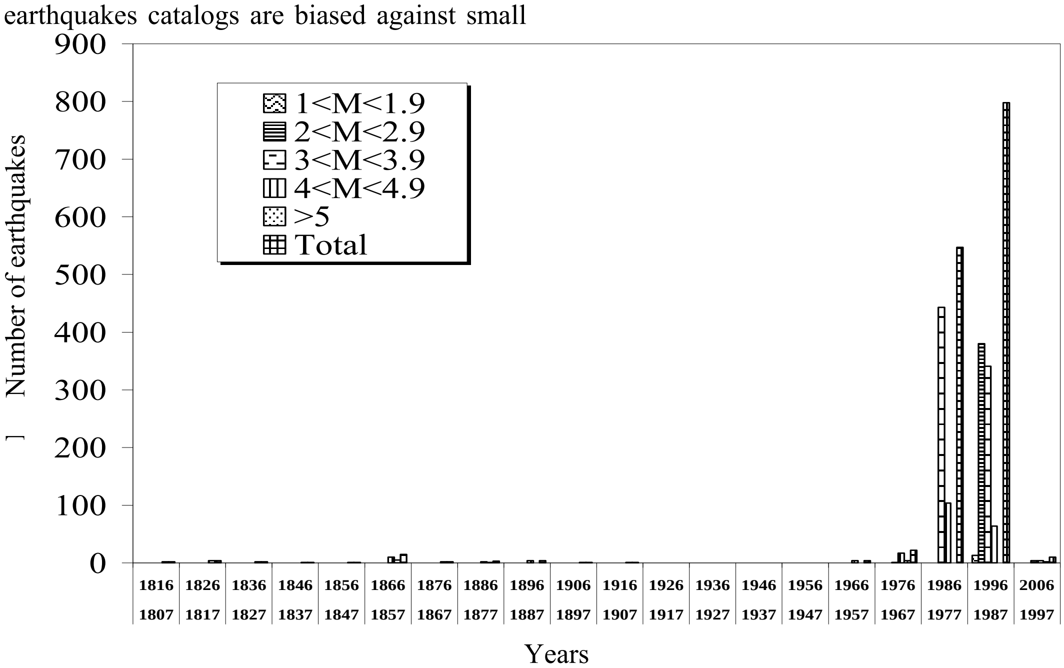

Figure 5: Histogram of the number of earthquake for Bangalore region

Data Completeness Analysis

From figure 5, it is clear that the data are severely incomplete. For the severely incomplete data set, Stepp[27] method was adopted in order to check the completeness of the earthquake data. Analysis has been carried out by grouping the earthquake data into several magnitude classes. Each magnitude class is modeled as a point process in time. The advantage of the property of statistical estimation is that the_variance of the estimate of a sample mean is inversely proportional to the number of observations in the sample[27]. Thus the variance can be made as small as desired by making the number of observation in the sample large enough, provided that reporting is complete in time and the process is stationary i.e. the mean variance and other moments of each observations remain the same. In order to obtain an efficient estimate of the variance of the sample mean, it is assumed that the earthquake sequence can be modeled by the Poisson distribution. If k_1, k_2, k_3…..k_n are the number of earthquakes per unit time interval, then an unbiased estimate of the mean rate per unit time interval of this sample is

$$\lambda = \frac{1}{n}\sum_{i=1}^{n} k_i \qquad (2)$$

and its variance is

$$\sigma_\lambda{}^2 = \frac{\lambda}{n} \qquad (3)$$

where n is the number of unit time interval. Taking the unit time interval as one year, we get:

$$\sigma_\lambda = \frac{\sqrt{\lambda}}{\sqrt{T}} \qquad (4)$$

where T is the sample length. Hence by assuming stationary process, one can expect that σ_λ behaves as $\frac{1}{\sqrt{T}}$ in the subintervals, in which the mean rate of occurrence in a magnitude class is constant. In other words, when λ is constant the standard deviation σ_λ varies as $\frac{1}{\sqrt{T}}$ where T is the time interval of the sample. If the mean rate of occurrence is constant, we expect the stability to occur only in the subinterval that is long enough to give a good estimate of the mean but short enough that it does not include intervals in which reports are complete[27].

The rate of earthquake occurrence as a function of time interval is listed in table 2 for the range of magnitudes. The rate is given as N/T where N is the cumulative number of earthquakes in the time interval T, for subintervals of the 200 year sample shown in the first column. These data are used to determine the standard deviation of the estimate of the mean through equation (4). The results are shown in figure 6.

Table 2 and figure 6 reveal several features significant to statistical treatment of earthquake data regardless of whether one uses empirical relationship log N = {a – b M} with the extreme value distribution. For each magnitude interval in figure 6, the plotted points are supposed to define a straight line relation as long as the data set for the magnitude interval are complete. For a given seismicity of the region the slope of the lines for all magnitude intervals should be the same. It can be observed from figure 6 that data set for all magnitude intervals seems to be complete for the last 40 years (1967 to 2006).

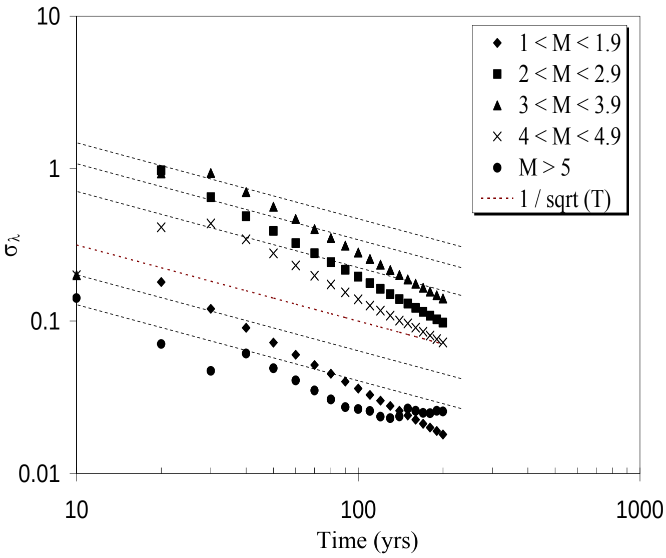

Figure 6: Estimation of the mean of the annual number of events as a function of sample length and magnitude class for Bangalore region

Temporal Frequency Magnitude Recurrence Relationship

The earlier analysis shows that the data set are not complete for the interval 1807 to 1967. Generally *"b"* value is computed from the analysis of whole set of data without testing the completeness of the data which gives error in the estimation of *"b"* value. Following the method proposed by Stepp[27], it was found that data set are complete for the last 40 years. Hence, computation of *"b"* value has been carried out using the data set from 1967 to 2006. Figure 7 presents the logarithm of the cumulative earthquake per year for M, where M is the magnitude in particular interval. An interval of 0.5 is taken for grouping the data while computing the *"b"* value. A straight line fit in least square sense for the complete set of each magnitude range is as follows:

$$\log(N) = 3.6 - 0.89M \qquad (5)$$

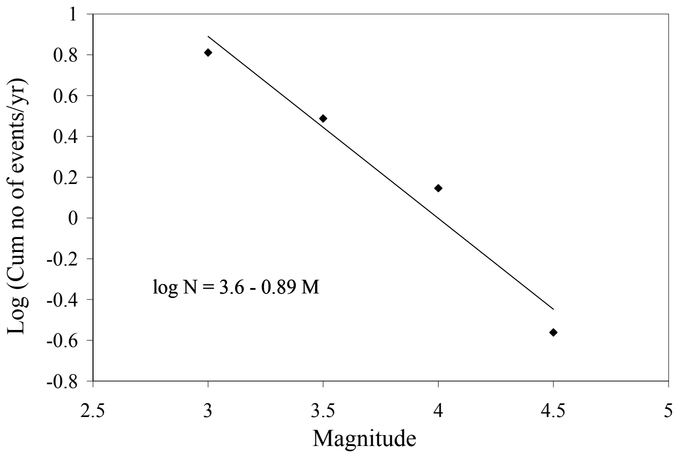

Figure 7: Frequency magnitude relationship for Bangalore region

From the above equation, the seismic hazard parameter "a" is 3.6 and "*b*" is 0.89 with a correlation coefficient of 0.96. Recurrence relation arrived for the region does not include major earthquake in the historic times, but includes micro seismic data less than Mw of 3.5. Hence G-R relation is also developed by considering all the data as two groups, one in the magnitude range of 3.5 to 6.2 and another 4 to 6.2. Figure 8 presents the logarithm of the cumulative earthquake per year for M, versus magnitude Mw of 3.5 to 6.2 and a straight line fit in least square sense for data set of each magnitude range is given as:

$$\log(N) = 3.56 - 0.87M \quad (6)$$

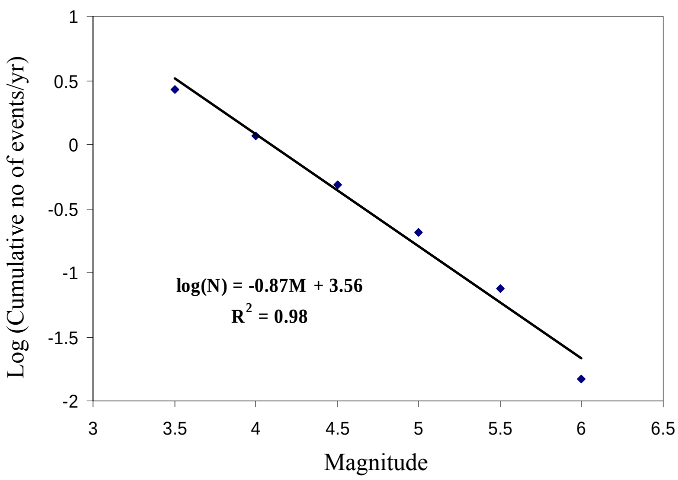

Figure 8: Frequency magnitude relationship for study area using Mw of 3.5 to 6.2

Figure 9 presents the logarithm of the cumulative earthquake per year for M versus magnitude Mw of 4 to 6.2 and a straight line fit in least square sense for data set of each magnitude range is as follows:

$$\log(N) = 3.82 - 0.92M \quad (7)$$

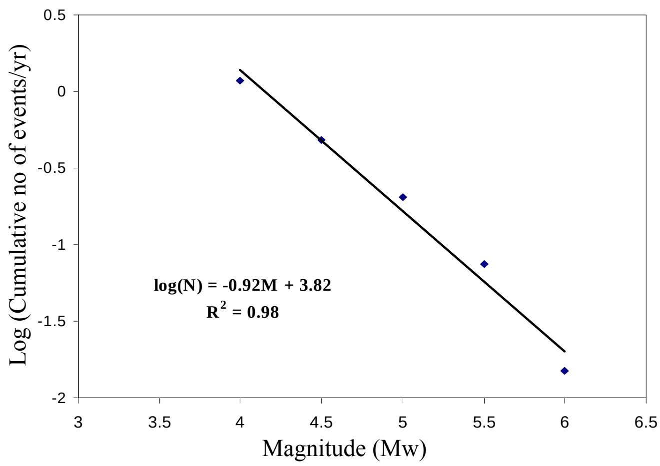

Figure 9: Frequency magnitude relationship for Study area using Mw of 4 to 6.2

From the above three equations, the values seismic parameter '*b*' of a region varies from 0.87 to 0.92. Further seismic hazard parameters are also evaluated using all the earthquake data set, which is also termed as mixed data set using Kijko and Sellevoll method[13,14].

Analysis based on Kijko and Sellevoll

Kijko and Sellevoll[13,14] have presented a versatile statistical method for analyzing such mixed data set. Using Kijko and Sellevoll's computer program HN2 (Release 2.10, 2005) analysis has been carried out to evaluate seismic hazard parameters. The program was developed by assuming the earthquake occurrence as a Poisson's model and the doubly truncated Gutenberg-Richter magnitude distribution for maximum likelihood estimation of the slope of the recurrence relationship. In the present investigation, a threshold magnitude value of 3.0 and standard deviation value of 0.2 is used. From the analysis it was observed that the value of beta (β) is 2.00 ± 0.07, value of Lambda (λ) is 0.386 (for M of 5.0), seismic parameter value of '*b*' is 0.87 ±0.03 and maximum magnitude is (M_{max}) 6.0± 0.54. Figure 10 shows the variation of return period with magnitude as obtained by mixed data analysis. Figure 10 shows that for lower magnitudes the return period are shorter. With increasing magnitude, the return period becomes longer.

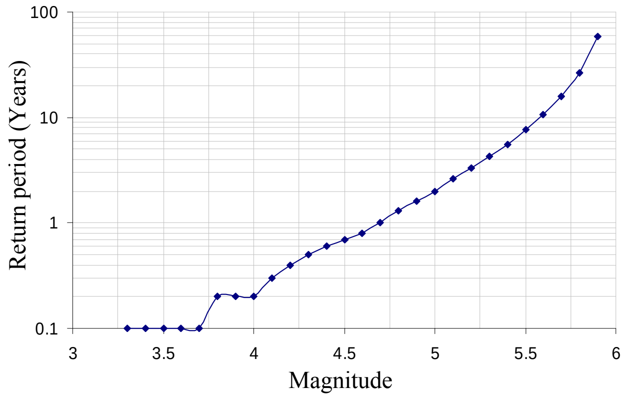

Figure 10: Return periods estimated using Kijko and Sellevoll[14] method

Probability of the magnitude for the time period (exposure time) of 50, 100 and 1000 years is shown in figure 11. Probability of occurrence of the lower magnitude is 100% in the specified return period. Further for higher magnitudes, probability of occurrence gets decreasing and this may be attributed considering only the magnitude uncertainty in the study. It shall be noted that in this analysis the probability values are only based on magnitude.

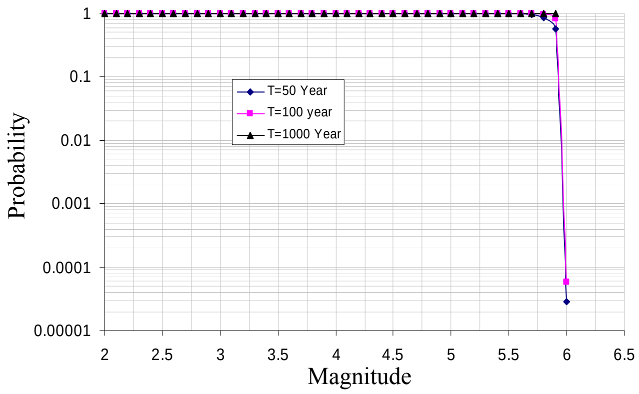

Figure 11: Probability of magnitude diagrams using Kijko and Sellevoll[14] method

Comparative Analyses

Table 3 compares the values of '*b*' obtained from the two methods presented in this paper[13, 14, 27]. In addition, the values of "*b*" reported by other researchers for south India by considering earthquake data stretched over different periods are also presented. It can be observed from the table 3 that "*b*" values obtained from both the analysis (G-R relation and Kijko and Sellevoll[13,14]) are quite comparable. The '*b*' value obtained in this study compared well with the previous studies of Kaila et al[11], Ramalingeswara Rao and Sitapathi Rao[19] and Jaiswal and Sinha[10] for southern India. Further it can be observed that "*b"* value reported in this paper is higher when compared to the earlier investigations. This higher value of "*b*" is attributed to the geological material heterogeneity and increased seismicity data in the study area. This clearly highlights that seismic activity of region is showing increasing trend when compared to the past.

Conclusion

The analysis of historical data of earthquakes around Bangalore has shown increased seismic activity in recent times. Seismic hazard "*b*" parameter was evaluated by using two methods. The frequency-magnitude relationship has been established for the study area after carrying out the completeness analysis. Completeness of the data has been observed for the last 4 decades for Bangalore region and '*b*' value of 0.89 is obtained using completed data and 0.87, 0.92 using incomplete data were obtained based on the procedure as proposed by Stepp[27]. The "*b*" value 0.87 ±0.03" was obtained based on the analysis of Kijko and Sellevoll[13,14], using mixed data set. The study shows that an increase in the value of 'b' parameter has been observed when compared to past.

Acknowledgement

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Table 1
Number of earthquakes reported in each decade since the beginning of the available historical records for Bangalore region

Time in	Number of earthquakes					
years	1<M<1.9	2<M<2.9	3<M<3.9	4<M<4.9	M>5	Total
1807-1816					2	2
1817-1826					4	4
1827-1836					2	2
1837-1846					1	1
1847-1856					1	1
1857-1866				10	5	15
1867-1876					2	2
1877-1886				2	1	3
1887-1896				4		4
1897-1906					1	1
1907-1916					1	1
1917-1926						0
1927-1936						0
1937-1946						0
1947-1956						0
1957-1966				4		4
1967-1976			1	17	4	22
1977-1986			443	104		547
1987-1996	13	380	341	64		798
1997-2006			4	4	2	10

Table 2
Earthquake distribution by time and magnitude for Bangalore region

Time period	Time Interval	1<M<1.9		2<M<2.9		3<M<3.9		4<M<4.9		M>5	
		N	N/T	N	N/T	N	N/T	N	N/T	N	N/T
1997-2006	10	0	0.00	0	0.00	4	0.40	4	0.40	2	0.20
1987-2006	20	13	0.65	380	19.00	345	17.25	68	3.40	2	0.10
1977-2006	30	13	0.43	380	12.67	788	26.27	172	5.73	2	0.07
1967-2006	40	13	0.33	380	9.50	789	19.73	189	4.73	6	0.15
1957-2006	50	13	0.26	380	7.60	789	15.78	193	3.86	6	0.12
1947-2006	60	13	0.22	380	6.33	789	13.15	193	3.22	6	0.10
1937-2006	70	13	0.19	380	5.43	789	11.27	193	2.76	6	0.09
1927-2006	80	13	0.16	380	4.75	789	9.86	193	2.41	6	0.08
1917-2006	90	13	0.14	380	4.22	789	8.77	193	2.14	6	0.07
1907-2006	100	13	0.13	380	3.80	789	7.89	193	1.93	7	0.07
1897-2006	110	13	0.12	380	3.45	789	7.17	193	1.75	8	0.07
1887-2006	120	13	0.11	380	3.17	789	6.58	197	1.64	8	0.07
1877-2006	130	13	0.10	380	2.92	789	6.07	199	1.53	9	0.07
1867-2006	140	13	0.09	380	2.71	789	5.64	199	1.42	11	0.08
1857-2006	150	13	0.09	380	2.53	789	5.26	209	1.39	16	0.11
1847-2006	160	13	0.08	380	2.38	789	4.93	209	1.31	17	0.11
1837-2006	170	13	0.08	380	2.24	789	4.64	209	1.23	18	0.11
1827-2006	180	13	0.07	380	2.11	789	4.38	209	1.16	20	0.11
1817-2006	190	13	0.07	380	2.00	789	4.15	209	1.10	24	0.13
1807-2006	200	13	0.065	380	1.90	789	3.95	209	1.05	26	0.13

Table 3
Values of ‘b’ compared with published literature

S. no	Authors	Year of publication	Value of ‘b’	Data analyzed for a period (years)
1	Avadh Ram and Rathor	1970	0.81	70
2	Kaila et al[11]	1972	0.7	14
3	Ramalingeswara Rao and Sitpathi Rao[19]	1984	0.85	170
4	Jaiswal and Sinha[10]	2006	0.84 to1.0	160
5	Present work (Bangalore region) G-R relation -completed data - Mw of 3.5 to 6.2 - Mw of 4.0 to 6.2 Kijko and Sellvoll method	 - - - -	 0.89 0.87 0.92 0.87±0.03	 40 200 200 200

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