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Probabilistic seismic hazard analysis for Bangalore

P. Anbazhagan · J. S. Vinod · T. G. Sitharam

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Abstract This article presents the results of probabilistic seismic hazard analysis (PSHA) for Bangalore, South India. Analyses have been carried out considering the seismotectonic parameters of the region covering a radius of 350 km keeping Bangalore as the center. Seismic hazard parameter '*b*' has been evaluated considering the available earthquake data using (1) Gutenberg–Richter (G–R) relationship and (2) Kijko and Sellevoll (1989, 1992) method utilizing extreme and complete catalogs. The '*b*' parameter was estimated to be 0.62 to 0.98 from G–R relation and 0.87 ± 0.03 from Kijko and Sellevoll method. The results obtained are a little higher than the '*b*' values published earlier for southern India. Further, probabilistic seismic hazard analysis for Bangalore region has been carried out considering six seismogenic sources. From the analysis, mean annual rate of exceedance and cumulative probability hazard curve for peak ground acceleration (PGA) and spectral acceleration (Sa) have been generated. The quantified hazard values in terms of the rock level peak ground acceleration (PGA) are mapped for 10% probability of exceedance in 50 years on a grid size of 0.5 km × 0.5 km. In addition, Uniform Hazard Response Spectrum (UHRS) at rock level is also developed for the 5% damping corresponding to 10% probability of exceedance in 50 years. The peak ground acceleration (PGA) value of 0.121 g obtained from the present investigation is slightly lower (but comparable) than the PGA values obtained from the deterministic seismic hazard analysis (DSHA) for the same area. However, the PGA value obtained in the current investigation is higher than PGA values reported in the global seismic hazard assessment program (GSHAP) maps of Bhatia et al. (1999) for the shield area.

Keywords Seismicity · '*b*' value · Probability · Seismic hazard analysis · Spectral acceleration and return period

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1 Introduction

The large earthquakes have caused massive loss of lives and extensive physical destruction throughout the world in the last three decades (Armenia, 1988; Iran, 1990; US, 1994; Japan, 1995; Turkey, 1999; Taiwan, 1999; India, 2001; Sumatra, 2004; Pakistan, 2005). In India, the devastating earthquakes of Assam (1950), Koyna (1967) Uttarakashi (1991), Killari (1993), Jabalpur (1997), Chamoli (1999), Bhuj (2001), Sumatra (2004), and Pakistan (2005) have caused extensive damages and losses. Seismic activity in India is clearly evident from these recent earthquakes and it is concentrated along the boundaries of Indo-Australian Plate and Eurasian Plate and also within the intra plate. Many researchers have addressed the intra plate earthquakes and seismicity of south India (Purnachandra Rao 1999; Ramalingeswara Rao 2000; Iyengar and RaghuKanth 2004). Many devastating earthquakes in recent times (Koyna, 1967; Killari, 1993, Jabalpur 1997; Bhuj 2001) have occurred in south India, a region that was predominantly considered as stable and aseismic shield region. It is very essential to estimate realistically the earthquake hazard associated with this shield region. The seismic hazard assessment can be quantified using either the deterministic or probabilistic seismic hazard analysis (PSHA) based on regional, geological, and seismological information. The seismic hazard analysis is used to estimate the strong ground motion parameters at a site for the purpose of earthquake resistant design. Sitharam et al. (2006) and Sitharam and Anbazhagan (2007) have presented the DSHA and have identified the seismogenic sources and maximum credible earthquake (MCE) for Bangalore in south India. The DSHA considers just one (or sometimes a few) maximum magnitude-distance scenario (Bommer and Abrahamson 2006), but the seismic hazard at a site is influenced by all the earthquakes with different magnitudes and distances. The widely used approach to estimate seismic-design loads for engineering projects is probabilistic seismic-hazard analysis (PSHA). The primary output from a PSHA is a hazard curve showing the variation of a selected ground-motion parameter, such as peak ground acceleration (PGA) or spectral acceleration (Sa), against the annual frequency of exceedance (or its reciprocal, return period). The design value is the ground-motion level that corresponds to a preselected design return period (Bommer and Abrahamson 2006). PSHA is able to reflect the actual hazard level due to earthquakes along with bigger and smaller events, which are also important in hazard estimation, due to their higher occurrence rates (Das et al. 2006). PSHA is able to correctly reflect the actual knowledge of seismicity (Orozova and Suhadolc 1999) and calculates the rate at which different levels of ground motion are exceeded at the site by considering the effects of all possible combinations of magnitude-distance scenarios. In the probabilistic approach, effects of all the earthquakes expected to occur at different locations during a specified life period are considered along with associated uncertainties and randomness of earthquake occurrences and attenuation of seismic waves with distance. Also PSHA produces uniform hazard spectrum (UHS), which is a convenient tool to compare the hazard representations of different sites (Trifunac 1990; Todorovska et al. 1995; Peruzza et al. 2000). Even though PSHA has many advantages, it has some limitations. The PSHA is not good for high hazard levels that are associated with small probabilities of exceedance that are generally defined for critical structures whose design often involves time-history analysis (Bommer et al. 2000). Other limitations rose by Klügel (2005, 2007a, b), Wang and Zhou (2007) can be overcome by properly accounting the variables, particularly ground-motion variability (Bommer and Abrahamson 2006; Klügel 2007a, b). Wang (2005) highlighted the three limitations of PSHA, i.e., (1) the physical meaning of the ground motion derived from PSHA is not easily explainable (2) the statistical characteristics of ground motion are lost in PSHA and (3) PSHA does not provide a unique choice for users and decision makers. In this study, to avoid procedural pitfalls raised by Wang (2005), a standard probabilistic procedure recommended by Cornell (1968) and McGuire (1976, 1978) is adopted and comparison is also done with similar studies by RaghuKant and Iyengar (2006). To overcome recurrence relation limitation resulting from incomplete data, the regional recurrence relation is arrived by considering historic, instrumented and total data using Gutenberg–Richter (G–R) relationship and mixed data using Kijko and Sellevoll (1989, 1992) method. In this study, one choice result of PGA has been presented considering total (mixed) data recurrence relation and 10% probability of exceedance in 50 years.

In this article, evaluation of seismic parameter '*b*' has been carried out using the seismic data over an area having a 350 km radius around Bangalore. Seismic parameter '*b*' has been evaluated from (1) G–R relationship (Gutenberg and Richter 1944) (2) Kijko and Sellevoll (1989, 1992) method utilizing extreme, instrumented and complete catalogs. The PSHA for Bangalore region has been carried out by considering six seismogenic sources identified in DSHA studies by Sitharam et al. (2006) and Sitharam and Anbazhagan (2007). The study area is divided into grid size of 0.5 km × 0.5 km, hazard parameters are estimated at center point of each grid using a newly developed MATLAB program. The hazard curves of mean annual rate of exceedance versus peak ground acceleration (PGA) and mean annual rate of exceedance versus spectral acceleration (Sa) are generated at the rock levels. The quantified hazard in terms of the rock level peak ground acceleration values are mapped 10% probability of exceedance in 50 years. These values correspond to return periods of nearly 475 years. In addition, Uniform Hazard Response Spectra (UHRS) for Bangalore city at rock level with natural periods of 1 s for 10% probability of exceedance in 50 years of exposure period have also been presented.

2 Probabilistic seismic hazard analysis

Probabilistic seismic hazard analysis is the most commonly used approach to evaluate the seismic design load for the important engineering projects. PSHA method was initially developed by Cornell (1968) and its computer form was developed by McGuire (1976, 1978) and Algermissen and Perkins (1976). McGuire developed EqRisk in the year 1976 and FRISK in the year 1978. Algermissen and Perkins (1976) developed RISK4a, presently called SeisRisk III. Site ground motions are estimated for selected values of the probability of ground motion exceedance in a design period of the structures or for selected values of annual frequency or return period for ground motion exceedance. The probabilistic approach offers a rational framework for risk management by taking account of the frequency or probability of exceedance of the ground motion against which a structure or facility is designed. The occurrence of earthquakes in a seismic source is assumed as the Poisson distribution. The probability distribution is defined in terms of the annual rate of exceeding the ground motion level z at the site under consideration ($v(z)$), due to all possible pairs (M, R) of the magnitude and epicentral distance of the earthquake event expected around the site, considering its random nature. The probability of ground motion parameter at a given site, Z, will exceed a specified level, z, during a specified time, T and it is represented by the expression:

$$P(Z > z) = 1 - \mathrm{e}^{-v(z)T} \leq v(z)T \tag{1}$$

where $v(z)$ is (mean annual rate of exceedance) the average frequency during time period T at which the level of ground motion parameters, Z, exceed level z at a given site. The function $v(z)$ incorporates the uncertainty in time, size and location of future earthquakes and uncertainty in the level of ground motion they produce at the site. It is given by:

$$v(z) = \sum_{n=1}^{N} N_n(m_0) \int_{m=m^0}^{m^u} f_n(m) \left[\int_{r=0}^{\infty} f_n(r \mid m) P(Z > z \mid m, r) \mathrm{d}r \right] \mathrm{d}m \tag{2}$$

where $N_n(m_0)$ is the frequency of earthquakes on seismic source n above a minimum magnitude m^0 that is taken as 4.0 in this work (magnitude less than 4 is considered to be insignificant). $f_n(m)$ is the probability density function for minimum magnitude of m^0 and maximum magnitude of m^u; $f_n(r \mid m)$ is the conditional probability density function for distance to earthquake rupture; $P(Z > z \mid m, r)$ is the probability that given a magnitude 'm' earthquake at a distance 'r' from the site, the ground motion exceeds level z. The integral in Eq. 2 is replaced by summation and the density function $f_n(m)$ and $f_n(r \mid m)$ are replaced by discrete mass functions. The resulting expression for $v(z)$ is given by:

$$v(z) = \sum_{n=1}^{N} \sum_{m_i=m^0}^{m_i=m^u} \lambda_n(m_i) \left[\sum_{r_j=r_{\min}}^{r_j=r_{\max}} P_n(R = r_j \mid m_i) P(Z > z \mid m_i, r_j) \right] \tag{3}$$

where $\lambda_n(m_i)$ is the frequency of events of magnitude m_i occurring on source n obtained by discretizing the earthquake recurrence relationship for source n. The estimation of uncertainty involved in magnitude, distance and peak ground acceleration are discussed respective sections.

3 Geology and seismotectonics of the region

Regional geology and seismotectonic details for Bangalore have been collected by carrying out extensive literature review, study of maps, and remote sensing data. Figure 1 shows the seismic study area selected for the present investigation along with Peninsular India (PI) geotectonic features. Seismic study area having a circular area of radius 350 km has been selected as per Regulatory Guide 1.165 (1997). The study area covers almost 35% of peninsular India including areas in Karnataka state, northern part of Tamil Nadu state, portion of Kerala state and Andhra Pradesh state, with in latitude 9.8° N to 16.2° N and longitude of 74.5° E to 80.7° E. Geological formation of the study area is considered as one of the oldest land masses of the earth's crust. Most of the study area is classified as Gneissic complex/Gneissic granulite with major inoculation of greenstone and allied supracrustal belt. The geology deposits close to the eastern and western side of the study area is coastline having the alluvial fill in the pericratonic rift. The major tectonic constituents in the southern India include the massive Deccan Volcanic Province (DVP), the South Indian Granulite Terrain (SIGT), the Dharwar craton (DC), the Cuddapah basin (CB), the Godavari graben (GG) and the Mahanadi graben (MG), the Eastern and the Western ghats on the east and west coast of India, respectively. The Eastern Ghat region in general is a quiet zone, characterized by diffused low-magnitude shallow focus earthquakes and an occasional earthquake of magnitude 5 to 6 (Mw). The reason for this fast movement of Indian plate is attributed to lower crustal thickness as reported by Kumar et al. (2007).

The Indian shield region is marked by several rift zones and shear/thrust zones. Although this region is considered to be a stable continental region, this region has experienced many earthquakes of magnitude of 6.0 since the eighteenth century and some of which were disastrous (Ramalingeswara Rao 2000). Among them are the

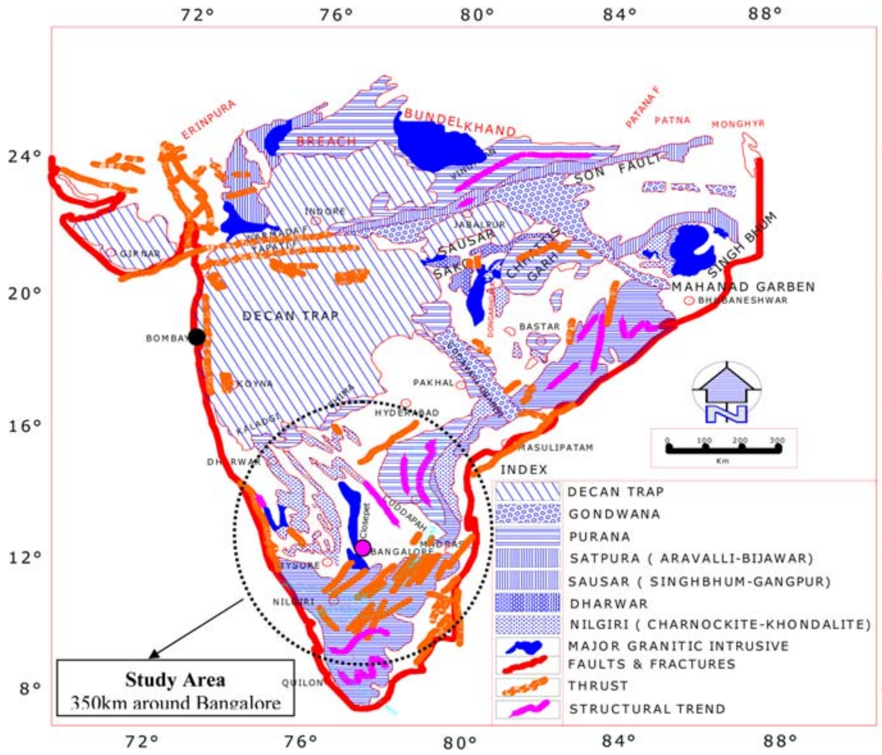


Fig. 1 Study area in Peninsular India along with geotectonic features

Mahabaleshwar (1764), Kutch (1819), Damooh hill (Near Jabalpur, 1846), Mount Abu (1848), Coimbatore (1900), Son-Valley (1927), Satpura (1938), Koyna (1967), Latur (1993), and Jabalpur earthquake (1997). Nath (2006) highlighted that the most common cause for the Indian shield appears to be the compressive stress field in the Indian shield oriented NNE-SSW on an average as a consequence of the relentless India-Eurasia plate collision forces. Sridevi (2004) highlighted that southern peninsular India moves as a rigid plate with about 20-mm/year velocity in the NNE direction (using Global positioning system measurement at Indian Institute of Science, Bangalore).

In general, for the evaluation of seismic hazards for a particular site or region, all possible sources of seismic activity must be identified and their potential for generating future strong ground motion should be evaluated. The seismic sources are broadly classified as point source, line source, and area sources. The seismic sources for this study were identified as line sources and mapped using geological, deep geophysical, and remote sensing studies. The well-defined and documented seismic sources are published in the Seismotectonic Atlas-2000 published by Geological Survey of India (SEISAT 2000). Geological survey of India has compiled all the available geological, geophysical and seismological data for entire India and has published a seismotectonic map in the year 2000. Seismotectonic atlas contains 43 maps in 42 sheets of 3° × 4° sizes with scale of 1:1 million, which also describes the tectonic framework and seismicity. This has been prepared with the intention that it can be used for the seismic hazard analysis of Indian cities. Ganesha Raj and Nijagunappa (2004) have also mapped major lineaments for Karnataka state with lengths more than 100 km using satellite remote sensing data and correlated with the earthquake occurrences. They have highlighted that there are 43 major lineaments and 33 earthquake occurrences with magnitude above 3 (since 1828) in the study area. About 23 of these earthquakes were associated with 8 major lineaments, which they have named as active lineaments. Both the data are used to generate new seismotectonic map of the Bangalore region (Sitharam et al. 2006; Sitharam and Anbazhagan 2007).

These sources matches well with major seismic sources considered by Bhatia et al. (1999) for global seismic hazard assessment program (GSHAP). The preferred fault plane solutions for the region generally indicate northeast southwest orientation with left-lateral strike slip motion. Alternate set of solution indicated in region is the thrust faulting along northwest orientation. GSHAP has delineated sources 70, 71 and 74 based on localized concentration of seismicity, along the Eastern Ghat region. The seismic source 72 is delineated to account some recent concentrated seismic activity in down south, near Trivandrum (Kerala state) along the western margin. It appears that this region has also been active in the historical times. In addition, the region around Latur is numbered as a seismic source zone 76. The source 69 covers the Godavari Graben region which had experienced a moderate sized earthquake of Magnitude 5.3 (known as Bhadrachalam earthquake), in the year 1969. The region around Bellary and Coimbatore have been demarcated as source zones 75 and 73 respectively on account of having experienced moderate sized earthquakes in the past (Bhatia et al. 1999).

4 Seismicity of the region

Seismicity of India and Peninsular India has been addressed by many researchers in particular Kaila et al. (1972), Chandra (1977), Ramalingeswara Rao and Sitapathi Rao (1984), Tandon (1992), Khattri (1992), Parvez et al. (2003), Bilham (2004) and Iyengar and RaghuKanth (2004). As per IS 1893 (BIS 2002), seismic study area falls in the upgraded zones II and III in the seismic zonation map of India. Srinivasan and Sreenivas (1977), Valdiya (1998), Purnachandra Rao (1999), Ramalingeswara Rao (2000), Subrahmanya (1996, 2002), Ganesha Raj (2001), Sridevi Jade (2004), Ganesha Raj and Nijagunappa (2004), Sitharam et al. (2006) and Sitharam and Anbazhagan (2007) highlight that seismic activity in the peninsular India has increased when compared to the past. Reddy (2003) highlighted that the south Indian seismicity is neither understood properly nor given importance since it is of micro-dimensions. There are no notable detailed probabilistic hazard studies carried out in southern India except Mumbai region. The first seismic hazard map available for southern India is BIS 1893, it was revised many times but seismic status of southern India is not classified in smaller scale. Recent publication BIS 1893–2002 shows that many part of the southern India is upgraded from existing zones I, II, and III to II, III and IV. Parvez et al. (2003) carried out the deterministic seismic hazard of India and adjacent areas using an input dataset of structural models, seismogenic zones, focal mechanisms and earthquake catalogues. The author generated synthetic seismograms at a frequency of 1 Hz at a regular grid of $0.2^\circ \times 0.2^\circ$ by the modal summation technique. They expressed seismic hazard in terms of maximum displacement (Dmax), maximum velocity (Vmax), and design ground acceleration (DGA) using extracted synthetic signals and mapped on a regular grid. They highlighted that the DGA estimates in Peninsular India are less than 0.15 g, and only in the Latur region DGA values close to this upper limit. The PSHA is carried out by Ravi Kumar and Bhatia (1999) for the global seismic hazard assessment programme in 1999. They considered 86 potential seismic source zones which are delineated based on the major tectonic features and seismicity trends. For South India, smaller seismic zones were delineated based on the locales of the major earthquakes and seismic lineaments, some of which are not so well defined. Using FRISK88M software, the Peak Ground Accelerations (PGA) estimated for 10% probability of exceedance in 50 years, at locations defined by a grid of 0.5° × 0.5°. At that time no reliable attenuation values are available for the Indian region, attenuation relation developed by Joyner and Boore (1981) was used. From the above it is clear that, detailed seismic hazard analysis is not carried out for south India by considering updated/available seismotectonic data. It is very much essential to study the seismic hazard at regional level to reveal regional hazard by considering updated seismotectonic information. For this purpose seismic data are collected from various agencies [United State Geological Survey (USGS), Indian Metrological Department (IMD), Geological Survey of India (GSI) and Amateur Seismic Centre (ASC) and Gauribidanur (GB) Seismic station], which contain information about the earthquake size in different scales such as intensity, local magnitude, surface wave magnitude and body wave magnitudes. These magnitudes are converted to moment magnitudes (Mw) to have a uniform magnitude by using magnitude relations given by Heaton et al. (1986). List of selected earthquake was presented in Sitharam and Anbazhagan (2007). A declustering algorithm was used to remove the dependent events from this catalogue. The declustering have been done by considering a criterion based on uniform time (>30 days) and space (>30 km) window between successive events. The earthquake events collated are about 1,421 with minimum moment magnitude of 1.0 and a maximum of 6.2. The dataset contains 394 events which are less than 3, 790 events from 3 to 3.9, 212 events from 4 to 4.9, 22 events from 5 to 5.9 and 3 events having magnitude 6 and above. The earthquake events collected (with latitudes and longitudes) are used to prepare the seismotectonic map for Bangalore region. Figure 2 shows the study area along with the earthquake data and the six seismogenic sources considered for PSHA. There are cluster of earthquakes of moment magnitude (Mw) of 2–2.9 found at intersection of 10.8° N and 76.9° E, 12.5° N and 76.5° E, 13.0° N and 76.5° E, 14.3° N and 78.0° E and 14.5° N and 78.6° E. Mw of 3–3.9 at more frequently occurred at intersection of 15.1° N and 76.8° E, Mw of 4–4.9 distributed throughout the study area and clustered at two locations (13.2° N and 75.1° E and 15.1° N and 76.6° E). The range of 5–5.9 events are randomly distributed in the study area and reported close to the study area. Magnitude 6 and above (3 events) are reported around Coimbatore and Bellary within the study area.

5 Seismic hazard parameter ‘*b*’

A simple and most widely used method to estimate the seismic hazard parameter ‘*b*’ is the Gutenberg–Richter (1944) recurrence law. It assumes an exponential distribution of magnitude and is generally expressed as:

$$\mathrm{Log}(N) = a - bM \tag{4}$$

For a certain range and time interval, Eq. 4 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 of events with $M = 0$) and ‘b’ which is typically close to 1 is a tectonics parameter describing the relative abundance of large to smaller shocks. The number of earthquakes per decade was divided in to five magnitude ranges, such as $2 = M < 3; 3 = M < 4; 4 = M < 5; M \geq 5$. Table 1 describes the number of earthquakes reported in each decade since the beginning of the available historical record. Figure 3 shows the histogram representing the data listed in Table 1 for the whole catalogue from

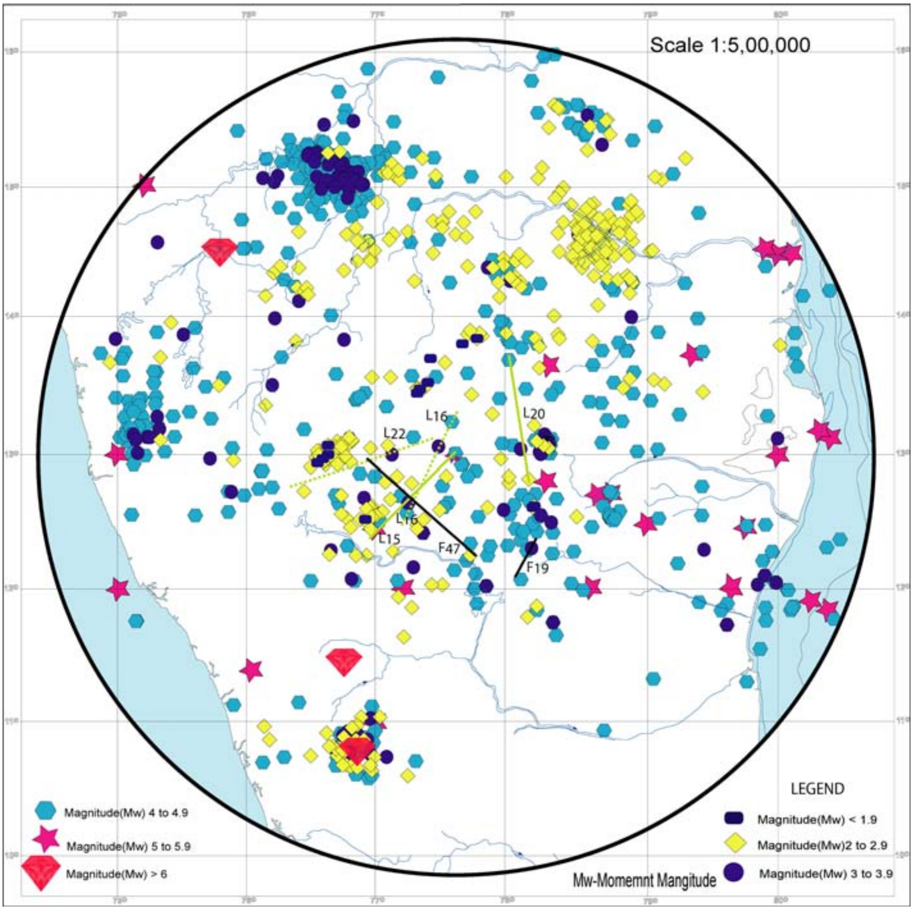


Fig. 2 Earthquake events distribution map with the most seismogenic sources in the study area (within a radius of 350 km)

1807 to 2006. The whole catalog shows that for the period 1807–1976 the data is poor may be due to lack of observations. However, it can be observed that moment magnitude greater than 3.5 is reported in this period. From 1976 to 1996, better recording of the data can be observed. The dataset has been divided into two, one historic data (1807–1960) and another is instrumented data (after 1960 to present) to develop the Gutenberg–Richter (1944) recurrence relation. Three recurrence relations have been developed: first one based on the historic data, second one based on the instrumented data and third one based on the total data. Figure 4 presents the time history of historic data with 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 which is as follows:

$$\log(N) = 2.14 - 0.62M \tag{5}$$

From the above equation a seismic hazard parameter "a" is 2.14 and 'b' is 0.62 with a correlation coefficient of 0.95 was obtained. This recurrence relation included only major

Table 1 Number of earthquakes reported in each decade for Bangalore region

From	To	$1 < M < 1.9$	$2 < M < 2.9$	$3 < M < 3.9$	$4 < M < 4.9$	>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	105	0	548
1987	1996	13	381	342	65		801
1997	2006			4	4	2	10
Total		13	381	790	211	26	1,421

earthquakes in the historic times and does not include micro seismic data of less than Mw of 4.2. Hence, G–R relation is also developed by considering instrumented data after 1960. Figure 5 presents the time history of instrumented data with corresponding frequency magnitude distribution plot, which is as follows:

$$\log(N) = 4.56 - 0.98M \tag{6}$$

The instrumented data has maximum reported magnitude of 5.5 and a correlation coefficient of 0.94. This relation does not include the major historic magnitude reported in the study area. Figure 6 presents the time history of historic and instrumented (total) data with corresponding frequency magnitude distribution plot which is as follows:

$$\log(N) = 3.52 - 0.86M \tag{7}$$

This recurrence relation includes all the data of micro to major earthquakes in the region. The total dataset has a high correlation coefficient of 0.97. From the above three equations, seismic parameter 'b' value of the region varies from 0.62 to 0.98.

Further seismic hazard parameters were also evaluated using all the earthquake dataset, which is also termed as mixed dataset. Kijko and Sellevoll (1989, 1992) have presented a versatile statistical method based on the maximum likelihood estimation of earthquake hazard parameters for the mixed dataset. Analysis was carried out using the computer program of Kijko and Sellevoll (HN2, Release 2.10, 2005). A threshold magnitude value of 3.0 and standard deviation value of 0.2 is used in the analysis. From the maximum likelihood solution, $M_{\max} = 6 \pm 0.5$ and 'b' value 0.87 ± 0.03 were obtained. From the

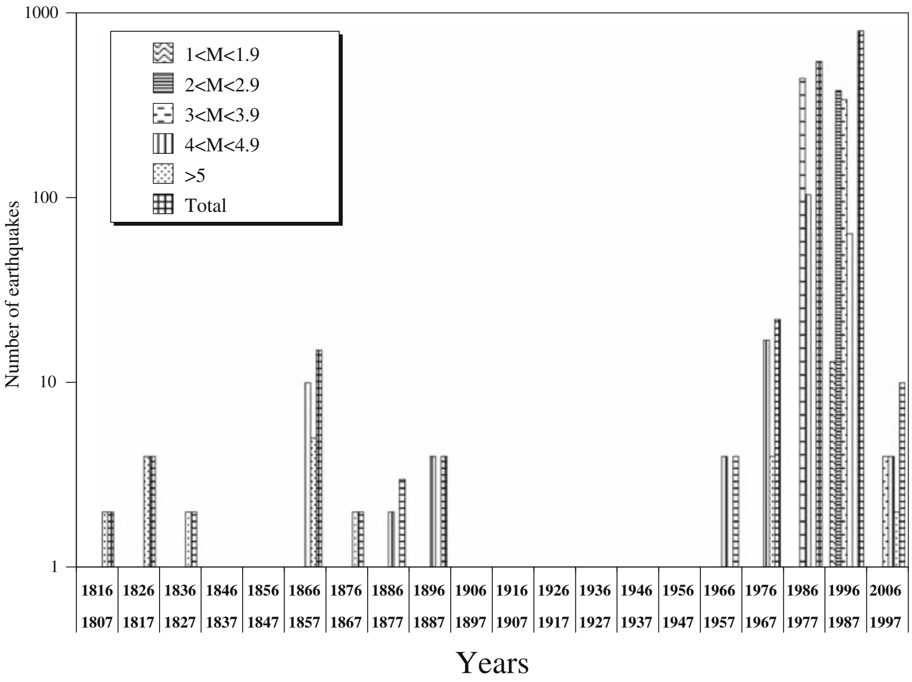


Fig. 3 Histogram of earthquake data in the study area

analysis it was observed that, seismic parameter for the region with a ‘*b*’ value of 0.87 ± 0.03, which matches well with the ‘*b*’ estimated using Gutenberg–Richter relation. The ‘*b*’ value obtained in this study matches well with the previous studies of Ram and Rathor (1970), Kaila et al. (1972), Ramalingeswara Rao and Sitapathi Rao (1984) and Jaiswal and Sinha (2006) for southern India. Table 2 presents the ‘*b*’ value presented by different authors for southern India along with the values obtained in the present study.

6 Seismogenic sources

Sitharam et al. (2006) and Sitharam and Anbazhagan (2007) have presented the deterministic seismic hazard analysis for Bangalore considering 48 possible sources within a circular area having a radius of 350 km. A DSHA has been carried out considering 48 seismic sources in the study area having earthquake events with moment magnitude of 3.5 and above. Two methods have been adopted to calculate Peak Ground Acceleration (PGA). PGA was calculated using maximum past earthquake close to each source using a regional attenuation relation. The attenuation relation developed by Iyengar and RaghuKanth (2004) for south India has been used. In the second method, PGA was estimated using expected magnitude (arrived based on subsurface fault rupture length) and the regional attenuation relation. The authors highlight that among 48 seismic sources, about 8 sources gave PGA values of 0.035 g and above. These seismogenic sources are selected for the study. DSHA considered these 8 seismogenic sources and the expected synthetic ground motion at rock level have been generated. Among the 8

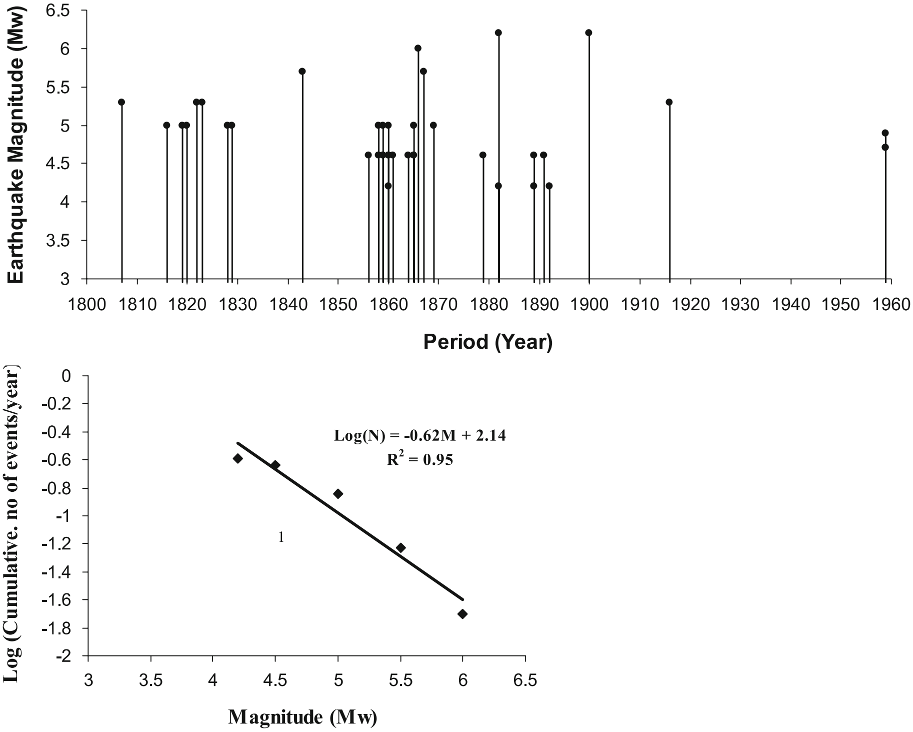


Fig. 4 The time history of historic data with corresponding frequency magnitude distribution plot

sources, Subramanya–Byadagi Gadag lineament and Holalkere–Herur lineament are far away from Bangalore (more than 150 km and also moment magnitude of more than 4 are very few on these two lineaments), hence the remaining 6 sources are considered for the PSHA. The details of 6 sources with reported number of earthquake data close to each source are shown in Table 3. In Table 3, the shortest and longest distance from Bangalore city is presented. These distances are used to calculate the hypocentral distances by assuming a focal depth of 15 km for all the sources (Sitharam and Anbazhagan 2007). The source recurrence relation weighting factors along with hypocentral distances for all the six selected sources are listed in Table 4. The seismogenic sources considered for the PSHA for Bangalore are shown in Fig. 2 along with past earthquakes.

7 Regional recurrence model

The magnitude recurrence model for a seismic source specifies the frequency of seismic events of various sizes per year. For hazard calculation, Eq. 7 determined using Gutenberg–Richter (G–R) magnitude-frequency relationship has been used. The recurrence relation of each fault capable of producing earthquake magnitude in the range m^0 to m^u is calculated using the truncated exponential recurrence model developed by Cornell and Van Mark (1969), and it is given by the following expression:

$$N(m) = N_i(m_0)\frac{\beta e^{-\beta(m-m^0)}}{1-e^{-\beta(m^u-m^0)}} \quad for\ m^0 \le m < m^u \tag{8}$$

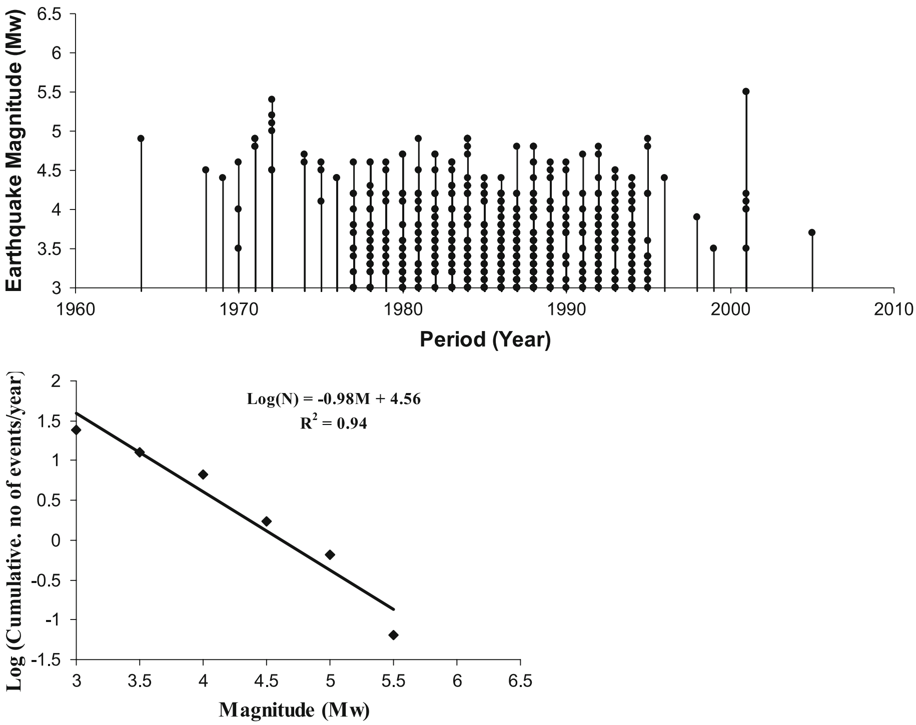


Fig. 5 The time history of instrumented data with corresponding frequency magnitude distribution plot

where $\beta = b \ln(10)$ and $N_i(m_0)$ proposed weightage factor for particular source based on the deaggregation.

7.1 Deaggregation

The recurrence relation (Eq. 7) developed for the study area represents the entire region and it is not for the specific source. Each source recurrence is necessary to discriminate near by sources from far-off sources and to differentiate activity rate for the different sources. Such seismic source recurrence relation is rarely known due to paucity of large amount of data accruing in historical times. An alternative is to empirically calculate the '*b*' value from known measured slip rate of each seismic source. For the sources under consideration, no such slip rate measurements are reported. Moreover, Peninsular India (PI) earthquakes are associated with poor surface expressions of faults and hence reliable estimation of slip rates has not been yet possible (Rajendran and Rajendran 1999; RaghuKanth and Iyengar 2006). Hence, it is necessary to proceed on a heuristic basis invoking the principle of conservation of seismic activity. According to this, the regional seismicity measured in terms of the number of earthquakes per year with $m \geq m^0$, should be equal to the sum of such events occurring on individual source. Deaggregation procedure followed by Iyengar and Ghosh (2004); RaghuKanth and Iyengar (2006) for PSHA of Delhi and Mumbai (in south India) have been used here to find the weightage factor for each source based on the length (α) and number of earthquakes (χ) for the corresponding source. The length weighting factor for the source i have been arrived from $\alpha_i = L_i / \sum L_i$

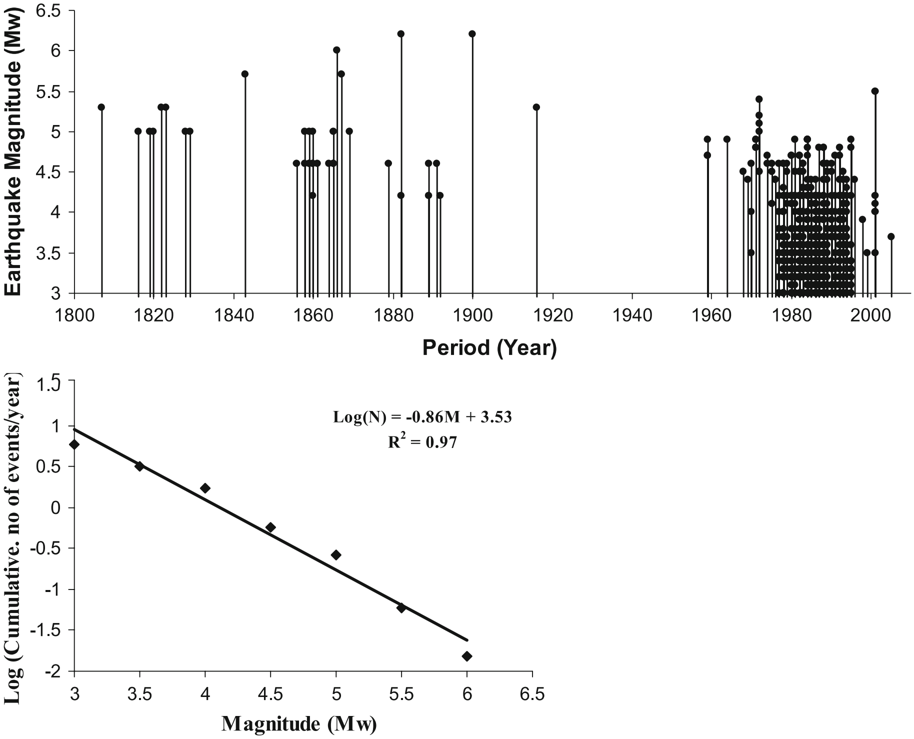


Fig. 6 The time history of historic and instrumented (total) data with corresponding frequency magnitude distribution plot

Table 2 Values of '*b*' compared with published literature

Sl no	Authors	Value of '*b*'	Data analyzed for a period (years)
1	Avadh Ram and Rathor (1970)	0.81	70
2	Kaila et al. (1972)	0.7	14
3	Ramalingeswara Rao and Sitpathi Rao (1984)	0.85	170
4	Jaiswal and Sinha (2006)	0.84–1.0	160
5	Present work (Bangalore region) G–R relation—historic data	0.62	153
	Instrumented/completed data	0.98	47
	Total data	0.86	200
	Kijko and Sellvoll method	0.87 ± 0.03	200

and earthquake event weighting factor (χ_i) has been taken as the ratio of the past events associated with source i to the total number of events in the region as given below:

$$\chi_i = \frac{\text{Number of earthquakes close to the source}}{\text{Total number of earthquakes in the region}} \tag{9}$$

Table 3 Seismogenic sources considered for the PSHA

Number and name of source		Maximum magnitude (Mw)	Length (km)	Shorter distance (km)	Longer distance (km)	No of EQ close to source	No of EQ > Mw 5 close to source
F19	Mettur East Fault	4.6	38	97	116	15	–
F47	Arkavati Fault	4.7	125	51	88	20	–
L15	Mandya-Channapatna-Bangalore	5.1	105	5.2	104	25	2
L16	Arakavathi-Doddaballapur	5.2	109	18	77	12	2
L20	Chelur-Kolar-Battipalle	5.2	111	58	104	50	2
L22	Nelamangala-Shravanabelagula	5.3	130	26	150	14	1

Table 4 Source recurrence relation weighting factors

Number and name of source		Hypocentral distance (km)		Length (km)	No EQ close to source	Weighting factor		
		Min	Max			α_s	β_s	Average
F19	Mettur East Fault	98	117	38	15	0.061	0.011	0.036
F47	Arkavati Fault	53	89	125	20	0.202	0.015	0.108
L15	Mandya-Channapatna-Bangalore	16	105	105	25	0.170	0.018	0.094
L16	Arakavathi-Doddaballapur	24	78	109	12	0.176	0.009	0.093
L20	Chelur-Kolar-Battipalle	60	105	111	50	0.180	0.037	0.108
L22	Nelamangala-Shravanabelagula	30	151	130	14	0.210	0.010	0.110

The recurrence relation of source *i* have been arrived by averaging both weighting and multiplying the regional recurrence relation as given below:

$$N_i(m_0) = 0.5(\alpha_i + \chi_i)N(m_0) \tag{10}$$

The weightage factors calculated for each source have considered the source length and number of events, which are shown in Table 4. Finally, the probability density function (PDF) for each source has been evaluated. Typical plot of PDF versus magnitude is shown in Fig. 7.

7.2 Uncertainty in the hypocentral distance

In the PSHA, other uncertainty involved is the distance of each source to the site. Seismogenic sources are considered as line sources. For each seismogenic source, each point/segment of the source can rupture and generate an earthquake. Thus, the relative orientation of each source with respect to Bangalore becomes important. The shortest and longest distance from each source to city center has been evaluated from Bangalore seismotectonic map presented by Sitharam and Anbazhagan (2007) considering all the sources as line sources. The hypocentral distance has been evaluated by considering focal depth of 15 km from the ground similar to the one used for DSHA in Sitharam et al. (2006) and Sitharam and Anbazhagan (2007). Shortest and longest hypocentral distances are presented in Table 3. The probability distribution for the hypocenter distances, from any

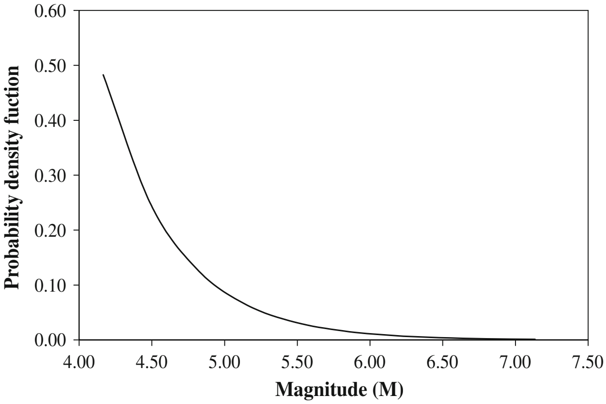


Fig. 7 Probability density functions of magnitude for L15

site to the earthquake rupture on the source, is computed conditionally for the earthquake magnitude. Generally, the rupture length is a function of the magnitude. The conditional probability distribution function of the hypocentral distance *R*, for an earthquake magnitude $M = m$ for a ruptured segment, is assumed to be uniformly distributed along a fault and is given by Kiureghian and Ang (1977),which is as follows:

$$P(R < r \,|\, M = m) = 0 \quad \text{for } R < (D^2 + L_0^2)^{1/2} \tag{11}$$

$$P(R < r \,|\, M = m) = \frac{(r^2 - d^2)^{1/2} - L_0}{L - X(m)} \quad \text{for } (D^2 + L_0^2) \le R < \left\{D^2 + [L + L_0 - X(m)]^2\right\}^{1/2} \tag{12}$$

$$P(R < r \,|\, M = m) = 1 \quad \text{for } R > \left\{D^2 + [L + L_0 - X(m)]^2\right\}^{1/2} \tag{13}$$

where $X(m)$ is the rupture length in kilometers for the event of magnitude *m* is estimated using the Wells and Coppersmith (1994) equation, which is as given below:

$$X(m) = \min\left[10^{(-2.44+0.59(m_i))}, L_f\right] \tag{14}$$

where L_f is the total fault length. The notations used in the equations 11, 12 and 13 are explained in Fig. 8 considering the source as a line source. Typical probability density function of the hypocentral distance for Mandya-Channapatna-Bangalore lineament (L15) is shown in Fig. 9.

7.3 Ground motion attenuation

Among the critical elements required in seismic hazard analysis, the attenuation relation of peak ground (PGA) and spectral acceleration (Sa) are very important. The ground motion attenuation relation gives the variation of peak ground acceleration at specific structural periods of vibration and damping ratios with earthquake magnitudes and the source-to-site distance. Strong ground motions depend on the characteristics of the earthquake source, the crustal wave propagation path, and the local site geology. Typically, attenuation relations are developed for specific tectonic environments. As the study area is located in peninsular India, the attenuation relation (for peak ground acceleration and spectral acceleration) for

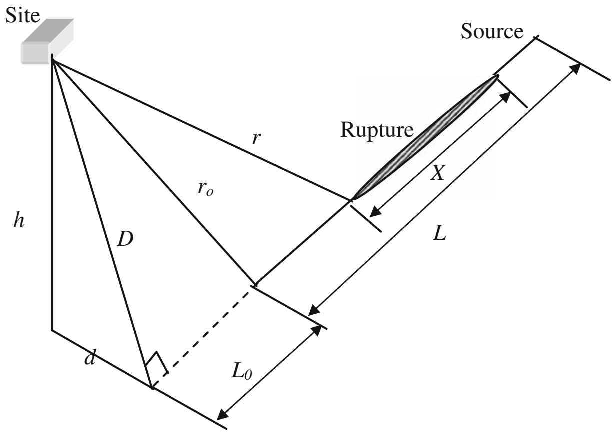
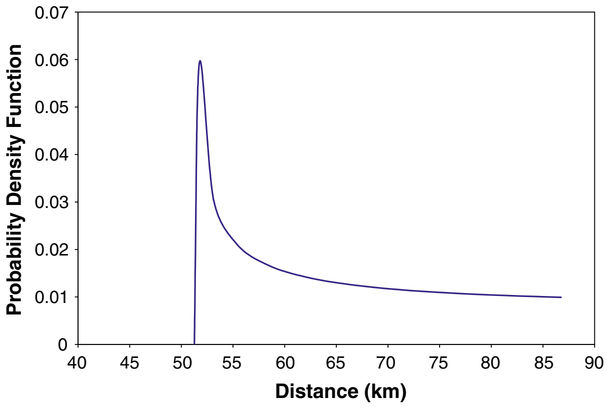


Fig. 8 Schematic representation of fault rupture model

Fig. 9 Typical PDF for the source L15



rock site in Peninsular India developed by RaghuKanth (2005) has been used in the present investigation:

$$\ln y = c_1 + c_2(M - 6) + c_3(M - 6)^2 - \ln R - c_4 R + \ln(\in) \qquad (15)$$

where y, M, R and $\in$ refer to PGA/spectral acceleration (g), moment magnitude, hypocentral distance, and error associated with the regression, respectively. The coefficients in Eq. 15, c_1, c_2, $c_{3,}$ and c_4 are obtained from RaghuKanth (2005) and RaghuKanth and Iyengar (2006). In hazard analysis the ground motion parameters are estimated from the predictive ground motion relation (Eq. 15) in terms of PGA and spectral acceleration. These attenuation relations are obtained from regression, which is associated with the randomness of predictive equations. Uncertainty involved in these equations can be accounted by calculating the probability of exceedance of a particular value by the attenuation equation. The normal cumulative distribution function has a value which is most efficiently expressed in terms of the standard normal variables (z) which can be computed for any random variables using transformation as given below (Kramer 1996):

$$z = \frac{\ln\ \mathrm{PGA} - \overline{\ln\ \mathrm{PGA}}}{\sigma_{\ln\ \mathrm{PGA}}} \tag{16}$$

where ln PGA is the various targeted peak acceleration levels that will be exceeded, $\overline{\ln\ \mathrm{PGA}}$ is the acceleration calculated using attenuation relationship and $\sigma_{\ln\ \mathrm{PGA}}$ is the uncertainty in the attenuation relation expressed by the standard deviation.

8 Results and discussions

The summation of all the probabilities is termed as hazard curve, which is plotted as mean annual rate of exceedance (and its reciprocal is defined as the return period) versus the corresponding ground motion. The mean annual rate of exceedance has been calculated for six seismogenic sources separately and summation of these representing the cumulative hazard curve. Analyses have been carried out using a MATLAB program that has been developed for this purpose. The hazard curves and UHRS 10% probability exceedance in 50 years are calculated for about 1,400 grid points.The mean annual rate of exceedance versus peak ground acceleration for all the sources at rock level is shown in Fig. 10 for typical grid point. This clearly highlights that the sources close to Bangalore produce more hazard when compared to the source far away from Bangalore. The results obtained from this study have been compared with seismic hazard estimation of Mumbai by RaghuKanth and Iyengar (2006). In the absence of good seismicity data (based on poor available data and short duration database) a simple approach, using deaggregation factors similar to what has been adopted in this article based on the fault and seismic activity gives a reasonable estimate of earthquake hazard. Average weights have been used for the analysis presented by RaghuKanth and Iyengar (2006) for Mumbai. City of Mumbai is also located in southern India (see Fig. 1) with similar seismotectonic background. Twenty three known faults that exist around the city has been considered for the study. The seismic hazard in Mumbai is considered to be less severe than the Himalayan inter plate boundary region. The return periods corresponding to PGA at rock level for Mumbai and Bangalore are presented in the Table 5. The return period for Bangalore is very large when compared to Mumbai. Further to define the seismic hazard at rock level for the study area, PGA at each grind point has been estimated. These values are used to prepare PGA distribution maps for 10% probability exceedance in 50 years, which corresponds to return periods of 475 years. Rock level PGA distribution map for Bangalore is shown in Fig. 11, PGA values varies from 0.17 to 0.25 g. Figure 11 shows that the maximum PGA value of 0.25 g on the western side of study area, decreasing toward eastern side and reaches minimum PGA value of about 0.17 g. This may be attributed to the seismogenic sources location and their orientations. Eastern side has only two sources and the western side has four sources (see Fig. 2). These values are comparable with the PGA map at rock level published by Sitharam et al. (2006) using deterministic approach. However, the PGA values presented in this study are slightly higher because Sitharam et al. (2006) used zero standard deviation (σ) for median hazard values. In this analysis ground-motion variability are included in PSHA calculations, addition of ground-motion variability to PSHA increasing the PGA values (Bommer and Abrahamson 2006). Even though PGA is used to characterize the ground motion, the spectral acceleration is generally used for design of engineering structures. Similar to the mean annual rate of exceedance calculation for PGA, the spectral acceleration at period of 1 s and 5% damping are also evaluated for all the sources.

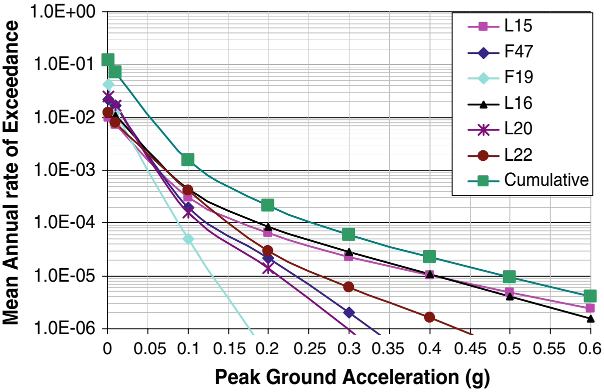


Fig. 10 Hazard curves for different sources at the rock level for Bangalore

Table 5 Return periods for different peak ground acceleration at bed rock level for Mumbai and Bangalore

PGA (g)	Return period (years)	
	Mumbai[a]	Bangalore
0.05	110	76
0.10	606	666
0.20	3,225	4,672
0.30	11,337	16,666
0.40	30,959	44,444

[a] Data from RaghuKanth and Iyengar (2006)

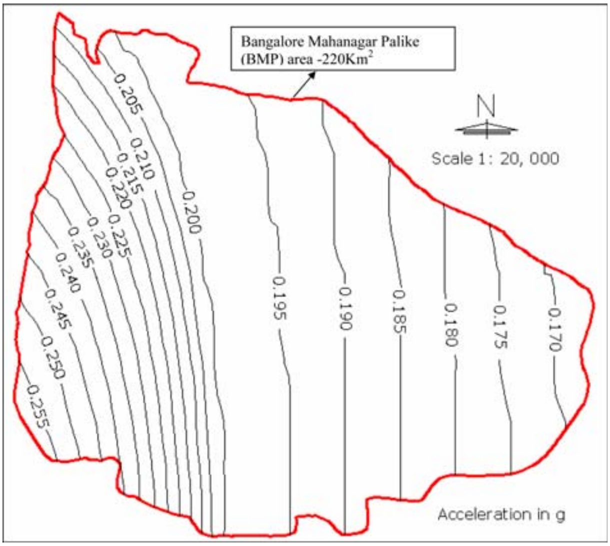


Fig. 11 Peak ground acceleration contours at rock level with 10% probability of exceedance in 50 years

Cumulative mean annual rate of exceedance versus spectral acceleration for period of 1 s and 5% damping (represented as hazard curve) is shown in Fig. 12. For the design of structures, a uniform hazard response spectrum (UHRS)/equivalent hazard spectrum is

Fig. 12 Spectral acceleration at the rock level corresponding to a period of 1 s and 5% damping for Bangalore

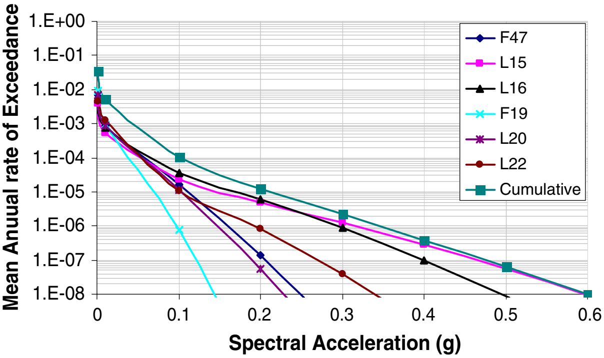
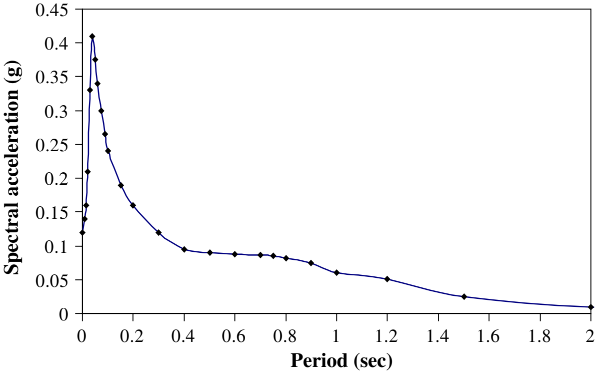


Fig. 13 Uniform Hazard Response Spectrum at rock level with 10% probability of exceedance in 50 years (5% damping) for Bangalore



used. UHRS is developed from a probabilistic ground motion analysis that has an equal probability of being exceeded at each period of vibration. For finding the UHRS, seismic hazard curves of spectral acceleration (Sa) are computed for the range of frequencies. From these hazard curves, response spectra for a specified probability of exceedance over the entire frequency range of interest are evaluated. Figure 13 shows the UHRS (with damping of 5%) at bed rock level for 10% probability of exceedance in 50 years. The shape of the spectrum is similar to the one of Mumbai city developed by RaghuKanth and Iyengar (2006). The zero-period median spectral acceleration (ZPA = PGA) evaluated in this study (0.121 g) is comparable with the value obtained in deterministic approach (0.136) by Sitharam et al. (2006) and Sitharam and Anbazhagan (2007). Generally PSHA predicts a lower PGA value than that is obtained from DSHA. This clearly brings out that the probabilistic method is inclusive of all the deterministic events with a finite probability of occurrence and both these methods complement each other to provide additional insights to the seismic hazard analysis. Also the reported PGA values are quite higher than the GSHAP study for India (which considers the focal depth of 10 km). From this study, PGA at bed rock level for the focal depth of 15 km is much higher than PGA obtained in GSHAP. If the focal depth of 10 km is considered, hazard values will be much higher. The lesser PGA resulting from GSHAP study may be due to (i) the study was carried out on a macro scale, (ii) attenuation relation (Joyner and Boore 1981) used in that study was proposed for else where and (iii) few seismic zones (source) based on the locales of the major earthquakes were used. GSHAP sources are described based on concentration of seismicity but in this study seismic sources are based on fault and lineament mapping.

In spite of other limitations in the above approach, this is the first seismic hazard study in southern India using PSHA till date. The limitations of this study are: (1) consideration of short duration incomplete database and hence the seismic character of the region would not be represented accurately; (2) The '*b*' value used in this study is based on available data, if the reliable slip rate of source is available, it may result in different '*b*' value, as now such information is not available for the region.

9 Conclusions

The article presents the estimation of seismic hazard parameter '*b*' and the PSHA for Bangalore. Seismic parameter is evaluated using the seismic data collected over a radius of 350 km around Bangalore city. The seismic hazard parameter '*b*' value was estimated to be 0.62–0.98 from G–R relationship considering historic, instrumented and total data and 0.87 ± 0.03 from Kijko and Sellevoll (1989, 1992) method using mixed data. Further, the PSHA for Bangalore city has been carried out using the regional recurrence relation of $\log(N) = 3.53 - 0.86M$ with appropriate deaggregation weighting factors for six seismogenic sources. The curves of the mean annual rate of exceedance for peak ground acceleration and spectral acceleration have also been generated at rock level. The hazard values are estimated using developed MATLAB program by dividing the study area in to 1400 grid point having size of 0.5 km × 0.5 km. The rock level PGA map for 10% probability of exceedance in 50 years corresponding to the return period of 475 years has been presented. Further, the uniform hazard response spectrum at rock level with 5% damping for Bangalore has been generated for 10% probability of exceedance in 50 years. The shape of response spectrum developed in this study is similar to the one presented by other researchers for the sites in southern India. The peak ground acceleration (PGA) value of 0.121 g obtained from the present investigation is comparable to PGA values obtained from deterministic seismic hazard analysis (DSHA) for the same area by Sitharam et al. (2006) and Sitharam and Anbazhagan (2007). However, the PGA value obtained from the current investigation is higher than GSHAP maps of Bhatia et al. (1999) for the shield area. The study brings that the probabilistic and deterministic approaches will lead to similar answers complementing each other and provides additional insights to the seismic hazard assessment.

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