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Evaluation of spatial variation of peak horizontal acceleration and spectral acceleration for south India: a probabilistic approach

T. G. Sitharam · K. S. Vipin

Abstract In this work, an attempt has been made to evaluate the spatial variation of peak horizontal acceleration (PHA) and spectral acceleration (SA) values at rock level for south India based on the probabilistic seismic hazard analysis (PSHA). These values were estimated by considering the uncertainties involved in magnitude, hypocentral distance and attenuation of seismic waves. Different models were used for the hazard evaluation, and they were combined together using a logic tree approach. For evaluating the seismic hazard, the study area was divided into small grids of size $0.1° \times 0.1°$, and the hazard parameters were calculated at the centre of each of these grid cells by considering all the seismic sources within a radius of 300 km. Rock level PHA values and SA at 1 s corresponding to 10% probability of exceedance in 50 years were evaluated for all the grid points. Maps showing the spatial variation of rock level PHA values and SA at 1 s for the entire south India are presented in this paper. To compare the seismic hazard for some of the important cities, the seismic hazard curves and the uniform hazard response spectrum (UHRS) at rock level with 10% probability of exceedance in 50 years are also presented in this work.

Keywords Earthquake hazard · Seismotectonic atlas · PSHA · Logic tree · PHA · SA and UHRS

1 Introduction

The Indian Peninsula, which is known as one of the oldest Archaean shield landmasses on earth, is considered as a stable continental region. Recent study by Ramalingeswara Rao (2000) has found that the strain rate in Indian shield region is 6.01×10^{-10} and it is the second highest in the stable continental region of the world (the highest strain rate of 6.80×10^{-10} is in the North American shield region). Moreover, the velocity of Indian plate was very high before its collision with the Eurasian plate (18–20 cm year^{-1};

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kumar et al. 2007), and it has slowed down 5.8 cm year^{-1} (Sridevi 2004) after the collision with the Eurasian plate. Gangrade and Arora (2000) have also reported that a slow and steady accumulation of seismic energy is occurring in this region, and it may lead to earthquakes of moderate to significantly high magnitudes. The deadliest stable continental earthquake (Rastogi et al. 2001) occurred at Bhuj (2001, M_w − 7.7), which is in the Peninsular Indian shield region. The total death toll in this earthquake was more than 20,000, and it has caused extensive damage in Bhuj region. South India has experienced about 10 earthquakes of moment magnitude 6 and above in the recent past, and the deadliest among them was the Killari earthquake (1993, Mw − 6.3) which killed about 9,000 people. South India is having a total population of around 300 million, and there are about eight cities with population exceeding one million in this region. Mumbai, the financial capital of India and the fifth most populous city in the world, alone accounts for a population of 19 million. These facts clearly demonstrate the need to identify the active
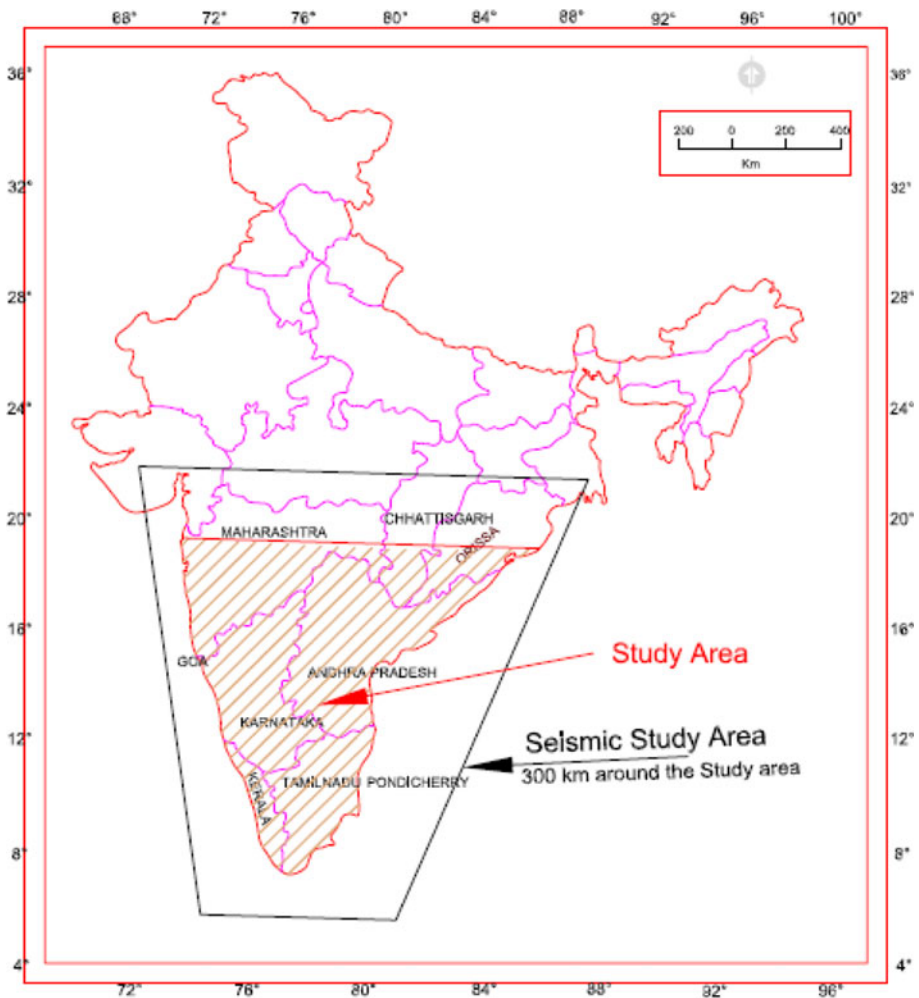

Fig. 1 Study area along with seismic study area

seismic sources and to assess the seismic hazard in this region. The study area is shown as the hatched portion in Fig. 1.

Earthquake hazard is controlled by three factors—source and path characteristics, local geological and geotechnical conditions and the type of structures. All these factors will require analysis and study of a large amount of geological, seismological and geotechnical data. For estimating the seismic hazard, the important factors to be considered are as follows: details of past earthquakes, earthquake source characteristics in the region and the attenuation relationships. In this work, an attempt has been made to evaluate seismic hazard at rock level in terms of peak horizontal acceleration (PHA) and spectral acceleration (SA) using probabilistic seismic hazard analysis (PSHA). A logic tree approach was adopted in the hazard analysis to incorporate multiple source and attenuation models.

2 Preparation of earthquake catalogue for south India

Estimation of seismic hazard in any region needs the past earthquake details with a uniform magnitude scale. Since a comprehensive earthquake catalogue was not available for the study area, it was prepared by consolidating the data obtained from different sources till December 2006. The earthquake data were collected from an area which falls within a radius of 300 km from the boundary of the study area (Regulatory Guide 1.165 1997). Earthquake data were collected from different sources like Indian Meteorological Department (IMD), International Seismological Centre (ISC), Kalpakkam Atomic Reactor (Kalpakkam), National Geophysical Research Institute (NGRI) Hyderabad, Incorporated Research Institutions for Seismology (IRIS), earthquakeinfo, Guaribidanur Array (GBA) and United States Geological Survey (USGS). The details of duration of data and the magnitude of data collected from different sources are given in Table 1. In addition to this, some more data were collected from the catalogues published by different researchers. The data obtained were in different magnitude scales such as body wave magnitude (m_b), surface wave magnitude (Ms), local magnitude (M_L) and the earthquake intensity scale (I). Hence, these data were converted to a common magnitude scale of moment magnitude (M_w).

Since there is no relation available for conversion of different magnitude scales for Peninsular India, the magnitude conversion was done using the relations suggested by Scordilis (2006). Scordilis (2006) proposed a relation to convert different magnitude scales to M_W based on 20,407 earthquake events occurred all over the world. Since no relation was suggested to convert the local magnitude values to Mw by Scordilis (2006), the

Table 1 Details of earthquake data from different sources

Source	Data period	Magnitude range
Kalpakkam	1820–1990	1.6–5.6
NGRI (Hyd)	1968–1981	2.1–5.2
GBA	1968–1995	0.9–5.7
Earthquakeinfo	1843–1997	3.2–5.9
USGS	1841–2006	2.2–6.4
IMD	1827–2006	2.8–6.3
ISC	1967–1994	4.1–6.4

relation suggested by Heaton et al. (1996) was used for this purpose. The intensity values were converted using the equation suggested by Reiter (1990) (M = (2/3) I + 1).

Earthquake occurrences are assumed to follow a Poisson distribution, and hence, only the main events should be included in the earthquake catalogue. A declustering algorithm was used to remove the dependent events from this catalogue. Most of the declustering algorithms are developed for active tectonic conditions; hence, it may not be suitable in the present study. The criterion used for declustering was based on uniform time (>30 days) and space (> 30 km) window between successive events. After declustering, there were 1585 events in the catalogue, out of which 10 events of $M_w > = 6.0$, 136 events of $M_w > = 5.0$. There were 598 events of $M_w > = 4.0$, and these events were used for further analysis. The magnitude time history is shown in Fig. 2, and the magnitude histogram is shown in Fig. 3.

3 Regional recurrence relation

The seismic activity of a region is characterized by the Gutenberg—Richter (1944) earthquake recurrence relation. According to this law,

$$\text{Log}_{10}N = a - bM \tag{1}$$

where N is the total number of earthquakes of magnitude M and above in a year, and 'a' and 'b' are the seismic parameters of the region. In the present study, the study area considered is very vast and the seismic activity in the study area is not uniform. This clearly points towards the need for dividing the study area into different seismic source zones, where each zone is having identical seismicity characteristics. There has been only a little work done till now in identifying and delineating the seismic sources zones in Peninsular India. Based on the past earthquake data, Bhatia et al. (1999) had delineated seismic sources for the entire India. However, this work did not evaluate the seismicity parameters or the m_{max} values for each of these zones. The delineation of seismic source zones in Peninsular India was done by Seeber et al. (1999) based on the evolutionary
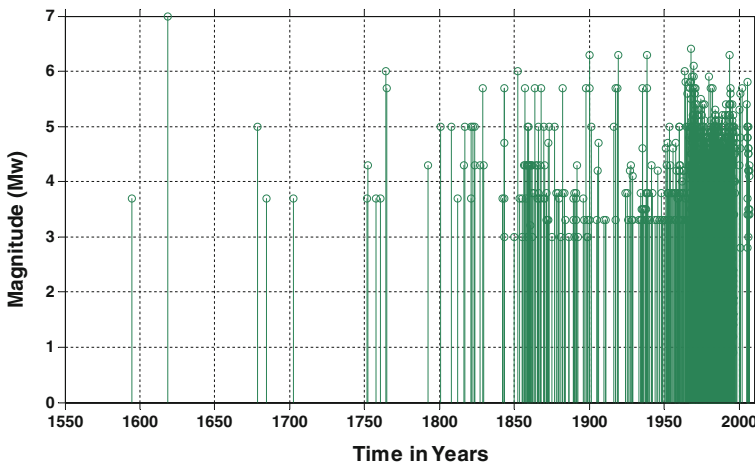

Fig. 2 Time history of magnitudes
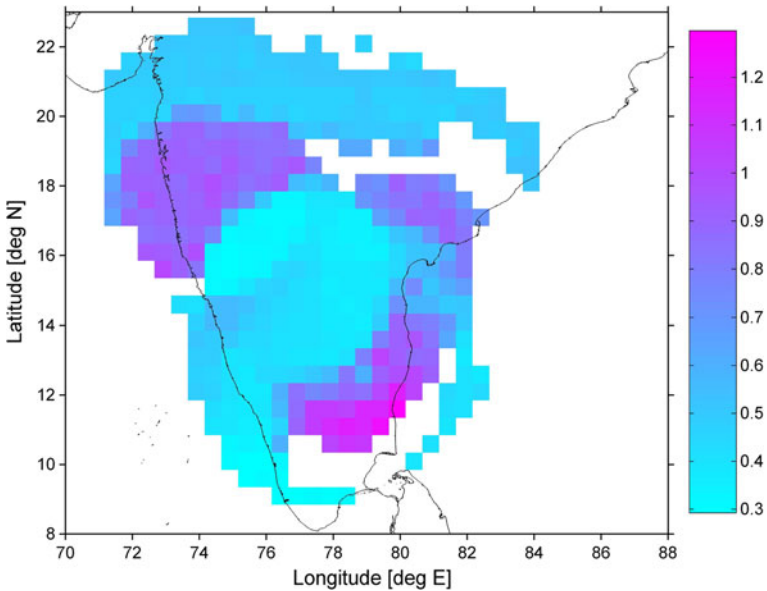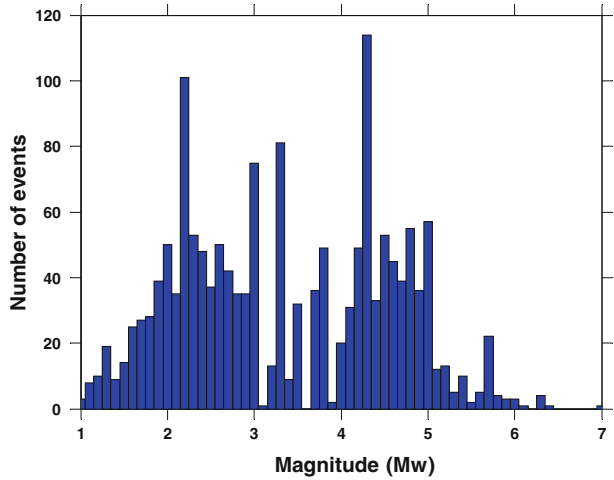
Fig. 3 Magnitude histogram

Fig. 4 Spatial variation of 'b' values

geologic and seismotectonic units identified by various other researchers. For these source zones, the recurrence rate and the m_{max} values were evaluated by Jaiswal and Sinha (2008).

To study the spatial variation of the seismicity parameters, 'a' and 'b' values, the study area was divided into small grids of size $0.5° \times 0.5°$ and the seismicity parameters were evaluated at the centre of each of these grid cells. The evaluation of these values was done based on the magnitude of completeness (M_c) of the catalogue using the methods suggested by Wiemer and Wyss (2000) and Wiemer (2001). The value of M_c was calculated at the centre of the grid points by considering the events within a radius of 300 km. After evaluating the M_c value, the 'b' value was evaluated using the maximum likelihood
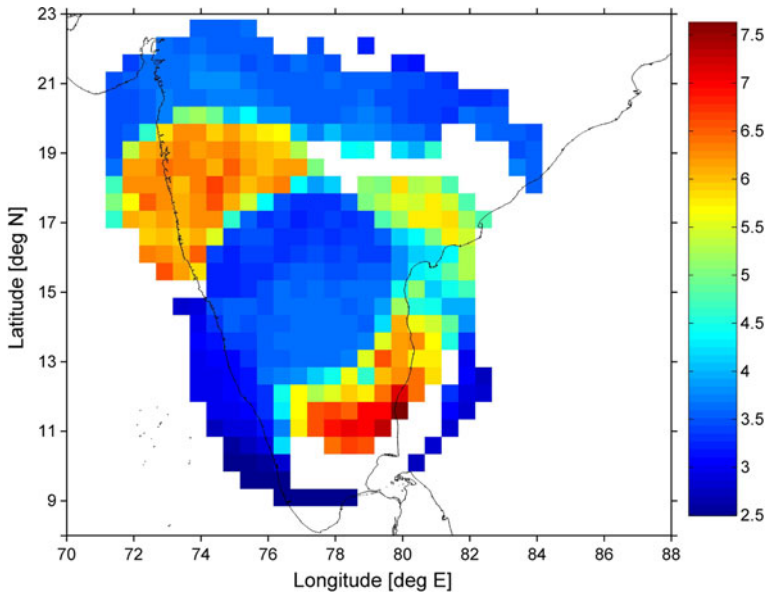
Fig. 5 Spatial variation of 'a' values

method (Aki 1965; Bender 1983; Utsu 1999) using the earthquake events, which are equal to or higher than the M_c. This evaluation was done using the software package ZMAP (Wiemer 2001).

The spatial variations of '*b*' values in the study area are shown in Fig. 4. The '*b*' values vary from 0.3 to 1.1, and for the majority of the study area, the value is around 0.5. Higher '*b*' values are obtained near the Koyna region and at the eastern Dhanwar Craton region. The '*b*' values for the Godavari Garben vary in the range of 0.7–0.9. The '*b*' values were not evaluated for some of the regions (shown in white colour in Fig. 4) because those cells were not having adequate number of earthquake events (50) with magnitude equal to or greater than M_c. This check is very essential to get an accurate measure of '*b*' values (Utsu 1965).

The '*a*' values for the study area vary from a lower value of 2.5 to a higher value of 7.5 and are shown in Fig. 5. For most of the study area, '*a*' value is around 4 and the higher values were obtained at the Koyna region, along the east coast of southern Andhra Pradesh and at parts of Tamil Nadu. Majority of the southern Craton and northern Craton are having '*a*' values around 3.5. The parts of the Godavari Garben are having '*a*' value of around 5.0.

In the present study, an attempt was made to delineate the seismic source zones based on the seismicity parameters. The Figs. 4 and 5 clearly indicate that there is a definite pattern in the variation of '*a*' and '*b*' values. The seismic source zones in the study area were delineated based on the variation of these seismicity parameters, and the five seismic source zones identified in the study area are shown in Fig. 6 (the spatial variations of '*b*' values are shown as background). By adopting this method, the regions with similar seismicity characteristics will be grouped together and this will be more helpful in evaluating the seismic hazard of the region more precisely. A similar method was adopted for the delineation of seismic source zones in north-east India by Kiran et al. (2008). For each
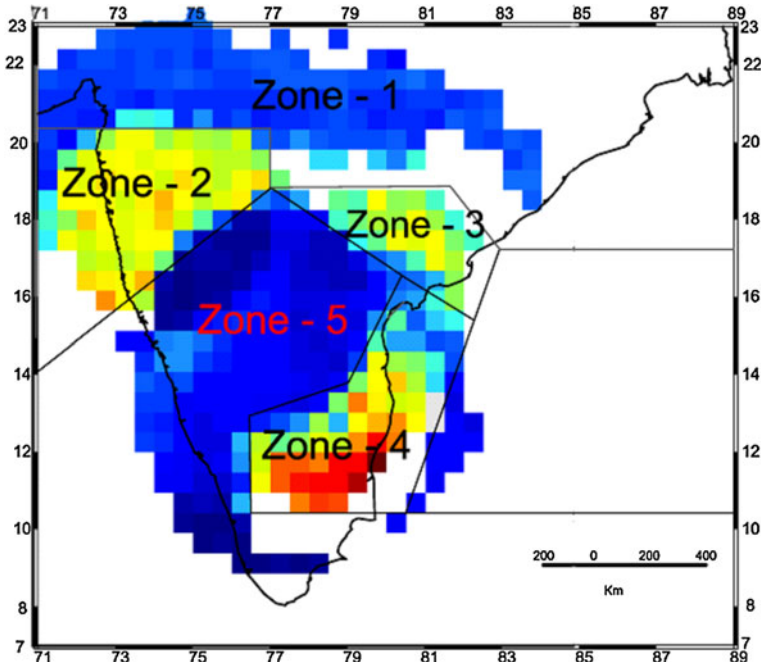
Fig. 6 Seismic source zones identified in the study area

Table 2 Seismicity parameters for different seismic source zones in south India

Seismic source zone no.	'a' value	'b' value	σ_b	Estimated m_{max}	
				Cramer's approx.	Bayesian approx.
1	1.42	0.48	0.08	6.33 ± 0.4	6.33 ± 0.4
2	4.08	1.0	0.17	7.05 ± 0.5	7.04 ± 0.5
3	3.18	0.9	0.46	6.17 ± 0.21	6.16 ± 0.21
4	4.21	1.01	0.19	6.33 ± 0.4	6.31 ± 0.4
5	1.25	0.39	0.02	6.36 ± 0.21	6.34 ± 0.2

of these zones, the seismicity parameters and the m_{max} values were evaluated and these values were used in the seismic hazard analysis. The evaluation of m_{max} was done using the method suggested by Kijko and Sellevoll (1989). The details of 'a', 'b' and m_{max} values for each of the zones are given in Table 2.

4 Identification of seismic sources

One of the major challenges in seismic hazard analysis is the identification of the vulnerable seismic sources. The present study uses two types of seismic sources—linear and smoothed areal sources. In this study, an attempt was made to identify the faults and lineaments, which are associated with earthquakes in the study area. The seismotectonic
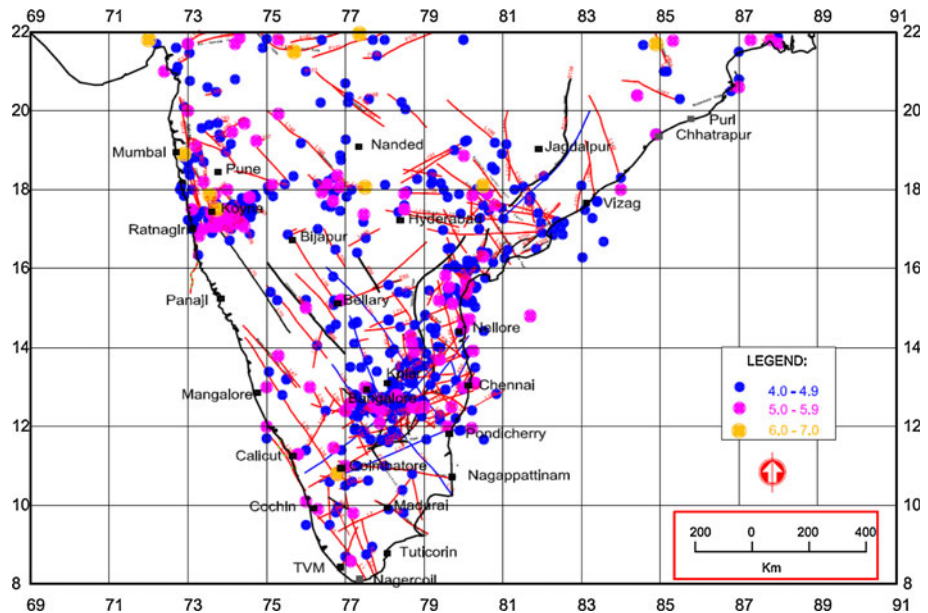
Fig. 7 Seismotectonic map of south India

atlas (SEISAT 2000), published by Geological Survey of India, was selected as the important reference document for selecting the linear seismic sources like faults and lineaments. The SEISAT is a comprehensive document regarding the seismotectonic and geomorphologic features in India and adjoining areas. The geophysical, structural, seismicity and geothermal data, relevant to seismotectonic studies, have been given in the SEISAT. The details of faults and lineaments are classified in detail due their direct bearing on seismicity. The seismic sources identified by SEISAT are being used by various researchers (Iyengar and Ghosh (2004) for Delhi, Nath (2006) for microzonation of Sikkim Himalayas, Nath et al. (2008) for north-east regions of India, Raghukanth and Iyengar (2006) for Mumbai, Anbazhagan et al. (2009) for Bangalore) working in this area. The SEISAT maps are available in A$_0$ size sheets, each map covers an area of 3° × 4°, and the study area was covered in 19 sheets of SEISAT. The required pages of SEISAT were scanned, and after georeferencing these images, the earthquake data were superimposed on this. The sources, which are associated with earthquake events of magnitude 4 and above, were identified and were used in the hazard analysis. Since SEISAT has not mapped the faults at the sea bed, we could not identify the seismic sources at the sea bed. Apart from this, some additional lineaments and faults, which are associated with earthquake events of four and above, were obtained from the remote sensing image analysis by Ganesha Raj and Nijagunappa (2004). The seismotectonic map prepared for the study area along with the details of earthquakes is shown in Fig. 7. A total of 189 seismic sources, which were associated with earthquake magnitude of four and above, were selected for the hazard analysis.

A detailed study of the seismotectonic atlas presented in Fig. 7 clearly indicates that there is some scatter in the earthquake data. There are some earthquake events that are not falling along any of the identified faults. In those cases, the linear source model alone may not be able to give the correct picture of seismic hazard levels. To overcome this limitation,

one more type of source model was selected in this study—smoothed gridded areal sources. The smoothed historic seismicity approach suggested by Frankel (1995) was adopted for smoothing the areal seismic sources. For the evaluation of seismic hazard, spatially smoothed 'a' value based on earthquakes of magnitude four and above was used.

5 Probabilistic seismic hazard analysis (PSHA)

The evaluation of seismic hazard was done using probabilistic seismic hazard analysis (PSHA), which was initially developed by Cornell (1968) and now widely being used in evaluation of seismic hazard. The occurrence of an earthquake in a seismic source is assumed to follow a Poisson distribution. The probability of ground motion parameter at a given site, Z, will exceed a specified level, z, during a specified time, T, is represented by the expression:

$$P(Z > z) = 1 - e^{-v(z)T} \leq v(z)T \tag{2}$$

where $v(z)$ is the mean annual rate of exceedance of ground motion parameter, Z, with respect to z. The mean annual rate of exceedance of ground motion parameter, Z, with respect to z for an earthquake of magnitude m occurring at a distance of r can be evaluated using the following equation.

$$v(z) = \sum_{n=1}^{N} N_n(m_0) \int_{m=m^0}^{m^u} f_n(m) \left[\int_{r=0}^{\infty} f_n(r|m) P(Z > z|m, r) dr \right] dm \tag{3}$$

where $N_n(m_0)$ is the frequency of earthquakes on a seismic source n, having a magnitude higher than a minimum magnitude m^0; $f_n(m)$ is the probability density function for a magnitude "m" having a minimum magnitude of m^0 and a maximum magnitude of m^u; $f_n(r|m)$ is the conditional probability density function for the occurrence of an earthquake of magnitude m at a distance r from the site for a seismic source n; $P(Z > z|m, r)$ is the probability at which the ground motion parameter Z exceeds a predefined value of z, when an earthquake of magnitude m occurs at a distance of r from the site. Thus, 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.

The maximum magnitude (m^u) for each linear source was estimated based on maximum reported magnitude along that particular source plus 0.5 (Iyengar and Ghosh (2004); RaghuKanth and Iyengar (2006); Anbazhagan et al. (2009)). The recurrence relation for each fault, capable of producing earthquake magnitudes in the range m^0 to m^u, is calculated using the truncated exponential recurrence model developed by McGuire and Arabasz (1990), and it is given by the following expression

$$N(m) = N_i(m_0) \frac{e^{-\beta(m-m_0)} - e^{-\beta(m^u-m^0)}}{1 - e^{-\beta(m^u-m^0)}} \quad \text{for } m^0 \leq m < m^u \tag{4}$$

where $\beta = b \ln(10)$ and $N_i(m_0)$ weightage factor for a particular source based on deaggregation. Deaggregation procedure is similar to the one followed by Iyengar and Ghosh (2004); RaghuKanth and Iyengar (2006); Anbazhagan et al. (2009) for PSHA of Delhi, Mumbai and Bangalore, respectively. The m_{max} for the areal sources was selected based on the m_{max} for the zone in which the particular location falls (Table 2).
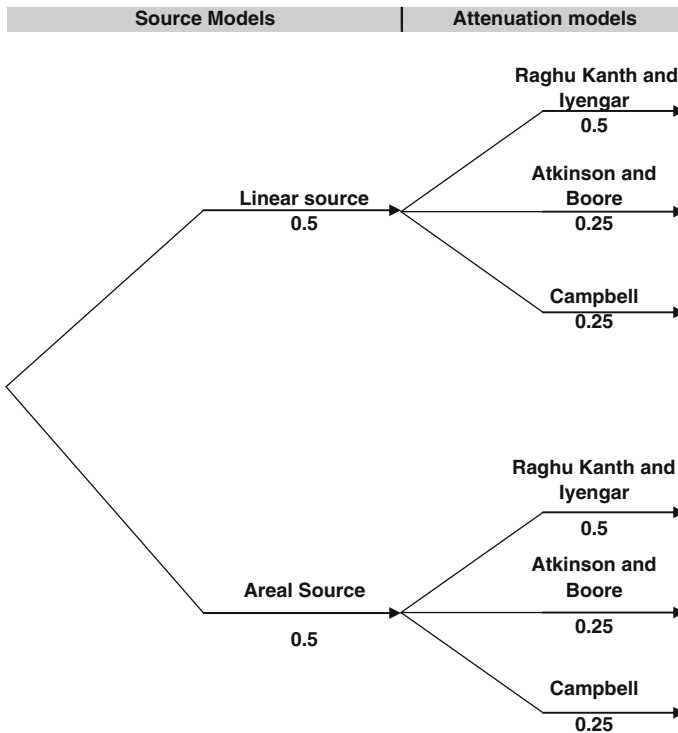
Fig. 8 Logic tree structure adopted

The magnitude ranges for each seismic source were divided into small intervals, and the probability for each of these values was calculated. In PSHA, the probability of occurrence of an earthquake anywhere in the fault is assumed to be same. The uncertainty involved in the source-to-site distance is described by a probability density function. The shortest and longest distance from each source to the site was calculated. The hypocentral distance has been calculated by considering focal depth of 15 km, similar to the one used for DSHA by Sitharam et al. (2006); Sitharam and Anbazhagan (2007) and Anbazhagan et al. (2009). A probable source zone depth of 10 km has been considered by Bhatia et al. (1999) in an exercise to develop seismic hazard map of the shield region of India in GSHAP. The conditional probability distribution function of the hypocentral distance for an earthquake is assumed to be uniformly distributed along a fault. This value was evaluated using the equations given by Kiureghian and Ang (1977).

There is only one attenuation relation available for south India, and this was developed by RaghuKanth and Iyengar (2007). In order to consider the epistemic uncertainties in the attenuation relations, it is always advisable to use multiple attenuation models. Based on the results of the ground motion attenuation analysis of Bhuj earthquake, Cramer and Kumar (2003) suggests that the ground motion attenuation in eastern North America (ENA) and Peninsular India is comparable. Hence, in addition to the relation suggested by RaghuKanth and Iyengar (2007), two more attenuation relations, which were developed for eastern North America (ENA), were also used in the present study. The attenuation relations developed for ENA by Campbell (2003) and Atkinson and Boore (2006) were used in the present seismic hazard analysis.

6 Logic tree approach

The uncertainties involved in different models may make the selection of appropriate seismic hazard methods difficult. In these cases, the logic tree approach allows a formal characterization of epistemic uncertainty by including alternative models in the analysis (Budnitz et al. 1997; Stepp et al. 2001; Bommer et al. 2005). Logic tree consists of a series of nodes, and several models (hypothesis) can be assigned to each node as different branches. Appropriate weightage can be given to each of these branches depending on the likelihood of being accurate, and the weightage for all the branches at a particular node should be equal to unity. The weightage of the terminal branch can be obtained by multiplying the weightage of all the branches leading to it. Even though it is possible to include as many branches as possible in the logic tree, this will increase the computational effort.

The logic tree adopted for the present study is shown in Fig. 8. Two types of seismic sources, linear and areal sources, were considered in the analysis. Since both of them were having equal importance, they were given equal weightage. The attenuation relation by RaghuKanth and Iyengar (2007) was developed for Peninsular India, and it was given the highest weightage of 0.5. The other two relations developed for ENA were given equal weightage of 0.25 each.

7 Results and discussions

The evaluation of spatial variation of PHA and SA was done by dividing the study area into grids of size $0.1° \times 0.1°$ (11 km × 11 km), and the values were calculated for the centre of the grid by considering all the seismic sources within a radius of 300 km. The entire analysis was done using a set of newly developed programs in MATLAB. The variation of PHA values with mean annual rate of exceedance for important cities is shown in Fig. 9. From these curves, the return period of different acceleration values at these cities can be obtained. It clearly indicates that the seismic hazard is high at Koyna and is relatively low for Panaji. Uniform hazard response spectrum (UHRS) at rock level with 10% probability of exceedance in 50 years (which corresponds to return periods of 475) was also calculated for all the grids cells. UHRS at rock level with 10% probability of exceedance in 50 years for important cities in south India is shown in Fig. 10. The variation of SA for different cities is similar to that obtained in Fig. 9. The frequency at which the value of SA is

Fig. 9 PHA (g) at rock level versus mean annual rate of exceedance (MARE) for important cities in south India
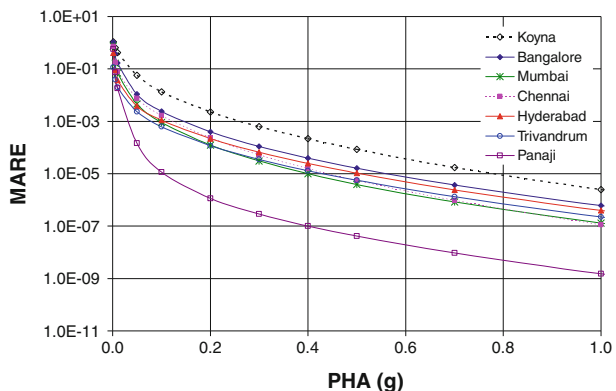
Fig. 10 UHRS at rock level with 10% probability of exceedance in 50 years for important cities in south India
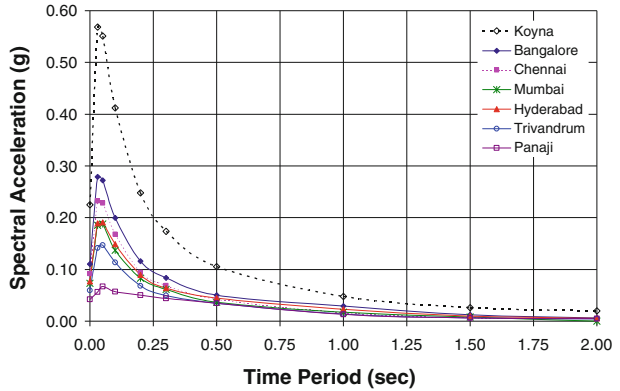

Fig. 11 Rock level PHA (g) values for 10% probability of exceedance in 50 years
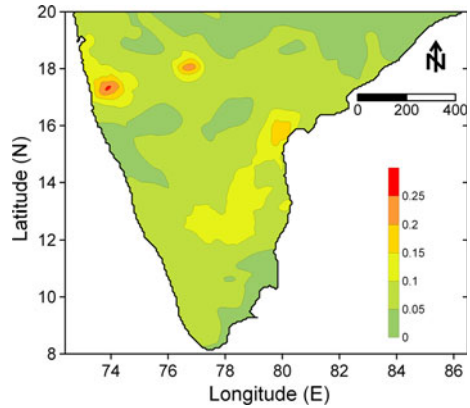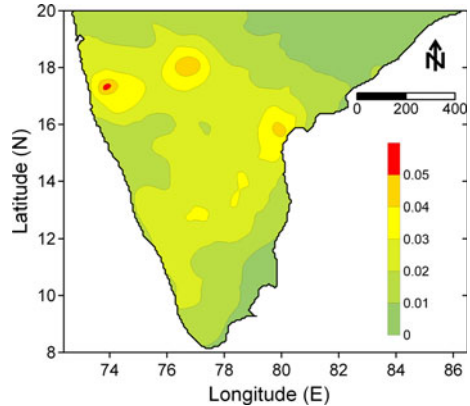

Fig. 12 Rock level spectral acceleration (g) for 1 s with 10% probability of exceedance in 50 years

maximum is around 20 Hz for all the cities. The rock level PHA values for 10% probability of exceedance in 50 years (return period of 475 years) are shown in Fig. 11. The maximum PHA value, about 0.25 g, is obtained at the Koyna region (73.75°E and 17.5°N). As per the Indian standard code, BIS-1893(2002), the Koyna region is in zone—IV, where the maximum expected acceleration is 0.24 g. However, the value obtained in the present

Fig. 13 Rock level spectral
acceleration (g) for 0.1 s with
10% probability of exceedance in
50 years
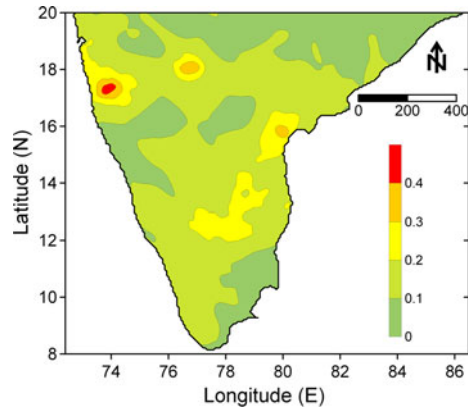
study is slightly higher than what is specified in BIS-1893 (2002). The PHA value obtained for regions near Bangalore (77.7°E and 13.0°N) was in the range of 0.1 g–0.15 g. As per BIS-1893 (2002), majority of this region falls in zone II, where the maximum expected acceleration is 0.1 g. This result matches well with the PHA values obtained for this region by Anbazhagan et al. (2009). The PHA values obtained for Latur (76.6°E and 18.24°N) and Ongole (80.04°E and 15.52°N) regions are also having higher PHA values that what is specified in BIS-1893 (2002). Whereas south-western parts of study area are showing lower PHA values than what is specified in BIS-1893 (2002). This points towards the inadequacy in the Indian seismic zonation code (BIS-1893, 2002). The variation of spectral acceleration for 1 and 0.1 s with 10% probability of exceedance in 50 years is shown in Figs. 12 and 13, respectively. The variation of SA values is similar to that observed in PHA values. The surface level acceleration values can be calculated by multiplying the rock level PHA values with the amplification factors.

The spatial variation pattern of PHA and SA values obtained in the present study matches well with the results obtained by Vipin et al. (2009). However, both PHA and SA values obtained in this study are less than that obtained by Vipin et al. (2009). This is mainly because Vipin et al. (2009) had used a single attenuation relation (by RaghuKanth and Iyengar 2007); a single source model (linear sources) and considered the entire study area as a single zone while evaluating the seismic hazard. These factors combined together produced a slightly higher PHA and SA values than the present study.

8 Concluding remarks

In the present work, a new seismotectonic map showing seismic sources which are associated with earthquake events of magnitude four and above has been prepared, and this can be used for similar works in this region. The spatial variation of PHA and SA values for south India was evaluated using probabilistic approach after incorporating the uncertainties in magnitude, hypocentral distance and attenuation of seismic waves. The multiple models used in the hazard evaluation were combined together using a logic tree approach. The PHA values obtained for some of the regions in the study area are higher than what is specified in the BIS-1893 (2002), and this needs further detailed investigation. The surface level acceleration values can be obtained by multiplying the rock level PHA values obtained in this study with the amplification factors, depending on different site conditions.

References

Aki K (1965) Maximum likelihood estimate of b in the formula log N = a-bm and its confidence limits. Bull Earthq Res Inst Univ Tokyo 43:237–239

Anbazhagan P, Vinod JS, Sitharam TG (2009) Probabilistic seismic hazard analysis for Bangalore. J Nat Hazards 48(2):145–166

Atkinson GM, Boore DM (2006) Earthquake Ground-Motion prediction equations for Eastern North America. Bull Seismol Soc Am 96(6):2181–2205

Bender B (1983) Maximum likelihood estimation of b values for magnitude grouped data. Bull Seismol Soc Am 73:831–851

Bhatia SC, Ravi Kumar M, Gupta H.K (1999) A probabilistic seismic hazard map of India and adjoining regions. Annali De Geofisica 1154–1164

BIS-1893 (2002) Indian standard criteria for earthquake resistant design of structures. Part 1—general provisions and buildings. Bureau of Indian Standards, New Delhi

Bommer JJ, Scherbaum F, Bungum H, Cotton F, Sabetta F, Abrahamson NA (2005) On the use of logic trees for ground-motion prediction equations in seismic hazard analysis. Bull Seismol Soc Am 95:377–389

Budnitz RJ, Apostolakis G, Boore DM, Cluff LS, Coppersmith KJ, Cornell CA, Morris PA (1997) Recommendations for probabilistic seismic hazard analysis: guidance on uncertainty and use of experts. U.S. Nuclear Regulatory Commission Report, NUREG/CR- 6372

Campbell KW, Bozorgnia Y (2003) Updated near-source ground motion (attenuation) relations for the horizontal and vertical components of peak ground acceleration and acceleration response spectra. Bull Seismol Soc Am 93:314–331

Cornell CA (1968) Engineering seismic risk analysis. Bull Seismol Soc Am 58:1583–1606

Cramer CH, Kumar A (2003) 2001 Bhuj, India, earthquake engineering seismoscope recordings and Eastern North America ground motion attenuation relations. Bull Seismol Soc Am 93:1390–1394

Earthquakeinfo (2007) http://www.earthquakeinfo.org/Catalog_Data.htm. Last accessed May 2007

Frankel A (1995) Mapping seismic hazard in the Central Eastern United States. Seismol Res Lett 66(4):8–21

Ganesha Raj K, Nijagunappa R (2004) Major lineaments of Karnataka state and their relation to seismicity remote sensing based analysis. J Geol Soc India 63:430–439

Gangrade BK, Arora SK (2000) Seismicity of the Indian peninsular shield from regional earthquake data. Pure Appl Geophys 157:1683–1705

Gutenberg B, Richter CF (1944) Frequency of earthquakes in California. Bull Seismol Soc Am 34:185–188

Heaton Tajima TF, Mori AW (1986) Estimating ground motions using recorded Accelerograms. Surv Geophys 8:25–83

IMD (2007) http://www.imd.ernet.in. Last accessed March 2007

IRIS (2007) http://www.iris.edu/. Last accessed May 2007

Iyengar RN, Ghosh S (2004) Microzonation of earthquake hazard in greater Delhi area. Curr Sci 87:1193–1202

Jaiswal K, Sinha R (2008) Spatial-temporal variability of seismic hazard in peninsular India. J Earth Syst Sci 117(S2):707–718

Kijko A, Sellevoll MA (1989) Estimation of earthquake hazard parameters from incomplete data files. Part I: utilization of extreme and complete catalogs with different threshold magnitudes. Bull Seismol Soc Am 79:645–654

Kiran KST, Nath SK, Yadav A, Raj A, Walling MY, Mohanty WK (2008) Recent seismicity in Northeast India and its adjoining region. J Seismol 12:107–123

Kiureghian DA, Ang AHS (1977) A fault-rupture model for seismic risk analysis. Bull Seismol Soc Am 67(4):1173–1194

Kumar P, Yuan X, Ravi Kumar M, Kind R, Li X, Chadha RK (2007) The rapid drift of Indian tectonic plate. Nature 449:894–897

McGuire PK, Arabasz WJ (1990) An introduction to probabilistic seismic hazard analysis. In: Ward SH (ed). Geotechnical and environmental geophysics, society of exploration geophysicist 1:333–353

Nath SK (2006) Seismic hazard and microzonation atlas of the Sikkim Himalaya, published by department of science and technology. Government of India, India

Nath SK, Thingbaijam KK, Singh RajA (2008) Earthquake hazard in the Northeast India—a seismic microzonation approach with typical case studies from Sikkim Himalaya and Guwahati city. J Earth Syst Sci 117(S2):809–831

RaghuKanth STG, Iyengar RN (2006) Seismic hazard estimation for Mumbai city. Curr Sci 91(11): 1486–1494

RaghuKanth STG, Iyengar RN (2007) Estimation of seismic spectral acceleration in peninsular India. J Earth Syst Sci 116(3):199–214

Ramalingeswara Rao B (2000) Historical seismicity and deformation rates in the Indian peninsular shield. J Seismol 4:247–258

Rastogi BK, Gupta HK, Mandal Prantik, Satyanarayana HVS, Kousalya M, Raghavan R, Jain Richa, Sarma ANS, Kumar N, Satyamurty C (2001) The deadliest stable continental region earthquake occurred near Bhuj on 26 January 2001. J Seismol 5:609–615

Regulatory Guide 1.165 (1997) Identification and characterization of seismic sources and determination of safe shutdown earthquake ground motion. Published by U.S. Nuclear Regulatory Commission, USA

Reiter L (1990) Earthquake hazard analysis: issues and insights. Columbia University Press, New York

Scordilis EM (2006) Empirical global relations converting ms and mb to moment magnitude. J Seismol 10:225–236

Seeber L, Armbruster JG, Jacob KH (1999) Probabilistic assessment of seismic hazard for Maharashtra. Government of Maharashtra, Maharashtra (Unpublished Report)

SEISAT (2000) Seismotectonic Atlas of India. Published by geological survey of India

Sitharam TG, Anbazhagan P (2007) Seismic hazard analysis for the Bangalore region. J Nat Hazards 40:261–278

Sitharam TG, Anbazhagan P, Ganesha Raj K (2006) Use of remote sensing and seismotectonic parameters for seismic hazard analysis of Bangalore. Nat Hazards Earth Syst Sci 6:927–939

Sridevi J (2004) Estimates of plate velocity and crustal deformation in the Indian subcontinent using GPS geodesy. Curr Sci 86:1443–1448

Stepp JC, Wong I, Whitney J, Quittemeyer R, Abrahamson N, Toro G, Youngs R, Coppersmith K, Savy J, Sullivan T (2001) Yucca mountain PSHA project members, probabilistic seismic hazard analyses for ground motions and fault displacements at Yucca Mountain, Nevada. Earthq Spectra 17:113–151

USGS (2007) http://earthquake.usgs.gov/regional/neic/. Last accessed May 2007

Utsu T (1965) A method for determining the value of b in the formula log N = a − bM showing the magnitude–frequency relation for the earthquakes. Geophy Bull Hokkaido Univ 13:99–103

Utsu T (1999) Representation and analysis of the earthquake size distribution: a historical review and some new approaches. Pure Appl Geophys 155:509–535

Vipin KS, Anbazhagan P, Sitharam TG (2009) Estimation of peak ground acceleration and spectral acceleration for South India with local site effects: probabilistic approach. Nat Hazards Earth Syst Sci 9:865–878

Wiemer S (2001) A software package to analyze seismicity: zmap. Seismol Res Lett 72(2):374–383

Wiemer S, Wyss M (2000) Minimum magnitude of complete reporting in earthquake catalogs: examples from Alaska, the Western United States, and Japan. Bull Seismol Soci Am 90:859–869