Nat Hazards (2012) 60:1325–1345
DOI 10.1007/s11069-011-9915-4

ORIGINAL PAPER

Seismic hazard map of Coimbatore using subsurface fault rupture

Panjamani Anbazhagan · Prabhu Gajawada · Aditya Parihar

Received: 31 July 2010 / Accepted: 18 July 2011 / Published online: 17 August 2011

Abstract This study presents the future seismic hazard map of Coimbatore city, India, by considering rupture phenomenon. Seismotectonic map for Coimbatore has been generated using past earthquakes and seismic sources within 300 km radius around the city. The region experienced a largest earthquake of moment magnitude 6.3 in 1900. Available earthquakes are divided into two categories: one includes events having moment magnitude of 5.0 and above, i.e., damaging earthquakes in the region and the other includes the remaining, i.e., minor earthquakes. Subsurface rupture character of the region has been established by considering the damaging earthquakes and total length of seismic source. Magnitudes of each source are estimated by assuming the subsurface rupture length in terms of percentage of total length of sources and matched with reported earthquake. Estimated magnitudes match well with the reported earthquakes for a RLD of 5.2% of the total length of source. Zone of influence circles is also marked in the seismotectonic map by considering subsurface rupture length of fault associated with these earthquakes. As earthquakes relive strain energy that builds up on faults, it is assumed that all the earthquakes close to damaging earthquake have released the entire strain energy and it would take some time for the rebuilding of strain energy to cause a similar earthquake in the same location/fault. Area free from influence circles has potential for future earthquake, if there is seismogenic source and minor earthquake in the last 20 years. Based on this rupture phenomenon, eight probable locations have been identified and these locations might have the potential for the future earthquakes. Characteristic earthquake moment magnitude (M_w) of 6.4 is estimated for the seismic study area considering seismic sources close to probable zones and 15% increased regional rupture character. The city is divided into several grid points at spacing of 0.01° and the peak ground acceleration (PGA) due to each probable earthquake is calculated at every grid point in city by using the regional attenuation model. The maximum of all these eight PGAs is taken for each grid point and the final PGA map is arrived. This map is compared to the PGA map developed based on the conventional

P. Anbazhagan (✉) · A. Parihar
Department of Civil Engineering, Indian Institute of Science, Bangalore, India
e-mail: anbazhagan2005@gmail.com

P. Gajawada
Department of Civil Engineering, National Institute of Technology, Warangal, India

deterministic seismic hazard analysis (DSHA) approach. The probable future rupture earthquakes gave less PGA than that of DSHA approach. The occurrence of any earthquake may be expected in near future in these eight zones, as these eight places have been experiencing minor earthquakes and are located in well-defined seismogenic sources.

Keywords Seismic hazard · Rupture length · PGA · DSHA

1 Introduction

Seismic hazard parameters are the essential components of earthquake-resistant design. Seismic hazard parameters are estimated and mapped in macro level and micro level based on the study area. The process of estimating seismic hazard parameters is called seismic hazard analysis. Seismic hazard can be analyzed both in deterministic and in probabilistic ways. Seismic hazards can be analyzed deterministically as and when a particular earthquake scenario is assumed. The probabilistic approach is the other way of hazard analysis, in which uncertainties in earthquake size, location, and time of occurrence are explicitly considered (Kramer 1996). Probabilistic seismic hazard analysis does not give a specific or unique choice but it gives infinite choices for the user (Wang 2005). Krinitzsky (2005) comments on the problems in the application of probabilistic methods and gives an account on a deterministic alternative that highlights that deterministic seismic hazard analysis (DSHA) uses geology and seismic history to identify earthquake sources and to interpret the strongest earthquake; each source is capable of producing regardless of time, because that earthquake might happen tomorrow. Those are the maximum credible earthquakes (MCEs), the largest earthquakes that can reasonably be expected.

Seismic zoning map given by the Bureau of Indian Standards, criteria for earthquake-resistant design of structures (IS 1893- BIS 2002), is based on the known magnitudes, epicenters, subsequently estimated modified Mercalli intensities and isoseismals. RaghuKanth and Iyengar (2006) have pointed that the Indian Standard in current form does not provide a quantified seismic hazard for each region but lumps large parts of the country into unstructured regions of equal hazard. The current hazard zoning map adopted by Indian Standards prescribes lower hazard for regions without significant record of historical earthquakes (Menon et al. 2010). Many researchers have developed their zoning maps of Indian Regions earlier, based on several approaches. This includes probabilistic seismic hazard macrozonation of Tamil Nadu by Menon et al. (2010), Seismic microzonation of Bangalore by Anbazhagan et al. (2010a, b), Probabilistic seismic hazard map for India and adjoining areas by Bhatia et al. (1997), and for many other areas by different researchers. These maps are based on past earthquake distribution and recurrence interval. In this study, an attempt has been made to map seismic hazard parameter of Coimbatore city for future earthquake by considering regional rupture characteristic and probable earthquake zones. A new seismotectonic map of Coimbatore city has been generated and areas of reported damaging earthquake and areas of little or no seismic activity in the past have been identified. Subsurface rupture length of past earthquakes was estimated and used to establish rupture character of the region. According to the energy release theory, earthquakes relive the strain energy that builds up on faults; they should be more likely to occur in areas where little or no seismic activity has been observed for some time (Kramer 1996). Potential seismogenic sources are identified in the places where there are no damaging earthquakes but minor earthquakes have been reported. These sources have not released the stored energy completely and hence have potential for future earthquake.

These locations are called as probable earthquake zones for the region. Eight such probable places are identified in and around Coimbatore. Maximum characteristic earthquake magnitude is estimated by considering regional rupture character and length of seismogenic source close to zone. Coimbatore is divided into grids, and hypocentral distances from these eight locations to each grid point are calculated. PGA at each grid is estimated by considering hypocentral distance and maximum credible earthquake at eight locations by using regional attenuation model. Maximum PGA value among eight PGA values from eight probable zones is considered as hazard value for each grid and these values are mapped. Then, conventional deterministic hazard analysis has been carried out and PGAs are estimated. PGA arrived from the DSHA is more than that obtained from the proposed rupture-based analysis. DSHA estimates PGA considering the source, which has experienced the damaging earthquakes and increased maximum reported magnitude close to this source. But chances of occurrence of the near-future earthquake in the same source are very limited as source needs some time to build energy for rupture to cause damaging earthquake. The proposed method eliminates past damaging earthquake locations and identifies the probable earthquake locations of minor earthquake and seismogenic sources. Maximum credible earthquake of the region is estimated by considering regional rupture character in terms of subsurface rupture length. Hence, the proposed methods' hazard values are representative values in terms of source identification and maximum magnitude calculation.

2 Study area of Coimbatore

The city of Coimbatore located between 10°10′ and 11°30′ of the northern latitude and 76°40′ and 77°30′ of eastern longitude in the extreme west of Tamil Nadu near Kerala state at an elevation of 432 m from the sea level. Its geographic location is mean valued to 11.01°N 76.96°E. The city has an area of 105.5 km^2 and a population of about more than one million. The city is surrounded by mountains on west and northern side with reserve forests and river basin (Nilgiri Biosphere Reserve), the eastern side of the district starting from the city is predominantly dry. The entire western and northern part of the district borders with Western Ghats with Nilgiri biosphere, Annamalai, and Munnar range with a western pass to Kerala popularly referred to as the Palghat Gap providing its boundary. It is generally a dry district apart from the Noyyal River basin and occasional over-flowing streams from the Western Ghats that terminate in the city's large tanks. The soil predominantly is black soil suitable for cotton cultivation with frequent interlude of a type of red loamy soil. Coimbatore falls under Class III Seismic Zone as per IS 1893 (BIS 2002) and has experienced an earthquake moment magnitude of 6.3 in the past. This earthquake was reported at 10.80°N, 76.80°E on 8th of February 1900. Recently, the city came into everyone's view by hosting World Classical Tamil Conference 2010. Figure 1 shows Coimbatore city map with important locations and its placement in India.

3 Rupture-based seismic hazard analysis

Most of the hazard analyses/zonations are being carried out considering the past earthquake location, size, and rate of occurrence of past earthquakes on the fault or in the region for future design of structures. Moderate to major earthquakes need sufficient energy to rupture the faults. Time required to buildup the required energy to create moderate to major

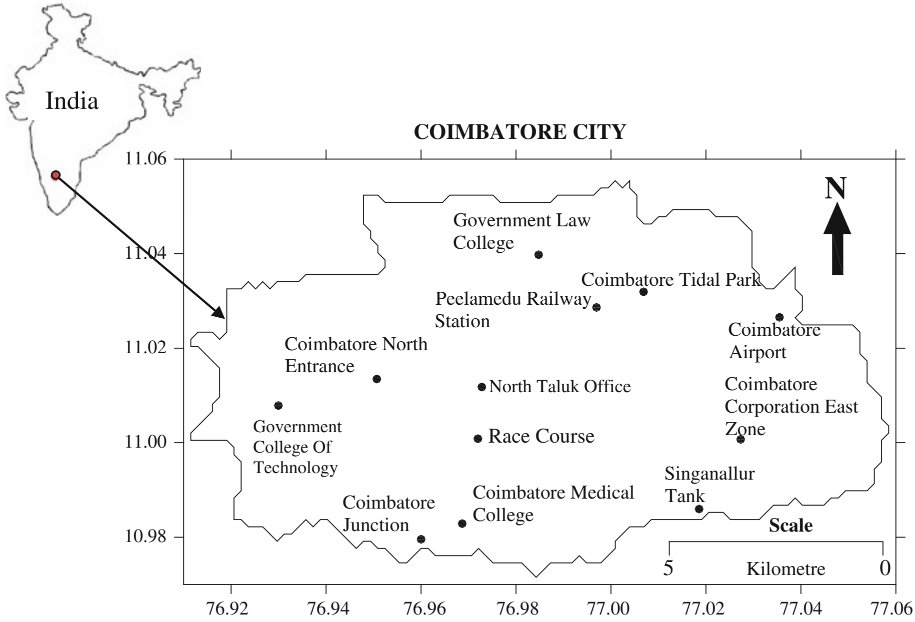

Fig. 1 Map of Coimbatore with important locations

earthquakes is a region-specific. So, interval between two consecutive earthquakes in the same location is considerable, but it is accounted poorly in the hazard analysis and future seismic zonation. Earthquakes relive the strain energy that builds up on faults, next earthquake in the region is more likely to occur in areas where little or no seismic activity has been observed for some time (Kramer 1996). Based on the average return period of earthquakes in the region, one can assess the potential of past earthquake location for generating the future similar earthquakes. Let the place/source having earthquake magnitude of M with an average return period of T has ruptured by an amount of R. Amount of rupture depends on the seismotectonic of the region and seismic sources. Maximum magnitude reported in the region is $M_{\max}$ and M is the average damaging earthquake in the region. If M and $M_{\max}$ are relatively comparable, the possibility of occurrence of the same M or $M_{\max}$ in the same (reported past) location is rare up to period T. Hence, for the future seismic zonation for period less than T, these locations can be eliminated or considered as areas with no potential for occurrence of near-future earthquake. But in the conventional hazard analysis for future zonation of time period less than T, these locations are considered and probable magnitude is arrived by adding 0.3–1 more to $M_{\max}$. Also, possibility of occurrence of damaging earthquake in other locations/sources is not accounted. In order to account the possibility of occurrence of earthquake in the locations other than past damaging earthquake locations, a new seismic hazard analysis has been attempted in this paper that is named as “Rupture Based Seismic Hazard Analysis” (RBSHA) for future zonation. Steps for rupture-based seismic hazard analysis are given below:

1. Prepare seismotectonic map of the study region and identify the maximum reported earthquake ($M_{\max}$) in the region.
2. Delineate the damaging earthquakes ($M_w > 5$ for study area) sources/area and minor earthquake source/area.

3. Select appropriate subsurface rupture equation and assess subsurface rupture character of the region. Validate the same if data are available for the region.
4. Mark zone of influence circles for damaging earthquakes based on subsurface rupture length of the event.
5. Identify probable future earthquake location considering minor earthquakes recorded, potential seismic sources, and eliminating damaging earthquake locations (identified in step 4)—these locations can be called as "Probable Future Earthquake Zones" (PFEZ).
6. Estimate maximum characteristic earthquake for study area by considering increased regional rupture characters estimated in step 3.
7. Measure the distance between PFEZ to required site and estimate PGA using regional attenuation model.
8. Identify the maximum PGA at each site/grid and prepare zonation map.

This zonation map is more representative for future design of structures for duration less than *T*. Site effects and liquefaction vulnerability can be assessed for microzonation based on maximum representative PGA distribution. This microzonation map will be more representative for future seismic disaster management and planning. Seismic hazard of Coimbatore city has been estimated using rupture-based seismic hazard analysis presented above and compared with conventional deterministic seismic hazard analysis.

4 Seismotectonics and regional seismicity

Southern India, once considered as part of stable continental region has recently experienced many small earthquakes and 11 earthquakes of magnitude more than 6 (Ramalingeswara Rao 2000), indicating that its perceived aseismicity is not true. South Indian seismicity is neither understood properly nor given importance since it is of micro-dimensions (Reddy 2003). Many reported earthquakes were poorly detected and recorded by the seismometer. The collision process of the Indian plate with the Eurasian plate is still underway at a rate of 45 mm/year inducing an anticlockwise rotation of the plate (Bilham 2004). Singh et al. (2005, 2008) noticed a series of unusual geological incidents throughout the southwest Peninsular India and which has resulted two moderate earthquakes in 2000 and 2001. This indicates unstable state of crustal blocks in this shield region (Singh et al. 2005, 2008). The seismicity of Peninsular India (PI) is characterized by relatively high frequency of large earthquakes but a relatively low frequency of moderate earthquakes (Menon et al. 2010). Seismic activity in PI is characterized by shallow earthquakes with average focal depths (0–12 km) within the upper crustal layers (Mandal 1999; Mandal et al. 2000). Seismicity of the south India can also be found in Srinivasan and Sreenivas (1977), Valdiya (1998), Purnachandra Rao (1999), Ravi Kumar and Bhatia (1999), Ramalingeswara Rao (2000), Subrahmanya (1996, 2002), Ganesha Raj (2001), Parvez et al. (2003), Jade (2004), Ganesha Raj and Nijagunappa (2004), Singh et al. (2005, 2008), Sitharam et al. (2006) and Sitharam and Anbazhagan (2007), Anbazhagan et al. (2009, 2010a, b).

Even though Coimbatore has experienced an earthquake of moment magnitude 6.3 in 1900, it was placed in seismic zone Zero, in the first version of the IS 1893 (BIS 1962). Presently, Coimbatore city is placed in Zone III as per the latest release of IS 1983 (BIS 2002). Coimbatore is located on thin lithosphere, part of Gondwanaland (Kumar et al. 2007). Geologically, this area is oldest sedimentary and is called as area of Dharwar

(Gupta 2006). There is no direct fault modeling and source mechanism available for south Indian cities. However, compiled earthquake data and seismogenic source details are available for specific cities such as Bangalore (Sitharam and Anbazhagan 2007; Anbazhagan et al. 2009) and Chennai (Boominathan et al. 2007). Comprehensive data base of seismic sources and past earthquakes is available in Seismotectonic atlas (SEISAT 2000) published by Geological Survey of India. Menon et al. (2010) has compiled earthquake data of magnitude more than 3, and delineation of seismic sources was done by Gupta (2006) and Ramasamy (2006). For this study, earthquake data compiled by Anbazhagan (2007), Menon et al. (2010) and seismic source details published by SEISAT (2000) have been merged together and seismotectonic map of Coimbatore has been generated. SEISAT (2000) has given many seismic sources; for this study, only the seismic sources that have experienced the earthquakes of magnitude 4 and above are considered. Figure 2 shows the seismic sources and previously reported earthquakes within radius of around 300 km from Coimbatore. There were many small earthquakes occurred in the past 200 years around Coimbatore city. Figure 2 also shows that many seismic sources around Coimbatore city have experienced the earthquake of magnitude 4 and above. Northeastern part of study area has many minor earthquakes that are recorded in Gauribidanur seismic array (GBA) and collected by Sitharam and Anbazhagan (2007). Even though seismic recording station is located in South part of study at Peechi, Kerala (maintained by Centre for Earth Science Studies Akkulam, Kerala), earthquake data are not available in the public domain. Hence, number of minor earthquake in southwestern part is less when compared to northeastern part.

5 Regional attenuation model

Seismic hazard analysis of particular region needs ground motion predictive equation/attenuation models. Most of the stable continental regions in the world have poor strong motion data and are not representative of the existing seismic hazard in the region (Menon et al. 2010). Coimbatore, south India, has almost no strong motion records for moderate to

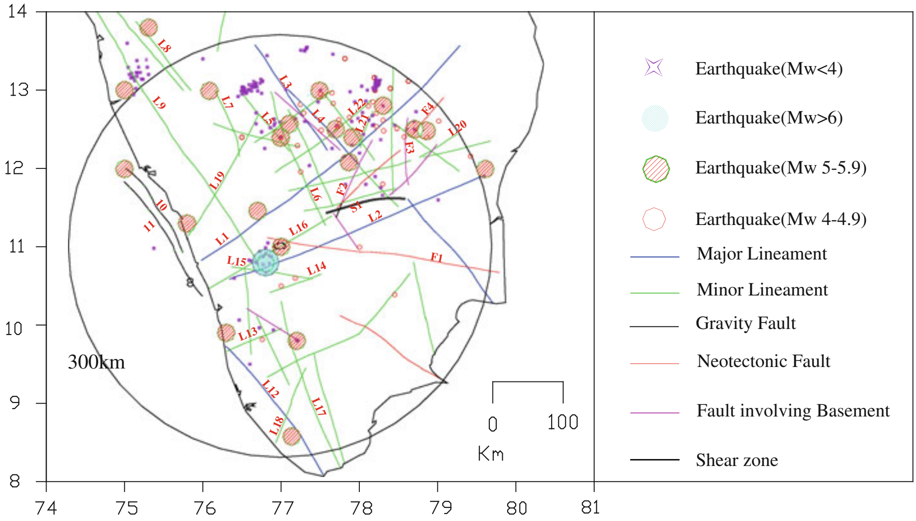

Fig. 2 Seismic sources and past earthquakes around Coimbatore city

larger earthquakes. Therefore, there is no ground motion predictive equation/attenuation model developed considering the recorded earthquake data. For the areas having poor seismic record, synthetic ground motion models are the alternative. Regional synthetic ground model should include seismotectonic and geological settings (e.g., shallow crustal intraplate earthquakes) in the region. Modeling of strong motion helps to estimate future hazard of the region and study the local effects in local scale. Seismological model by Boore (1983, 2003) can be used for generating the synthetic acceleration-time response study (Atkinson and Boore 1995; Hwang and Huo 1997; Sitharam and Anbazhagan 2007). There is no ground motion predictive equation before 2004 for Peninsular India, in particular, South India. Iyengar and RaghuKanth (2004) have developed first ground motion attenuation relation based on the statistically simulated seismological model. Authors have developed an empirical attenuation relationship for Peninsular India (PI) (below 24°N latitude) and for three subregions within PI (Koyna-Warna, southern India and western–central India), based on a stochastic seismological point source model and subsequently compared with the instrumental data from the Koyna (1967) and Bhuj (2001) earthquakes. Relation given by Iyengar and RaghuKanth (2004) is for rock site without considering soil condition. RaghuKanth and Iyengar (2007) have arrived at an empirical relations by estimating 5% damped response spectra covering bedrock and soil conditions internationally followed. Authors have also given the standard error for the proposed relationship as a function of the frequency, for the application of probabilistic seismic hazard analysis. For rock site, the correlation given by Iyengar and RaghuKanth (2004) and RaghuKanth and Iyengar (2007) are similar. In this study, PGA at rock sites has been estimated considering relation given by Iyengar and RaghuKanth (2004), which is given below:

$$\ln y = c_1 + c_2(M-6) + c_3(M-6)^2 - \ln R - c_4 R + \ln \in \tag{1}$$

where y, M, and R refer to PGA (g), moment magnitude and hypocentral distance, respectively. Since PGA is known to be distributed nearly as a lognormal random variable, $\ln y$ would be normally distributed with the average of ($\ln \varepsilon$) being almost zero. Hence, with $\varepsilon = 1$, coefficients for the southern region are (Iyengar and RaghuKanth 2004):

$$c_1 = 1.7816;\ c_2 = 0.9205;\ c_3 = -0.0673;\ c_4 = 0.0035;\ \sigma(\ln \varepsilon) = 0.3136\,(\text{taken as zero}) \tag{2}$$

Proposed study is intended to estimate PGA at rock level and hence the equation that is valid for rock site is used. It should be noted here that the prediction of peak ground acceleration (PGA) values using Iyengar and RaghuKanth 2004) tends to be upper bound, but for Jabalpur earthquake (1997), the values match rather well. The prediction of PGA values by other models suitable for SCRs (Stable Continental Region) (Abrahamson and Silva 1997; Campbell and Bozorgnia 2008) lies between the recorded PGA values (Menon et al. 2010).

6 Subsurface rupture length of the region

The tectonic features of the region should refer to various faults, folds, shear zones, and lineaments with associated past earthquakes and future seismicity be expected to occur (Gupta 2006). Seismotectonic parameters are also useful to build knowledge on the rupture character of earthquakes in the region and to foresee the seismic hazard parameters. The knowledge of the maximum size of fault ruptures in the region helps one to estimate the maximum earthquake magnitude that may occur in the region. Mark (1977) recommends that the surface rupture length may be assumed as 1/3–1/2 of the total fault length (TFL) based on the worldwide data. However, assuming such large subsurface rupture length yields very large moment magnitude and also it does not match with the past earthquake data in south India (Sitharam and Anbazhagan 2007). Wells and Coppersmith (1994) developed empirical relationship between moment magnitude and subsurface fault length using past worldwide earthquakes. The relationship between moment magnitude and subsurface rupture length (RLD) was developed using reliable source parameters, and this is applicable for all types of faults, shallow earthquakes, and interplate or intraplate earthquakes (Wells and Coppersmith 1994). The developed regression relationships for subsurface rupture length and magnitude also provide a basis for estimating the magnitudes of earthquakes that may occur on subsurface seismic sources such as blind faults, which cannot be evaluated from surface observations. These relations on subsurface parameters include data for moderate magnitude earthquakes (moment magnitude of 5–6), allowing the characterization of relatively small seismic sources that may not rupture the surface. They believed that subsurface rupture length relations are appropriate for estimating magnitudes for expected ruptures along single or multiple fault segments. These relations are determined from shallow-focus (crustal) continental interplate or intraplate earthquakes (stable and non stable continental) on the basis of a rather comprehensive database of historical events. Different correlation coefficients for these relations are given for strike-slip, reverse and normal faulting, and also the average relation for all slip types are developed to be appropriate for most of the applications. Best established are the relationships between moment magnitude M_w and subsurface rupture length (RLD) and is valid for the magnitude range of 4.8–8.1 and length/width range of 1.1–350 km, which is as follows.

$$\log(\mathrm{RLD}) = 0.59 M_W - 2.44 \tag{3}$$

Wells and Coppersmith (1994) equations are widely used to estimate source parameters and magnitudes. Wells and Coppersmith (1994) have also considered the magnitude and source parameters from Indian earthquake data. Rupture character of the region has been established by carrying out parametric studies between subsurface rupture length and earthquake magnitude. The subsurface rupture length is assumed as a percentage of total length of the fault for each event. In total, 19 faults are associated with reported earthquake of moment magnitude of 5 and above. The magnitude has been estimated using Eq. 3 for the subsurface length 1–10% of total length of fault. Estimated earthquake magnitudes are compared with reported earthquake magnitude. Figure 3a–c shows the percentage matching of the reported magnitudes and associated seismic sources. It has been noticed that the estimated magnitude matches very well with the reported earthquake magnitude for an average subsurface rupture length of 5.2% of the total length, for faults having a length less than 130 km. Magnitude obtained for a average subsurface rupture length equal to 2.5% of total length matches with the reported magnitude for faults having a length more than 130 km. For more than 55% of the seismic sources, the estimated magnitude is found to be matching with the reported magnitude for the RLD of 5.2% of the total fault length. This value has been taken as "Regional rupture character" for the study area. Regional rupture character is combined with Wells and Coppersmith (1994) correlation and used to estimate credible earthquake of the source zone.

6.1 Probable future rupture zone

Earthquake data discussed previously are divided into two categories. The first category includes the earthquakes of moment magnitude 5.0 and above, i.e., damaging earthquakes.

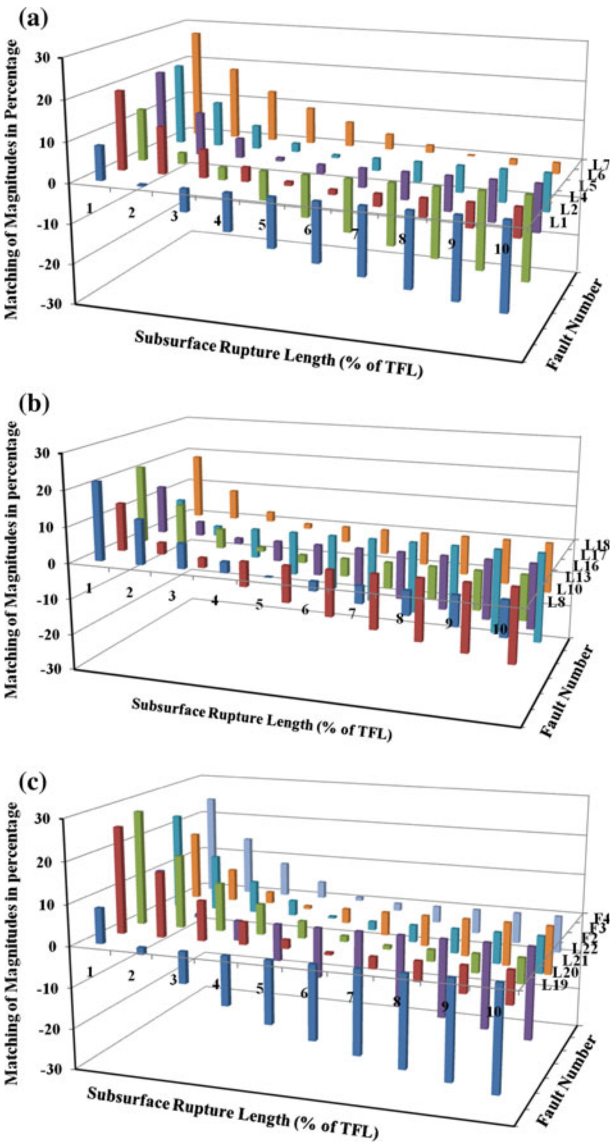

Fig. 3 a–c Estimated magnitude matching with reported magnitude for a different subsurface rupture length in terms of percentage of total length

Here, damaging earthquake (M_w of 5 and above) is close to maximum magnitude (M_{max} of 6.3) reported in the region. It is assumed that damaging earthquakes have released all the strain energy stored in the faults and hence it takes some time (return period) to build this strain energy to cause another similar earthquake. Martin and Szeliga (2010) have said that no earthquake in India or its surroundings in the past 500 years has repeated. No fault segment has re-ruptured in this time, with the exception of the eastern plate boundary. The return period of 200 years is a short time interval compared to the recurrence interval for earthquakes in India (Martin and Szeliga 2010; Szeliga et al. 2010). Hence, past damaging earthquake locations have less potential for producing the similar damaging earthquake in near future (50–100 years). The average return periods of similar earthquakes are about 200–500 years for the seismotectonic province. The subsurface rupture length for all the earthquakes has been calculated using Wells and Coppersmith (1994) correlation (Eq. 3). The radius of the influence circles for the earthquakes of moment magnitude 5.0–6.0 is taken as 12.589 km, which is the subsurface rupture length upper side magnitude of M_w 6.0. The locations which fall under these influence circles have less potential for similar earthquakes in near future, because the seismic sources will have already ruptured and would need minimum time (return period) to build strain for similar earthquake. Figure 4 shows past earthquakes with associated sources and zones of influence circles. Earthquake circles for earthquake magnitude 5 and above are represented by influence circle zones. The second category includes all earthquakes of moment magnitude less than 5.0 (minor earthquakes). It is assumed that these earthquakes have not ruptured the seismic source sufficiently and have not released the entire strain energy stored in the faults during this event. Hence, the locations of these earthquakes may be the potential locations of future earthquakes. The locations where no influence circles are present, there is a possibility for earthquakes of similar magnitudes to occur if these locations have weak zones (seismic sources like faults and active lineaments) and minor earthquakes. In order to precisely locate probable future earthquake zone, the zone must satisfy the following conditions:

1. The location must have experienced at least one minor earthquake in the last 20 years to indicate seismic activity
2. There must be a defined seismic source within 10 km radius

In the seismic study area (i.e., 300 km around Coimbatore city), eight such zones are identified. There may be a possibility of occurrence of future damaging earthquakes in these zones. These eight probable future rupture zones are named as Z-1 to Z-8 for further discussion (See Fig. 4). The eight zones have satisfied the above-mentioned requirements and are located at 10.98°N 75.38°E, 11.60°N 79.01°E, 9.50°N 76.62°E, 13.44°N 76.82°E, 11.74°N 78.27°E, 11.94°N 77.32°E, 10.51°N 77.13°E, and 11.00°N 78.00°E. One probable

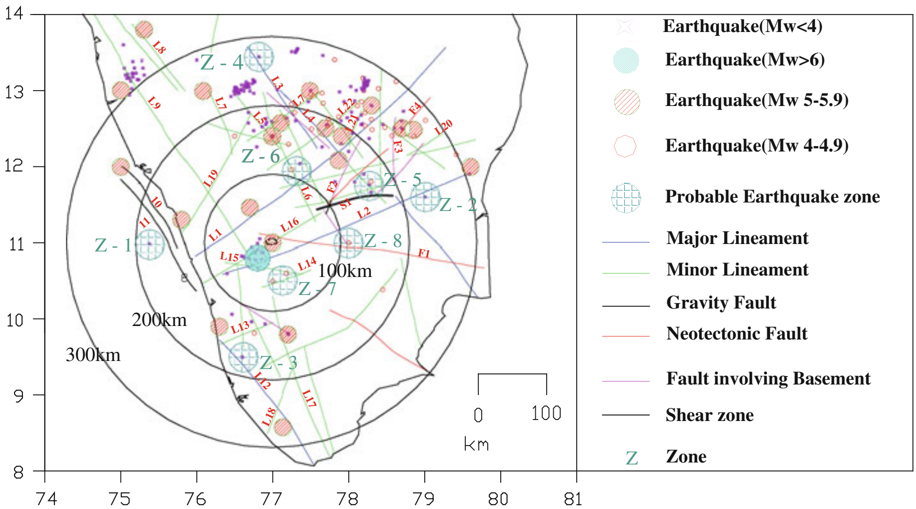

Fig. 4 Probable future earthquake locations in the seismic study area

Table 1 Probable zones for future earthquake around Coimbatore

Zone location (in degree)	Distance from Coimbatore (km)	Minor earthquake (M_w) (max of all)	Number of minor earthquake within 10 km
10.98 N 75.38E	180	3.0	1
11.60 N 79.01E	230	2.5	1
09.50 N 76.62E	175	3.7	1
13.44 N 76.82E	270	2.1	1
11.74 N 78.27E	165	4.6	5
11.94 N 77.32E	110	4.7	2
10.51 N 77.13E	60	4.5	2
11.00 N 78.00E	110	4.9	1

zone is indentified within 100 km, five probable zones are within 100–200 km, and two zones are located within 200–300 km radius from Coimbatore city. Table 1 shows probable zones for Coimbatore city with past smaller earthquakes and distance from Coimbatore city center.

6.2 Probable rupture zones and seismogenic sources

Probable future earthquake locations were identified considering past larger earthquake around Coimbatore, recent smaller earthquakes and seismic source mapped in SEISAT (2000). The seismic sources in SEISAT (2000) were identified and mapped before 2000 but the seismicity and activity of the plate tectonics will always change based on recent neotectonic activity. Many devastating earthquakes are reported after 2000 in Indian plate boundary and in the interior. Thus, it is necessary to include the recent neotectonic activity in the seismic hazard analysis. In this section, probable future earthquakes zones identified in the above section are compared with the recent seismogenic sources mapped by Ramasamy (2006) and Gupta (2006).

Ramasamy (2006) has painted a fair picture of active tectonic scenario of South India using remote sensing and analyzing ground-based dataset/observations. Ramasamy (2006) studied active tectonics of south India using remote sensing and identified a number of faults and lineaments in the southern part of India. Identified faults and lineaments are correlated with geological features that are also used for seismic hazard mapping of Tamil Nadu (Menon et al. 2010). Ramasamy (2006) has amalgamated these details with visibly displayed tectonic, fluvial, coastal, and hydrological systems. Seismogenic sources mapped by remote sensing are also compared with past earthquakes and Bouger gravity anomaly. The map showing these faults and lineaments of south India was given in Fig. 16 of his paper. This map gives the Pleistocene tectonic scenario of south India. The probable future earthquakes zone identified in this study is superimposed on the Fig. 16 of Ramasamy (2006). Figure 5 shows the seismogenic sources mapped by Ramasamy (2006) as a base and the superimposed probable future earthquake locations identified in this study. From Fig. 5, it can be observed that the probable earthquake locations identified at 11.94°N 77.32°E and 11.00°N 78.00°E are closely associated with NW–SE dextral fault no. 15 mapped by Ramasamy (2006). The probable earthquake location at 13.44°N 76.82°E also is very near to this fault. The probable earthquake location at 10.51°N 77.13°E is associated with NE–SW Sinistral fault no. 9 mapped by Ramasamy (2006). The probable earthquake location

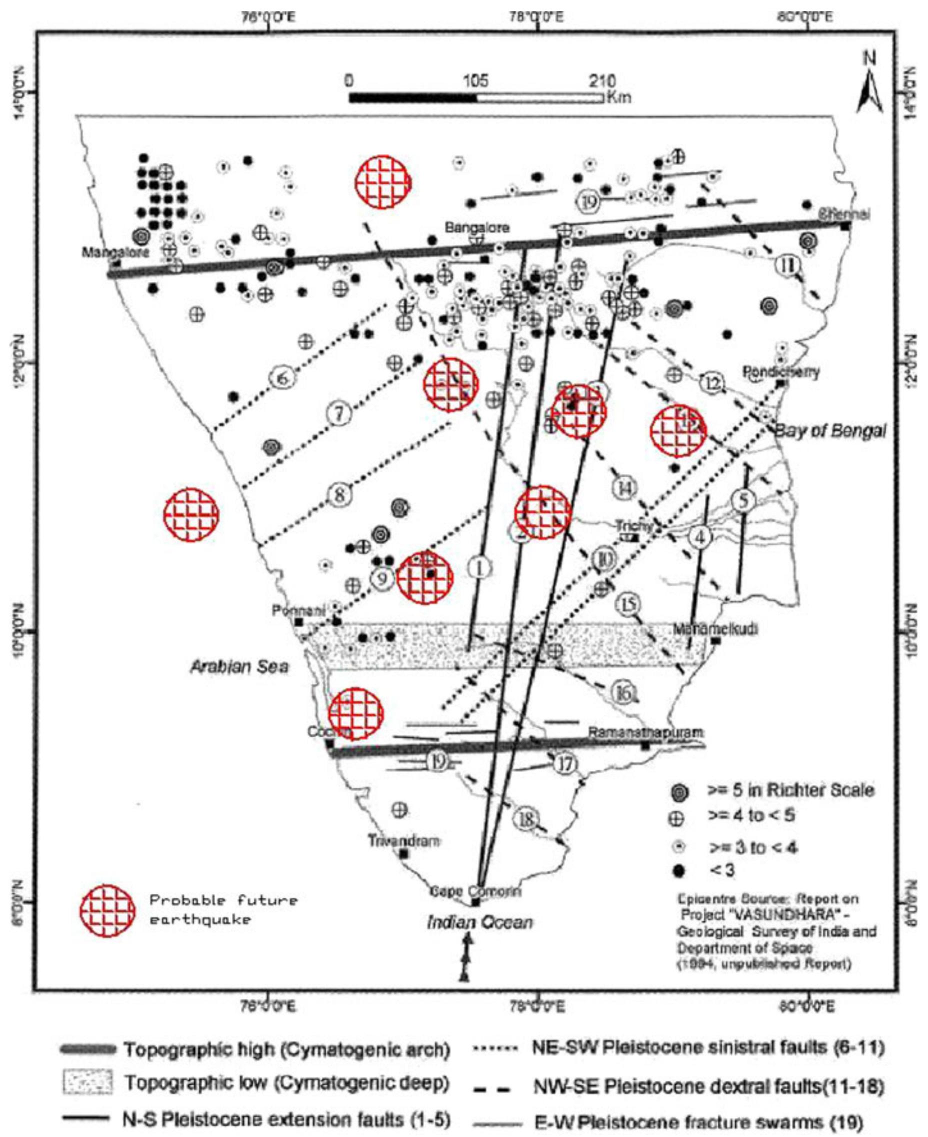

Fig. 5 Seismogenic sources identified by Ramasamy (2006) and probable future earthquake locations identified in this study

identified at 11.74°N 78.27°E is associated with NW–SE dextral fault no. 14 mapped by Ramasamy (2006). The probable earthquake location identified at 11.60°N 79.01°E is associated with NW–SE dextral fault no. 13 mapped by Ramasamy (2006). Here, it can be observed that the probable locations identified in this study for possible future earthquake match well with the recent seismogenic sources mapped by Ramasamy (2006). From Fig. 5, it can be observed that six probable future earthquake zones identified in this study coincide well with the seismically active sources mapped by Ramasamy (2006) and remaining two zones are located outside the Ramasamy's study area.

Gupta (2006) has carried out comprehensive analysis of seismotectonic characteristics of India and neighborhood and has delineated the probable seismic sources. Gupta (2006) has stated that the peninsular India was subjected to great structural disturbances during the geological past, which resulted in the development of local zones of weakness along which crustal adjustments are likely to take place. The occurrence of different types of seismic activities in various parts of the peninsula is a manifestation of such adjustments (Gupta 2006). He has delineated 5 subsources that together form source no 73 in Gupta (2006); this area covers the south Indian granulite terrain. A system of NE–SW and NW–SE trending faults and lineaments exists in this zone. The subsources "*a*" to "*e*" in this zone are described based on the clustering of epicenters around some faults and lineaments. The probable future earthquakes identified in this paper are superimposed on the seismic sources delineation by Gupta (2006) and shown in Fig. 6. It is observed that most of the probable future earthquakes zones are either in or nearby to the seismic sources delineated by Gupta (2006).

6.3 Peak ground acceleration due to probable earthquakes

The study area, Coimbatore city, is divided into number of grid points having size of $0.01° \times 0.01°$. There were a total of 160 grid points with approximate square size of 1.1×1.1 km. Distances between each grid center point and each of eight probable earthquake zones are estimated and used for hypocenter distance estimation. Hypocenter distance has been estimated by considering average hypocentral depth of 10 km based on the past earthquakes in this region. Maximum credible earthquake (MCE) of the study area has been estimated by considering rupture character of the region and seismic sources close to identified probable zones. The regional rupture character (RLD) of 5.2% of total length is increased to 6% (i. e., 15% extra) to estimate future earthquake magnitudes i.e., Maximum credible earthquake (MCE). MCE of 5.8–6.4 in moment magnitude is arrived for the probable future earthquake zones, if seismic sources close to zone have ruptured by 6% of its length. The moment magnitude of 6.4 is considered as the Maximum credible earthquake (MCE) of the study area and used to estimate seismic hazard of Coimbatore city. The peak ground acceleration at each grid point due to MCE at each zone has been estimated. PGA distribution map of Coimbatore city for the eight probable earthquake zones has been estimated and are presented below:

6.3.1 PGA from zone 1

Probable future earthquake zone (Z-1) located at 10.98°N latitude and 75.38°E longitude is to the west of Coimbatore and it is very close to the gravity fault no. 11 as shown in Fig. 4. This zone has experienced a past earthquake of magnitude 3.0 (M_w). The maximum PGA due to this earthquake in Coimbatore is 0.0276 g and it is observed in the western part of Coimbatore city. Figure 7a shows PGA distribution in Coimbatore city due to MCE of 6.4 at zone 1.

6.3.2 PGA from zone 2

Probable future earthquake zone (Z-2) located at 11.60°N 79.01°E is on the northeastern side of Coimbatore city and is very close to a major lineament no. 2 as shown in Fig. 4. This zone has experienced a past earthquake of magnitude 2.5 (M_w). The maximum PGA of 0.017g was observed at northeastern part of Coimbatore due to this earthquake. Figure 7b shows PGA distribution in Coimbatore city due to MCE of 6.4 at zone 2.

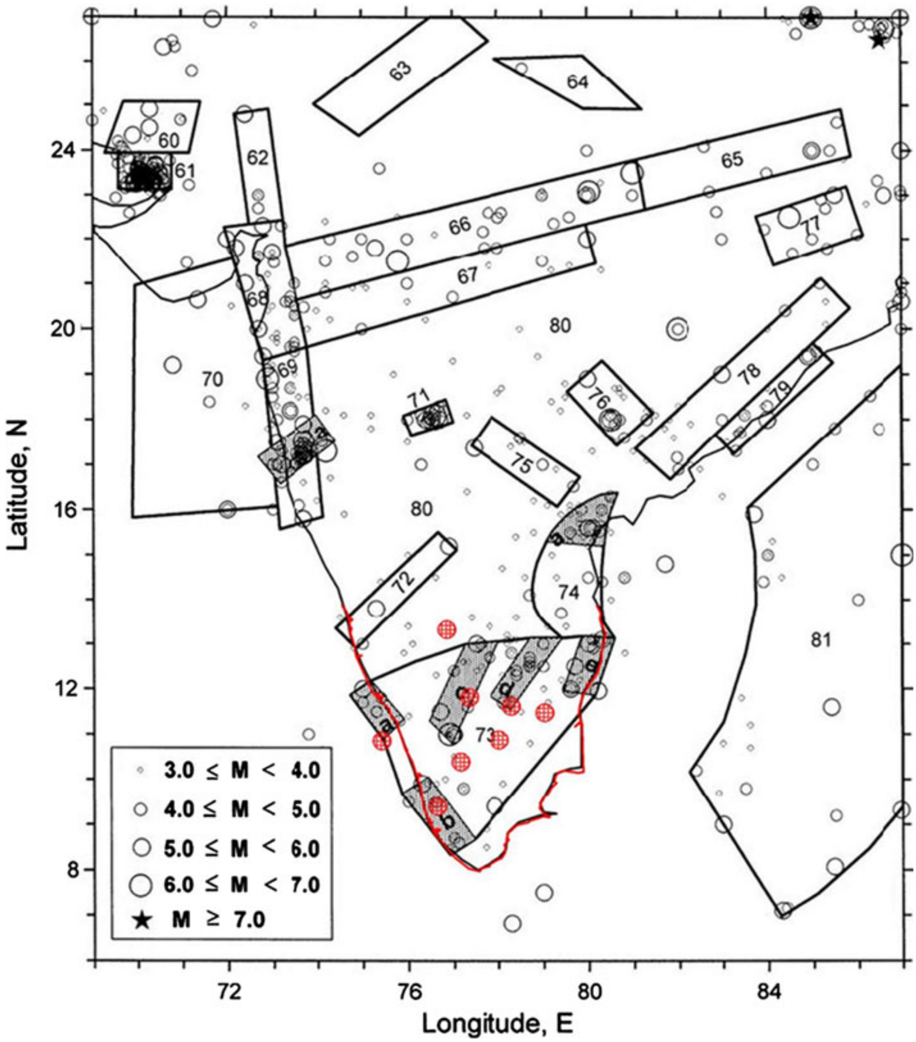

Fig. 6 Probable earthquake locations with seismogenic sources mapped by Gupta (2006)

6.3.3 PGA from zone 3

Probable future earthquake zone (Z-3) located at 9.50°N 76.62°E is on the southern side of Coimbatore and is very close to a major lineament no. 12 as shown in Fig. 4. This zone has experienced a past earthquake of magnitude 3.7 (M_w). The maximum PGA in Coimbatore due to this earthquake is 0.028 g in the southern part of Coimbatore city. Figure 7c shows PGA distribution in Coimbatore city due to MCE of 6.4 at zone 3.

6.3.4 PGA from zone 4

Probable future earthquake zone (Z-4) located at 13.44°N 76.82°E is on the northern side of Coimbatore and is very close to a major lineament no. 3 as shown in Fig. 4. This zone

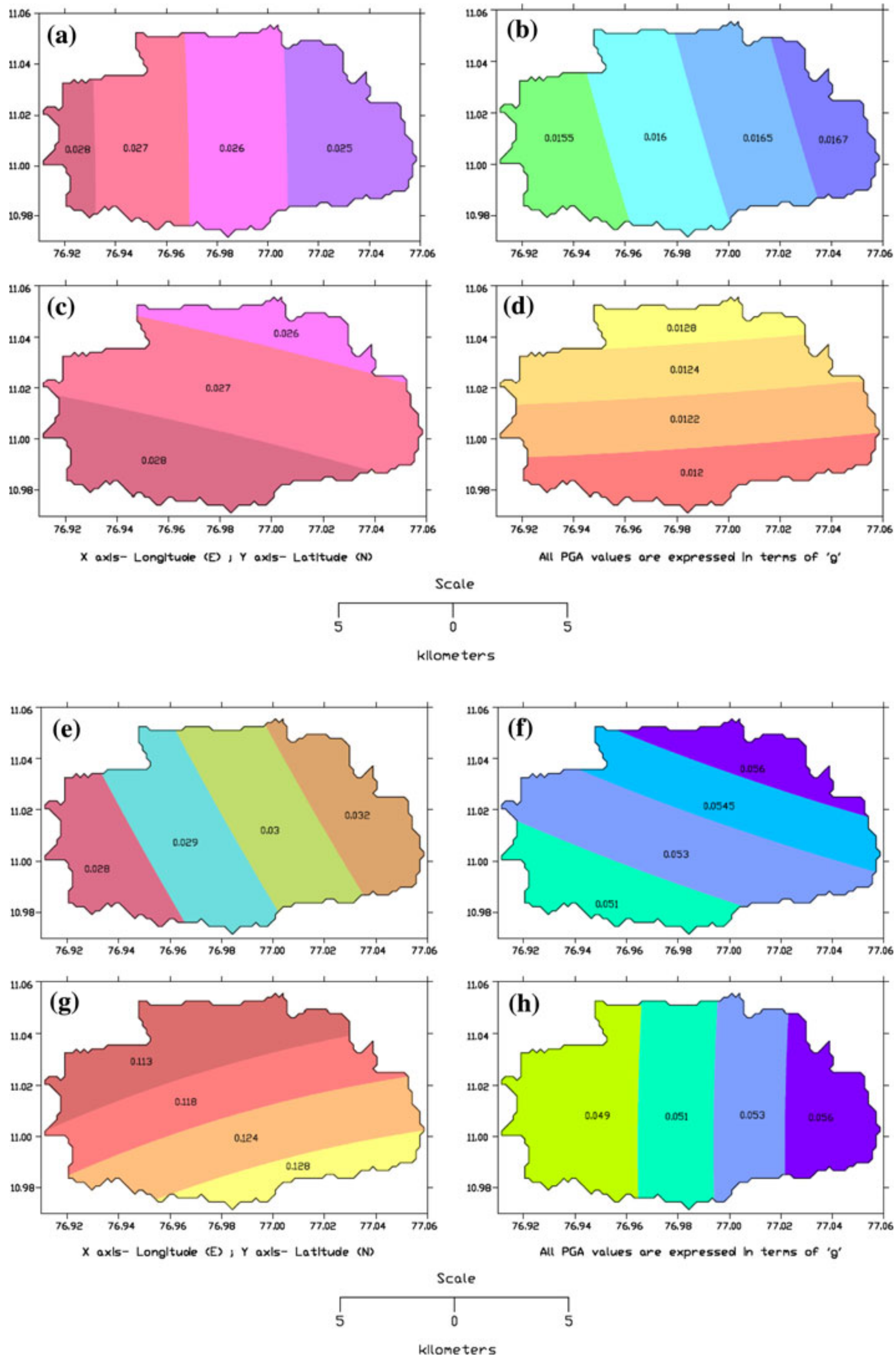

Fig. 7 **a**–**h** PGA map of Coimbatore city for probable earthquake locations

has experienced a past earthquake of magnitude 2.1 (M_w). The maximum PGA in Coimbatore due to this earthquake is caused in the northern part and its value is around 0.013 g. Figure 7d shows PGA distribution in Coimbatore city due to MCE of 6.4 at zone 4.

6.3.5 *PGA from zone 5*

Probable future earthquake zone (Z-5) located at 11.74°N 78.27°E is on the northeastern side of Coimbatore and it is very close to many minor lineaments, shear zones, and faults. There were five minor earthquakes in the range of magnitude 3 in the past. The maximum PGA in Coimbatore due to this earthquake is 0.032 g, and it was observed in the northeastern part of the city. Figure 7e shows PGA distribution in Coimbatore city due to MCE of 6.4 at zone 5.

6.3.6 *PGA from zone 6*

Probable future earthquake zone (Z-6) located at 11.94°N 77.32°E is on the northern side of Coimbatore and is very close to a three lineaments as shown in Fig. 4. This zone has experienced a past earthquake of magnitude 4.7 (M_w). The maximum PGA in Coimbatore due to this earthquake is caused in the northern part of Coimbatore and its value is around 0.056 g. Figure 7f shows PGA distribution in Coimbatore city due to MCE of 6.4 at zone 6.

6.3.7 *PGA from zone 7*

Probable future earthquake zone (Z-7) located at 10.51°N 77.13°E is on the southern side of Coimbatore and is very close to a minor lineament no. 14 as shown in Fig. 4. This zone has experienced a past earthquake of magnitude 4.5 (M_w). The maximum PGA in Coimbatore due to this earthquake is caused in the southern part of Coimbatore and its value is around 0.134 g. Among all above probable future earthquakes, this one gives the maximum PGA in Coimbatore city. Figure 7g shows PGA distribution in Coimbatore city due to MCE of 6.4 at zone 7.

6.3.8 *PGA from zone 8*

Probable future earthquake zone (Z-8) located at 11.00°N 78.00°E is on the eastern side of Coimbatore and is very close to a Neotectonic Fault no.1 (known as Caveri fault) as shown in Fig. 4. This zone has experienced a past earthquake of magnitude 4.9 (M_w). The maximum PGA in Coimbatore due to this earthquake is caused in the eastern part of Coimbatore and its value is around 0.056 g. Figure 7h shows PGA distribution in Coimbatore city due to MCE of 6.4 at zone 8.

6.4 New seismic zonation map for Coimbatore city

Eight PGA distribution maps are generated considering eight possible future earthquake zones. For microzonation and estimation of earthquake effects, one final map is warranted. In order to develop seismic zonation map at micro level, PGA values from eight probable zones have been compiled for each grid points and maximum PGA value has been selected at each grid point. The maximum probable PGA map of Coimbatore is generated by

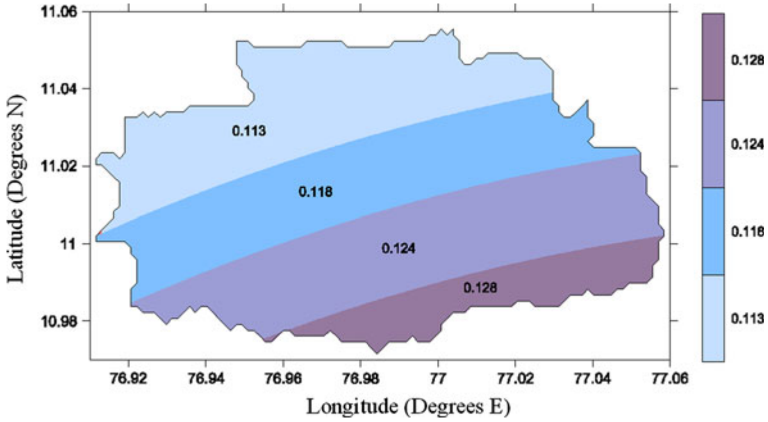

Fig. 8 New seismic zonation map of Coimbatore by considering maximum Peak ground acceleration due to eight probable future earthquake locations

considering the maximum PGA caused by different zones at every grid point. Figure 8 shows the maximum PGA due to MCE of 6.4 at eight locations identified in this study. This map has been divided as five groups and called as a "New seismic zonation map of Coimbatore" for further studies. Northwestern part of the City is relatively having a less PGA when compared to south eastern part of the city. The city may be expected to experience the minimum PGA of above 0.1 g at rock level due to any earthquakes around Coimbatore in near future. In order to assess effectiveness of proposed rupture-based seismic hazard analysis, final PGA map obtained in this study is compared with the PGA map by deterministic seismic hazard analysis (DSHA) that is presented in the next section.

7 Deterministic seismic hazard analysis of Coimbatore

Seismic hazard analysis is usually carried out by considering possible earthquake sources around 100–300 km radius of study area and by determining maximum credible earthquake for each source (Kramer 1996). Maximum credible earthquake (MCE) of each seismic source is usually calculated based on slip rate of fault and past seismic history. In the absence of slip rate, the maximum magnitude (MCE) can be arrived by increasing 0.3–1 unit to past reported earthquake magnitude close to source. RaghuKanth and Iyengar (2006), Sitharam and Anbazhagan (2007), and Anbazhagan et al. (2009) have estimated maximum magnitude of each source by adding 0.5 units to past earthquake close to the source. Menon et al. (2010) have arrived at the maximum cutoff magnitude for each source by considering maximum historical earthquake (MHE) close to the source zone. Maximum cutoff magnitude of each source in this region is arrived by increasing MHE by 0.3 units. Seismotectonic map in Fig. 2 shows that many minor to damaging earthquakes are reported within the radius of 100 km around Coimbatore city. There were three damaging earthquakes, i.e., M_w greater than 5.0 namely, M_w 6.3 and 5.7 at 10.80°N 76.80°E, M_w 5.7 at 11.46°N 76.7°E, and M_w 5.3 at 11°N 77°E. These three earthquakes and associated sources have been considered for PGA estimation. MCE has been estimated by increasing 0.5 units to past earthquake similar to previous studies in the region. The PGA for every grid point in Coimbatore is calculated for this earthquake, and the PGA map is plotted.

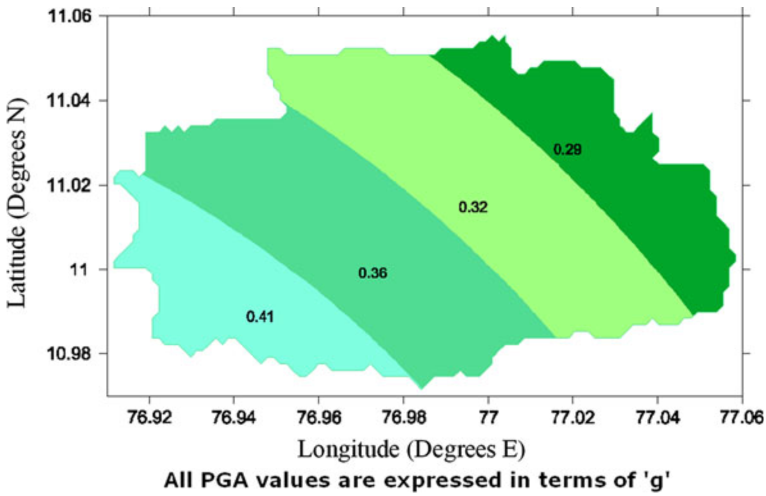

Fig. 9 Seismic zonation map of Coimbatore based on deterministic seismic hazard analysis

Figure 9 shows PGA distribution in Coimbatore city by DSHA approach. The maximum PGA in Coimbatore is found to be 0.44 g and is observed at southwestern part of the city. The minimum PGA is found to be 0.29 g and is observed at Northeastern part of Coimbatore city. By comparing Figs. 8 and 9, it can be easily observed that DSHA PGA values and distribution pattern completely differ from those of proposed rupture based analysis.

8 Results and discussion

Expected peak ground acceleration at rock level for Coimbatore city has been mapped based on rupture-based seismic hazard analysis (RBSHA) proposed in this study and compared with that mapped based on "Deterministic seismic hazard analysis (DSHA)." PGA mapped in this study is relatively more when compared to that mapped in previous studies and comparable with recent studies. Indian seismic code IS 1893 (BIS 2002) has given design-based peak ground acceleration of 0.08 g for Coimbatore, which is relatively lower than the predicted values in this study. Mapped PGA values in this study are lower than effective peak ground acceleration of 0.16 g given in IS 1893 (BIS 2002) based on maximum credible earthquake (MCE). Indian code has arrived at a PGA using past earthquake intensity by considering deterministic approach. PGA values obtained in this study are more than the PGA reported for the study area by Bhatia et al. (1997) and Ravi Kumar and Bhatia (1999) by probabilistic approach and Parvez et al. (2003) by deterministic approach. Jaiswal and Sinha (2006) mapped PGA based on probabilistic approach; according to them, Coimbatore falls in contour interval of PGA 0.05–0.06 g. These values are much less than the rupture-based approach followed in this study. Menon et al. (2010) found Coimbatore PGA value of 0.086 g for 475 years return period and 0.164 g for 2475 years return period based on logic tree probabilistic approach. Maximum PGA reported in this study is well within PGA for the return period of 2475 years and more than 475 years return period PGA. PGA obtained by carrying out conventional DSHA is much more than previous studies and present study of RBSHA, which may be attributed due to 1900 earthquake, as this event is reported very close to Coimbatore city. Chances for similar earthquakes to occur in same fault in the near future are very less. PGA mapped for Coimbatore in this study is slightly higher than PGA obtained for 475 year return period by probabilistic approach. It is difficult to define exact source locations in probabilistic approach. Source location and resulting time histories are very important to calculate seismic hazard parameters for microzonation. In the present method, source is well known; seismic hazard parameters of amplification and liquefaction factor can be assessed using these sources. Here, it is noted that Venkatanathan et al. (2005) has said that there is possibility of occurrence of earthquake similar to 1900 earthquake close to Coimbatore in near future based on planetary configuration. Location of predicated earthquake is away from previously reported locations, but coordinates are given in right ascension and declination and it is difficult to locate the predicated earthquake in our seismotectonic map. Maximum PGA mapped at rock level from eight zones may represent the PGA due to this predicated earthquake also.

9 Conclusions

Seismic hazard values of PGA are conventionally mapped considering past earthquake and its recurrence interval. Most of the time, earthquakes may not occur in the same zone because it needs time to store strain energy, particularly in intraplate regions. In this paper, a new attempt has been made to locate future probable earthquake zones considering subsurface rupture phenomena and hazard values are estimated at rock level considering proposed approach. Coimbatore city has been selected as the study area, and it was divided as $0.1^\circ \times 0.1^\circ$ grids to map the hazard values. Seismotectonic map for Coimbatore has been prepared by considering past earthquakes and seismic sources. Earthquake data were divided as damaging earthquakes (M_w of 5 and above) and minor earthquakes (less than 5). Rupture character of the region has been established by considering damaging earthquakes and fault lengths. Subsurface rupture length of the region is 5.2% of total length of seismic source for damaging earthquakes. Ruptured seismic sources are delineated by drawing influence circles considering subsurface length of the damaging earthquakes. These locations are considered as limited probable locations for future earthquake for a period of 50–100 years, because the average return period of intraplate damaging earthquakes is about 200–500 years. Eight probable earthquakes zones are identified for near-future earthquakes. These eight zones identified in this study are matching with the seismogenic sources in the region identified by other researchers and away from past major earthquakes. Maximum credible earthquake of 6.4 (M_w) is arrived by considering 15% increased rupture character of the region. Peak ground acceleration at rock level has been estimated considering maximum possible earthquake at focal depth of 10 km. Eight PGA maps are generated, and final seismic hazard map of Coimbatore has been arrived considering maximum PGA at each grid from these eight zones. PGA values arrived from new approach are more than that of previous studies in the region and are comparable with recent studies. PGA values arrived from new method are compared to conventional deterministic approach. Conventional approach gives higher PGA values when compared to proposed approach. Proposed approach may be more appropriate for future zonation and microzonation for disaster management as the seismic zones are well defined and are not associated with past damaging earthquake locations.

Acknowledgments First Author thanks “The Seismology Division,” Ministry of Earth Sciences, Government of India for funding the project.

References

Abrahamson NA, Silva WJ (1997) Empirical response spectral attenuation relations for shallow crustal earthquakes. Seism Res Lett 68(1):94–127

Anbazhagan P (2007) Site characterization and seismic hazard analysis with local site effects for microzonation of Bangalore. PhD Dissertation, Indian Institute of Science, Bangalore, India

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

Anbazhagan P, Thingbaijam KKS, Nath SK, Narendara Kumar JN, Sitharam TG (2010a) Multi-criteria seismic hazard evaluation for Bangalore city, India. J Asian Earth Sci 38:186–198

Anbazhagan P, Vinod JS, Sitharam TG (2010b) Evaluation of seismic hazard parameters for Bangalore Region in South India. Disaster Adv 3(3):5–13

Atkinson GM, Boore DM (1995) Ground-motion Relations for Eastern North America. Bull Seismol Soc Am 85(1):17–30

Bhatia SC, Ravi Kumar M, Gupta HK (1997) A probabilistic seismic hazard map of india and adjoining regions. http://www.seismo.ethz.ch/gshap/ict/india.html. Accessed on 25 Aug 2008

Bilham R (2004) Earthquakes in India and the Himalaya—tectonics, geodesy and history. Ann Geophys 47(2):839–858

BIS (1962) IS 1893–1962 Indian standard criteria for earthquake resistant design of structures. Bureau of Indian Standards, New Delhi

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

Boominathan A, Dodagoudar GR, Suganthi A, Uma Maheswari R (2007) Seismic hazard assessment considering local site effects for microzonation studies of Chennai city. In: Proceedings of Microzonation A workshop at Indian Institute of Science, Bangalore, pp 94–104

Boore DM (1983) Stochastic simulation of high-frequency ground motions based on seismological models of the radiated spectra. Bull Seismol Soc Am 73:1865–1894

Boore DM (2003) Simulation of ground motion using the stochastic method. Pure Appl Geophys 160:635–675

Campbell KW, Bozorgnia Y (2008) NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD and 5% damped linear elastic response spectra for periods ranging from 0.01 to 10 s. Earthq Spectra 24(1):139–171

Ganesha Raj K (2001) Major lineaments of Karnataka and their significance with respect to seismicity—remote sensing based analysis. Ph.D Dissertation, Gulbarga University, Karnataka, India

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

Gupta ID (2006) Delineation of probable seismic sources in India and neighborhood by a comprehensive analysis of seismotectonic characteristics of the region. Soil Dyn Earthq Eng 26:66–790

Hwang H, Huo JR (1997) Attenuation relations of ground motion for rock and soil sites in eastern United States. Soil Dyn Earthq Eng 16:363–372

Iyengar RN, RaghuKanth STG (2004) Attenuation of strong ground motion in peninsular India. Seismol Res Lett 75(4):530–540

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

Jaiswal K, Sinha R (2006) Probabilistic modeling of earthquake hazard in stable continental shield of the Indian Peninsula. ISET J Earthq Technol 43(3):49–64

Kramer SL (1996) Geotechnical earthquake engineering. Pearson Education Ptd. Ltd, Delhi, India (Reprinted 2003)

Krinitzsky E (2005) Discussion on Problems in the application of the SSHAC probability method for assessing earthquake hazards at Swiss nuclear power plants. Eng Geol 78:285–307. Eng Geol 82:66–68

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

Mandal P (1999) Intraplate stress distribution induced by topography and crustal density heterogeneities beneath the south Indian shield. Tectonophysics 302:59–172

Mandal P, Rastogi BK, Gupta HK (2000) Recent Indian earthquakes. Curr Sci 79(9):1334–1346

Mark RK (1977) Application of linear statistical model of earthquake magnitude versus fault length in estimating maximum expectable earthquakes. Geology 5:464–466

Martin S, Szeliga W (2010) A catalog of felt intensity data for 589 earthquakes in India, 1636–2008. Bull Seismol Soc Am 100(2):562–569

Menon A, Ornthammarath T, Corigliano M, Lai CG (2010) Probabilistic seismic hazard macrozonation of Tamil Nadu in Southern India. Bull Seismol Soc Am 100(3):1320–1341

Parvez AI, Vaccari Franco, Panza October GF (2003) A deterministic seismic hazard map of India and adjacent areas. Geophys J Int 155:489–508

Purnachandra Rao N (1999) Single station moment tensor inversion for focal mechanisms of Indian intra-plate earthquakes. Curr Sci 77:1184–1189

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

Ramasamy SM (2006) Remote sensing and active tectonics of south India. Int J Remote Sens 27(20):4397–4431

Ravi Kumar M, Bhatia SC (1999) A new seismic hazard map for the Indian plate region under the global seismic hazard assessment programme. Curr Sci 77(3):447–453

Reddy PR (2003) Need for high-resolution deep seismic reflection studies in strategic locales of South India. Curr Sci 84(8):25

SEISAT (2000) Seismotectonic atlas of India. Geological Survey of India, India

Singh HN, Mathai J, Neelakandan VN, Shanker D, Singh VP (2005) A database on occurrence pateerns of unusual geological incidents in Southwest Peninsular India and its implication of future seismic activity. Acta Geod Geoph Hung 40(1):69–88

Singh HN, Shanker D, Neelakandan VN, Mathai J, Singh VP, Banerjee M (2008) Spurt of geosignatures signifying possible precursors to an major Earthquake in Southwestern Indian Peninsula. Icfai J Earth Sci 2(2):7–38

Sitharam TG, Anbazhagan P (2007) Seismic hazard analysis for the Bangalore region. 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

Srinivasan R, Sreenivas BL (1977) Some new geological features from the Landsat imagery of Karnataka. J Geol Soc India 18:589–597

Subrahmanya KR (1996) Active intraplate deformation in south India. Tectonophysics 262:231–241

Subrahmanya KR (2002) Deformation related lineaments in the Indian Peninsula near 13^{o}. J Geophys 23(2):59–68

Szeliga W, Hough SE, Martin S, Bilham R (2010) Intensity, magnitude, location, attenuation in India for felt earthquakes since 1762. Bull Seismol Soc Am 100(2):570–584

Valdiya KS (1998) Late quaternary movements and landscape rejuvenation in South-eastern Karnataka and Adjoining Tamil Nadu in South India shield. J Geol Soc India 51:139–166

Venkatanathan N, Rajeshwara Rao N, Sharma KK, Periakali P (2005) Planetary configuration: implications for earthquake prediction and occurrence in Southern Peninsular India. J Indian Geophys Union 9(4):263–276

Wang Z (2005) Discussion on problems in the application of the SSHAC probability method for assessing earthquake hazards at Swiss nuclear power plants. Eng Geol 78:285–307; 82:86–88

Wells DL, Coppersmith KJ (1994) New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. Bull Seismol Soc Am 4(84):975–1002