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ORIGINAL PAPER

Seismic intensity map of South India for estimated future earthquakes

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Abstract In this study, an attempt has been made to prepare the seismic intensity map for south India considering the probable earthquakes in the region. Anbazhagan et al. (Nat Hazards 60:1325–1345, 2012) have identified eight probable future earthquake zones in south India based on rupture-based seismic hazard analysis. Anbazhagan et al. (Eng Geol 171:81–95, 2014) has estimated the maximum future earthquake magnitude at these eight zones using regional rupture character. In this study, the whole south India is divided into several grids of size $1^{o} \times 1^{o}$ and the intensity at each grid point is calculated using the regional intensity model for the maximum earthquake magnitude at each of the eight zones. The intensity due to earthquakes at these zones is mapped and thus eight seismic intensity maps are prepared. The final seismic intensity map of south India is obtained by considering the maximum intensity at each grid point due to the estimated earthquakes. By looking at the seismic intensity map, one can expect slight to heavy damage due to the probable earthquake magnitudes. Heavy damage may happen close to the probable earthquake zones.

Keywords Earthquake · Probable earthquake zone · Intensity · South India

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Introduction

Indian cities face threats from a variety of natural hazards, among which damages and loss of lives caused by the earthquake and related hazards are predominant, even though it occurs infrequently. Seismic hazard values are the essential components of earthquake resistant design and disaster management. The results of earthquake hazard analysis are useful to estimate the site effects of liquefaction, landslide, and tsunami for microzonation of city, which can be further useful for urban planning and disaster management. Macro level and micro level hazard parameters are estimated and mapped. Macro level hazard values are given in the seismic codal provision of India based on observed seismicity. The spate of earthquakes in the recent past which have caused extensive damage has heightened the sensitivity of administrators, engineers, and general public to the looming hazard due to future earthquakes which might occur near densely populated cities worldwide, particularly in India. Major earthquakes are rare events in south India, but moderate earthquakes can be expected in this region (Anbazhagan et al. 2014). The increasing population in India has resulted in unplanned constructions and the mushrooming of buildings. These are damageable even for a moderate earthquake and its associated effects. The risk faced by human habitat due to earthquakes can be reduced by making man made systems and structures less vulnerable and more robust to withstand the expected earthquake ground motion.

The purpose of mapping intensity is that there is no straightforward way to associate the recorded ground motions with damage which is a complex function of ground motion level, duration, local site conditions, and building vulnerability. Moreover, the macroseismic intensity is assigned based on the observed ground shaking/damage and thereby it can be directly related to the damage potential of future earthquakes (Sørensen et al. 2009). Due to the absence of well-recorded acceleration time history, most of ground motion prediction equations (GMPEs) developed for Peninsular India are from synthetic ground motion (Anbazhagan et al. 2014). Summary of applicable GMPE and its limitations can be found in Anbazhagan et al. (2014). In addition, very limited GMPEs are available to estimate the surface acceleration with site effects. In this study, surface level intensity due to probable future earthquakes has been estimated by considering the intensity-based attenuation relation developed by Szeliga et al. (2010) considering Indian earthquake data.

Study area and seismicity

Southern India is an area encompassing states of Andhra Pradesh, Karnataka, Kerala, and Tamil Nadu as well as the union territories of Lakshadweep and Pondicherry, occupying 19.31 % of India's area. The geography of the region is diverse, encompassing two mountain ranges, the Western and Eastern Ghats, and a plateau heartland. South India is a peninsula in the shape of a vast inverted triangle, bounded on the west by Arabian Sea, on the east by the Bay of Bengal, on the south by Great Indian Ocean, and on the north by the Vindhya and Satpura ranges. The Western Ghats continue towards south, forming the Malenadu (Canara) region along the Karnataka coast, and terminate at the Nilgiri Mountains, an inward (easterly) extension of the Western Ghats. The Nilgiri range runs approximately along the borders of Tamil Nadu with northern Kerala, Karnataka and encompasses the Palakkad, Wayanad hills, and the Sathyamangalam range extending on to the relatively low-lying hills of the Eastern Ghats in the western portion of the Tamil Nadu, Andhra Pradesh border.

Figure 1 shows the south India and its seismotectonics. The southern India, once considered as part of the 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 real. 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). 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), Ramalingeswara Rao (2000), Subrahmanya (2002, 1996), Parvez et al. (2003), Sridevi Jade (2004), Ganesha Raj and Nijagunappa (2004), Sitharam et al. (2006), Sitharam and Anbazhagan (2007), Jaiswal and Sinha (2008), Boominathan et al. (2007)), Lai et al. (2009), Anbazhagan et al. (2009), Vipin et al. (2009). Martin and Szeliga (2010), Szeliga et al. (2010), Menon et al. (2010), RaghuKanth (2010), and Anbazhagan et al. (2013, 2014). Among these researchers, Parvez et al. (2003), Sitharam et al. (2006), Sitharam and Anbazhagan (2007), Anbazhagan et al. (2009), Jaiswal and Sinha (2008), Boominathan et al. (2007)), Lai et al. (2009), Anbazhagan et al. (2009), Vipin et al. (2009), Menon et al. (2010), and Anbazhagan et al. (2013, 2014)) have carried out seismic hazard analysis of south India or selected cities in south India.

Probable future location and maximum magnitude

The location of past damaging earthquake plays a very important role in the seismic hazard analysis of the region. In well-known deterministic and probabilistic seismic hazard analyses, more weights are given for past major earthquakes and location rather than future probable locations. In order to overcome this, Anbazhagan et al. (2012) proposed a new method of seismic hazard analysis called 'Rupture based seismic hazard analysis'. Here, authors considered an average return period of the damaging earthquake in the region and delineated probable future earthquake location by considering recent past earthquakes. The probable locations were identified by considering the minor earthquakes, potential seismic sources, and by eliminating the damaging earthquake location. These are called as the 'Probable Future Earthquake Zones' (PFEZ). Eight probable future earthquake zones have been identified in south India as shown in Fig. 1. These eight probable future rupture zones are named as Z-1 to Z-8 for further discussion. Summary of probable earthquake zones is given in Table 1. Anbazhagan et al. (2014) reported that many minor earthquakes occurred recently in the region close to the probable zones. These minor earthquakes may be indicative of seismic activity in the area.

Maximum credible earthquake (MCE) of each source is important as this value is used to arrive at reliable seismic hazard values. Maximum earthquake of each seismic source is usually calculated based on slip rate of fault and past seismic history. In the absence of slip rate and considering low seismicity of the region, the maximum magnitude is estimated by the addition of an increment to the largest historical earthquake close to the source. This procedure is widely followed in India because of the absence of slip rate model and limited seismic database. Recently, Anbazhagan et al. (2012) have established rupture character of the region by carrying out a parametric study between subsurface rupture lengths and associated past earthquake magnitude for 18 faults which have caused earthquake of M_w 5 and above for Coimbatore region. The total fault length was taken from seismotectonic map and RLD was calculated using Wells and Coppersmith (1994) considering past earthquake

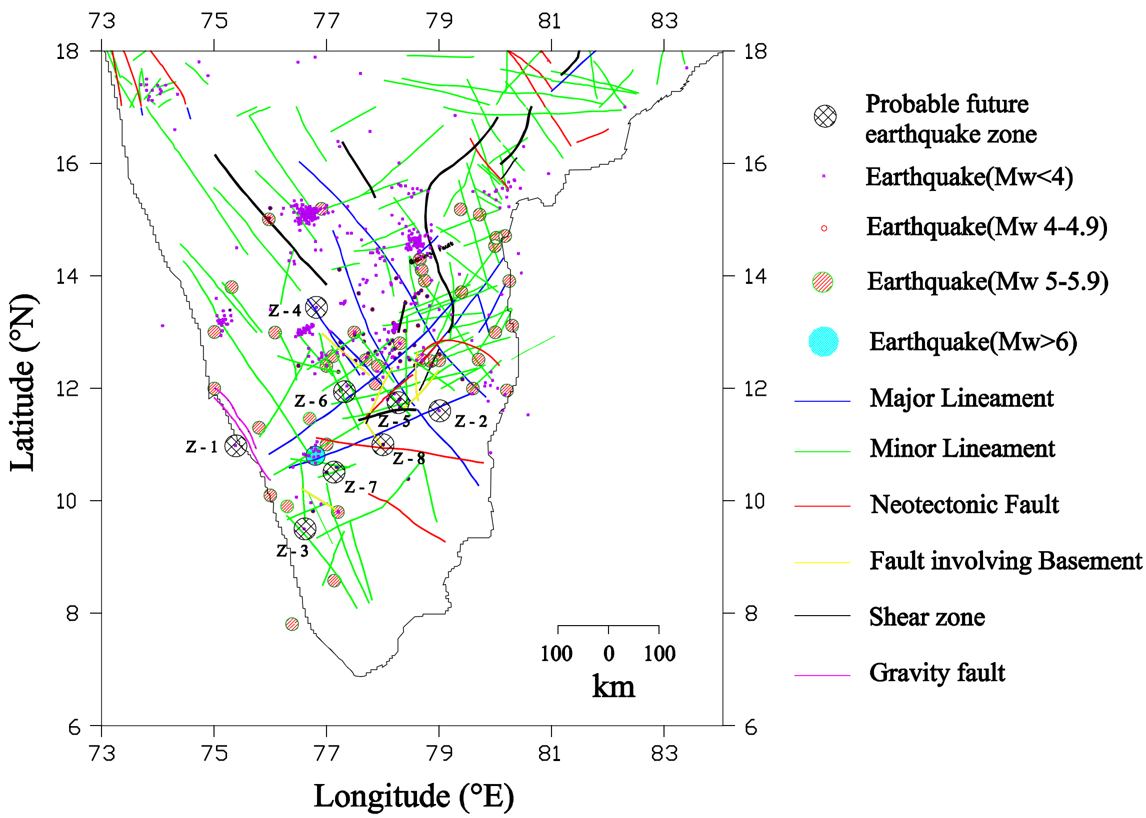

Fig. 1 Seismotectonic map of study area with location of probable zones

magnitude. RLD values are divided by the total length of the fault and subsurface rupture length is represented as a percentage of the total length of the fault. Anbazhagan et al. (2012) noticed that the estimated magnitude matches very well with the reported earthquake magnitude for subsurface rupture length of 1.65 to 6.6 % of total length. It was noticed that the percentage of the total fault ruptured for shorter faults is more when compared to that of longer faults, showing a decreasing trend with an increase in the fault length. This indicates that most of the damaging earthquakes in the region follow some trend. Based on the observed trend, the curve was divided into two segments, considering the average percentage of fault ruptured and total length of the fault. Segment-I consists of faults with a total length up to 120 km and average RLD equal to 4.86 % of total length of the fault. Segment-II consists of faults with a total length of 120 to 450 km and average RLD equal to 2.15 % of total length of the fault. The rupture values of these two segments can be taken as an average rupture character of the region and may be considered to estimate design basis earthquakes in the region. However, unusual rupture can cause large events where RLD is larger than the average regional rupture values. Therefore, the maximum possible earthquake in the region is increased to account for the variations and increased value is used to estimate representative maximum earthquake of the source considering Wells and Coppersmith (1994) relation. In Anbazhagan et al. (2014), average regional rupture length value is increased to 6 % of the total fault length and used to estimate maximum possible earthquake magnitude of the seismic source close to probable seismic zones. Maximum possible earthquake magnitude for each zone estimated using the increased rupture character of the region is listed in Table 1. Maximum of the possible earthquake magnitudes in each source zone is considered as the Maximum Credible Earthquake (MCE) in the study area.

Table 1 Summary of eight probable future earthquake zones considered in the study

Probable zone	Zone location		Maximum earthquake magnitude for each source zone (M_W) by considering the regional rupture character
	Latitude	Longitude	
Z-1	10.98	75.38	5.8
Z-2	11.60	79.01	6.4
Z-3	09.50	76.62	6.0
Z-4	13.44	76.82	5.8
Z-5	11.74	78.27	5.5
Z-6	11.94	77.32	6.5
Z-7	10.51	77.13	5.5
Z-8	11.00	78.00	6.3

Intensity relation for the study region

Region-specific ground motion predictive equation helps to predict reliable seismic hazard values. There was no region-specific ground motion predictive equation before 2004 for Peninsular India, in particular, south India (Anbazhagan et al. 2014). There are two region-specific attenuation equations developed by the same research group to determine the PGA values for a given magnitude and hypocentral distance. Of these, one can be used to estimate surface PGA. Both attenuation equations were developed considering the synthetic acceleration-time histories based on seismological model by Boore (1983, 2003). Most of the stable continents/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 large earthquakes. Therefore, there are no ground motion predictive equation/attenuation models developed considering the recorded earthquake data. There are many comprehensive catalog of felt intensities available for Indian region, and summary of these can be found in Martin and Szeliga (2010). Szeliga et al. (2010) compiled these data and developed intensity attenuation relationship for Craton and Himalayan region separately. The study region falls under Craton part. Szeliga et al. (2010) also highlighted that intensity attenuation for Cratonic events is higher than that of

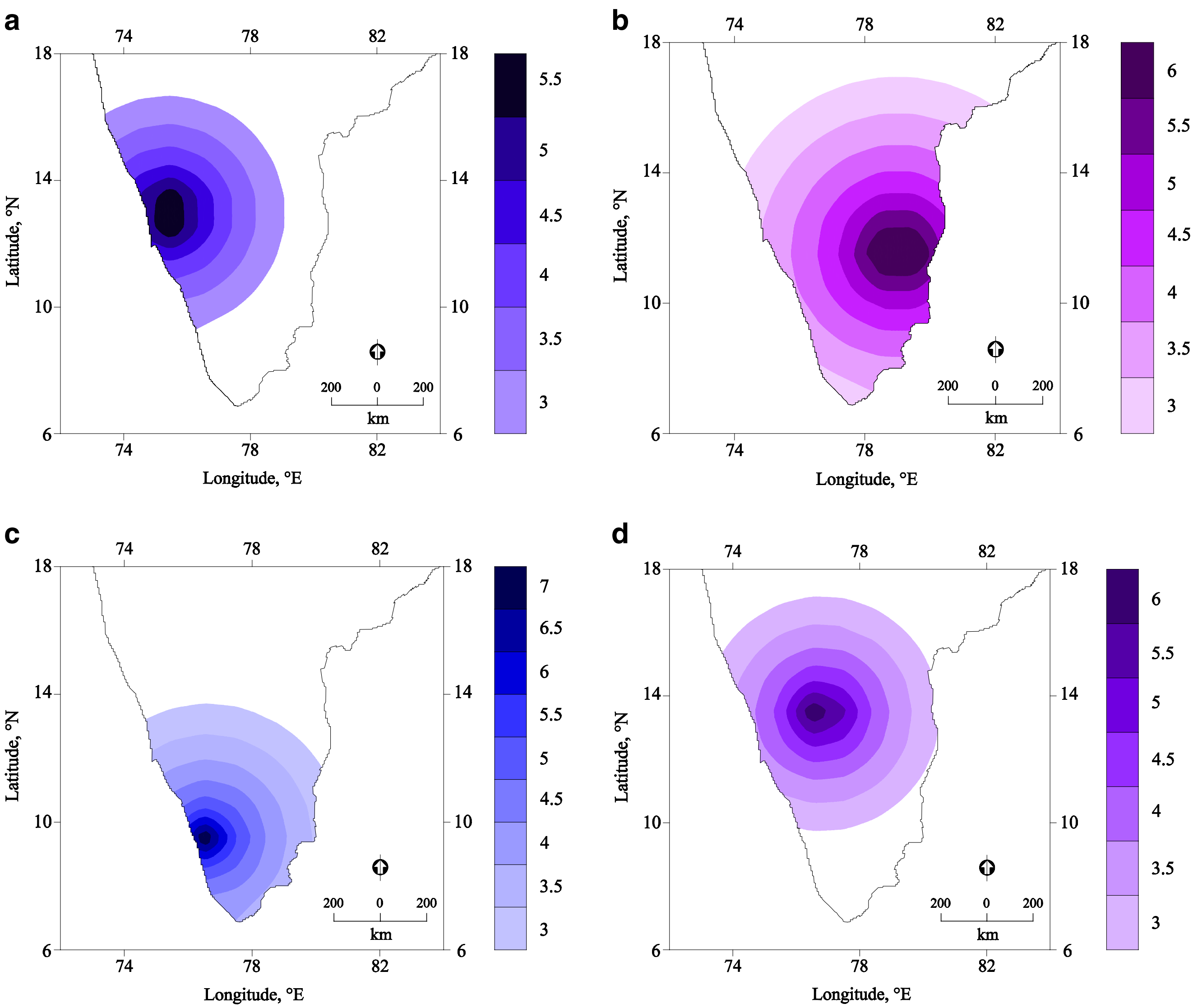

Fig. 2 **a** Expected intensity due to probable source zone 1 (Z-1) with maximum magnitude of M_w 5.8. **b** Expected intensity due to probable source zone 2 (Z-2) with maximum magnitude of M_w 6.4.**c** Expected Intensity due to probable source zone 3 (Z-3) with maximum magnitude of M_w 6.0. **d** Expected intensity due to probable source zone 4 (Z-4) with maximum magnitude of M_w 5.8. **e** Expected intensity due to probable source zone 5 (Z-5) with maximum magnitude of M_w 5.5. **f** Expected intensity due to probable source zone 6 (Z-6) with maximum magnitude of M_w 6.5. **g** Expected intensity due to probable source zone 7(Z-7) with maximum magnitude of M_w 5.5. **h** Expected intensity due to probable source zone 8 (Z-8) with maximum magnitude of M_w 6.3

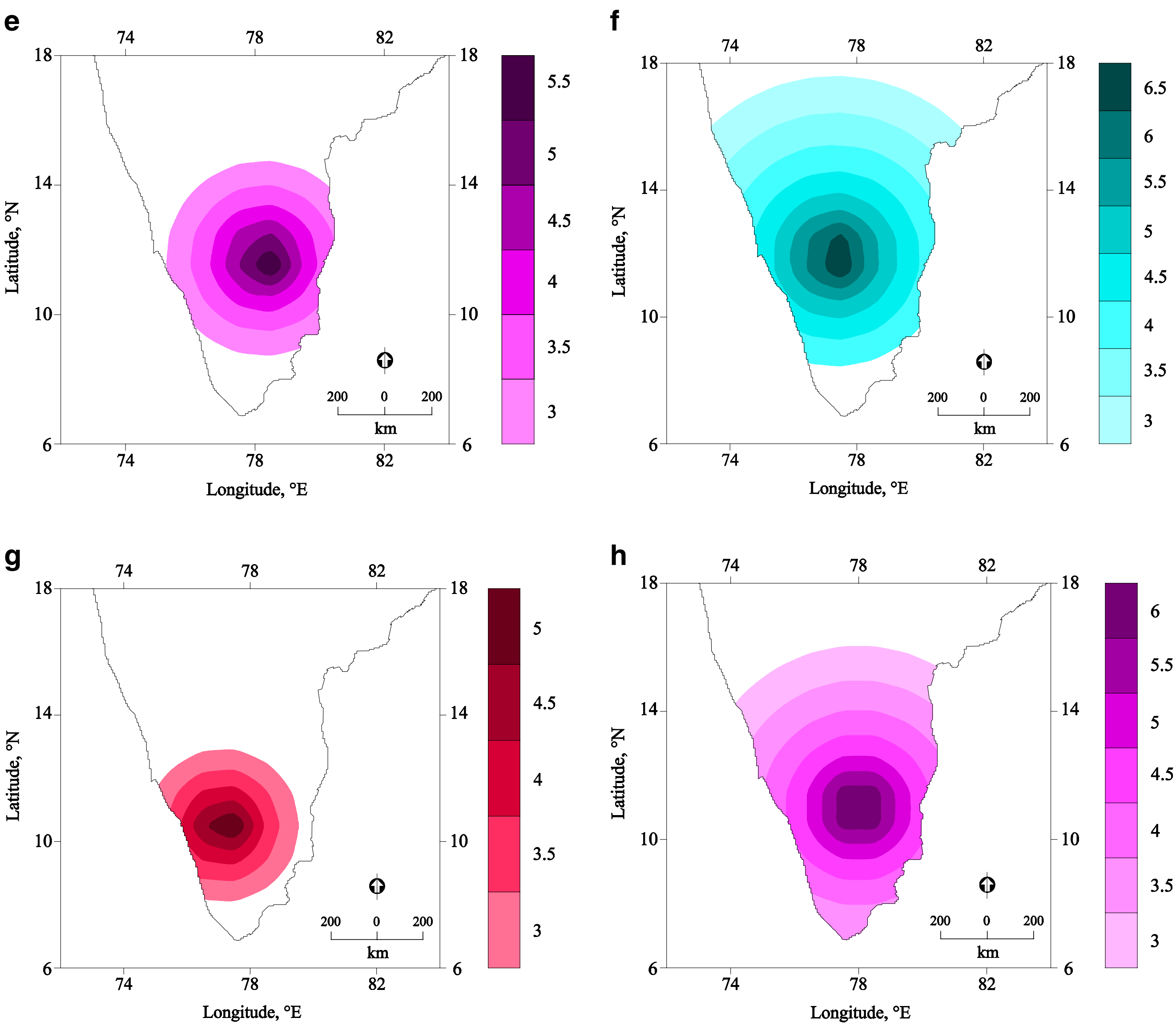

Fig. 2 (continued)

intensity attenuation reported for central/eastern North America. The intensity attenuation relationship developed by Szeliga et al. (2010) is used in this study, which is given below:

$$I = 3.67 + 1.28M_w - 0.0017R - 2.83\log(R) \quad (1)$$

where R is the hypocentral distance, M_w is the moment magnitude. Equation (1) was derived by assuming that the intensity is logarithmically proportional to the energy density of a point source (Szeliga et al. 2010). In this study, above intensity relation to predict European Macroseismic Scale 1998 (EMS-98) (Grünthal and Levret 2001) is used.

Analysis and results

In this paper, the study area of south India is divided into grids of size $1^0 \times 1^0$, forming around 160 grids. Intensities are calculated at the center of these grids considering the eight probable future earthquake zones and the estimated earthquake magnitude for each zone. For the estimated magnitude at zone-1, intensities are calculated at each grid point and mapped. Thus, eight seismic intensity maps for the study area is obtained. Intensity is calculated using the intensity attenuation relationship for Indian subcontinent developed by Szeliga et al. (2010). To further assess the damage distribution due to estimated earthquakes, the intensity map has been generated for south India. Intensities do vary substantially as a consequence of local site geology and other factors (Szeliga et al. 2010). The intensity distribution in

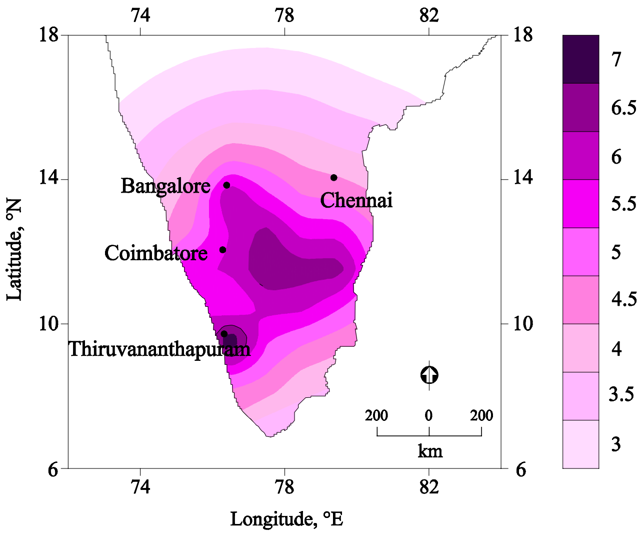

Fig. 3 Expected maximum intensity due to occurrence of earthquake in the any of the probable source zones

south India due to estimated earthquake at eight probable future earthquake zones is mapped and shown in Fig. 2a to h. The maximum intensity at each grid point due to the estimated earthquakes at eight probable zones is estimated. Predicted intensity map of south India is shown in Fig. 3. From figure, it can be noticed that central part of south India is expected to have more intensity values than the other part of south India, which may be due to location of probable zones. It can be also highlighted that ground shaking news is reported in this area. From this study, it is noticed that the area close to Thiruvananthapuram will experience a maximum intensity of 6 to 7 if an earthquake of magnitude 5.8–6.5 (M_w) occurs at any of the eight zones. Both Bangalore and Coimbatore will experience an intensity of 5 to 6 and Chennai will experience an intensity of 4 to 5 if an earthquake of magnitude 5.8–6.5 (M_w) occurs at any of the eight zones. These are the maximum intensities that these major cities can experience due to estimated earthquake at any of the eight zones. EMS intensity scale of 6 to 8 implies slight damage to heavy damage. Heavy damages are expected close to the epicenter and slight damage is expected away from the epicenter.

In this study, EMS gives damage level and projected loss and is helpful for disaster management and insurance. Loss estimation requires predictive model between intensity values and amount of project loss. As per Munich Reinsurance Group (2000), a damage band that expresses the inherent uncertainty in the expected loss due to the different behavior of buildings and structures during an earthquake is a function of the degree of felt. Most of existing loss estimation models are derived from western country earthquake loss and intensity values. Available model is based on interplate earthquake and building constructions in developed countries are completely different from the study area in the intraplate region. Therefore, new loss estimation model needs to developed to arrive projected loss from the estimated intensity value in the region. At present, there is no such model that can predict the projected loss of estimated intensity for Peninsular India.

Conclusion

The expected seismic intensity was mapped for south India by considering probable future earthquake zones and region-specific maximum magnitude. Eight probable future zones considered in this study were arrived by eliminating damaging earthquake locations and accounting recent minor earthquake and seismic sources. Region-specific maximum magnitude used in the study was estimated by establishing region-specific rupture character. Maximum possible intensity due to these eight probable zones was mapped. Maximum expected intensity due to any of these probable source is in the range of 6 to 7 EMS. Many seismic hazard analysis results given for the region mapped only peak or spectral accelerations, but in this study expected seismic intensity was mapped based on a probable source zone, which will be useful for disaster planning and management.

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