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ORIGINAL PAPER

Seismotectonic map and seismicity parameters for Amaravati area, India

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Abstract
The objective of the present study is to develop a seismotectonic map and seismicity parameters for the Amaravati area, part of Peninsular India. Amaravati is the proposed capital of Andhra Pradesh, India. The seismic influence zone for the present study is considered as a circular area within a 400 km radius from the High Court of Andhra Pradesh. A total of 919 earthquake events of all ranges of magnitude are covered under a specified influence zone. An earthquake catalog containing both historical and instrumental earthquake events of a moment magnitude (M_W) ≥ 3.5 from the year 1800 to 2020 is compiled from various sources. Main shocks were identified from the raw catalog and the completeness analysis was carried out. The magnitude of completeness for the present catalog data is fairly complete at the moment magnitude (M_W) of 2.7. The completeness period for different classes of magnitude such as 3.5–3.99, 4.0–4.49, 4.5–4.99, 5.0–5.49, 5.5–5.99, and $M_W \geq 6$ is 50, 60, 60, 65, 220, and 220 years respectively. The estimated seismicity parameters *a* and *b* values for the Amaravati area are in the range of 2.70 to 3.6 and from 0.75 to 0.88, respectively. The maximum expected earthquake magnitude of Amaravati was found to be 6.7. The fault map and seismotectonic map of the Amaravati region were also developed, which are very useful for seismic hazard analyses.

Keywords Fault map · Seismicity parameters · Seismotectonic map · Magnitude of completeness · Gutenberg-Richter law · Completeness analysis · Amaravathi

Introduction

Earthquakes are one of the disastrous natural phenomena like landslides and tsunamis. An earthquake is the disturbance of the surface of the earth originate from a sudden release of energy when the rupture of the bedrock takes place. The fluctuating behavior of earthquakes has generated interest among scientists for several years and continues to challenge people to catch a viable solution. Recent earthquakes, such as the India-Bangladesh earthquake of magnitude (M_W) 5.7 in 2017, the Sikkim Earthquake of magnitude (M_W) 6.9 in 2011, and Bhuj earthquake of magnitude (M_W) 7.7 in 2001, are enhanced the importance of seismic hazard analysis for every region in India. Earthquake hazard can be defined as an estimation of the mean probability (over space and time) of the occurrence of an earthquake event with a certain magnitude within a given time interval. The earthquake-induced hazard is uneven in space and has obvious directionality, i.e., after the occurrence of the earthquake, the degree of disaster may vary considerably at the same distance but in different directions (Ma et al. 2019a, b). These aspects make the seismic hazard assessment one of the challenging problems of geotechnical earthquake engineering. The first step of the earthquake hazard analysis is the determination of the seismicity parameters and development of seismotectonic map.

Amaravati is a city in the Guntur district of the Indian state of Andhra Pradesh, on the southern bank of the Krishna river. The city is the proposed legislative capital of Andhra Pradesh with 217 km^2 and has a population of about 0.1 million (Census, 2011). The population of Amaravati is expected to reach about 3.58 million by 2050 because of its industrial growth and urbanization (Goodess et al. 2019).

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Amaravati has been recognized by the Bureau of Indian Standards (IS 1893 Part-I 2016) under seismic zone III. This zone can be defined as a moderate risk zone of damage subject to VII severity on the Medvedev–Sponheuer–Karnik (MSK) scale with a zone factor of 0.16 g (PGA). In addition, the study area includes dams such as Nagarjuna Sagar dam, Srisailam dam, which have an engineering significance. The role of characterizing and assessing the risk potential to make Amaravathi capital city immune to seismic activity is extremely important because of its socio-economic significance. Seismicity maps play a vital role in seismic hazard analysis of any region. Several researchers have developed fault, seismicity maps for different regions in India in the past (Kumar and Suman 2020; Baruwal et al. 2020; Joshi et al. 2020; Mehta and Thaker 2020; Sandhu et al. 2020; Khan et al. 2020; Naik and Choudhury 2015; Kataria et al. 2013: Thaker et al. 2012; Kolathayar et al. 2012) Shanker and Sharma (1998) attempted to evaluate seismic hazard parameters for the Himalayas and the surrounding region by considering boundary lies between 20° N–36° N and 69° E–100° E for the catalog data of a period 1900–1990. The author has divided the entire Himalayan region into six seismogenic zones depending on its seismotectonic style. The reported b value for the six zones varied between 0.58 and 1.52. However, the authors have not attempted catalog completeness analysis. Iyenger and Ghosh (2004) conducted

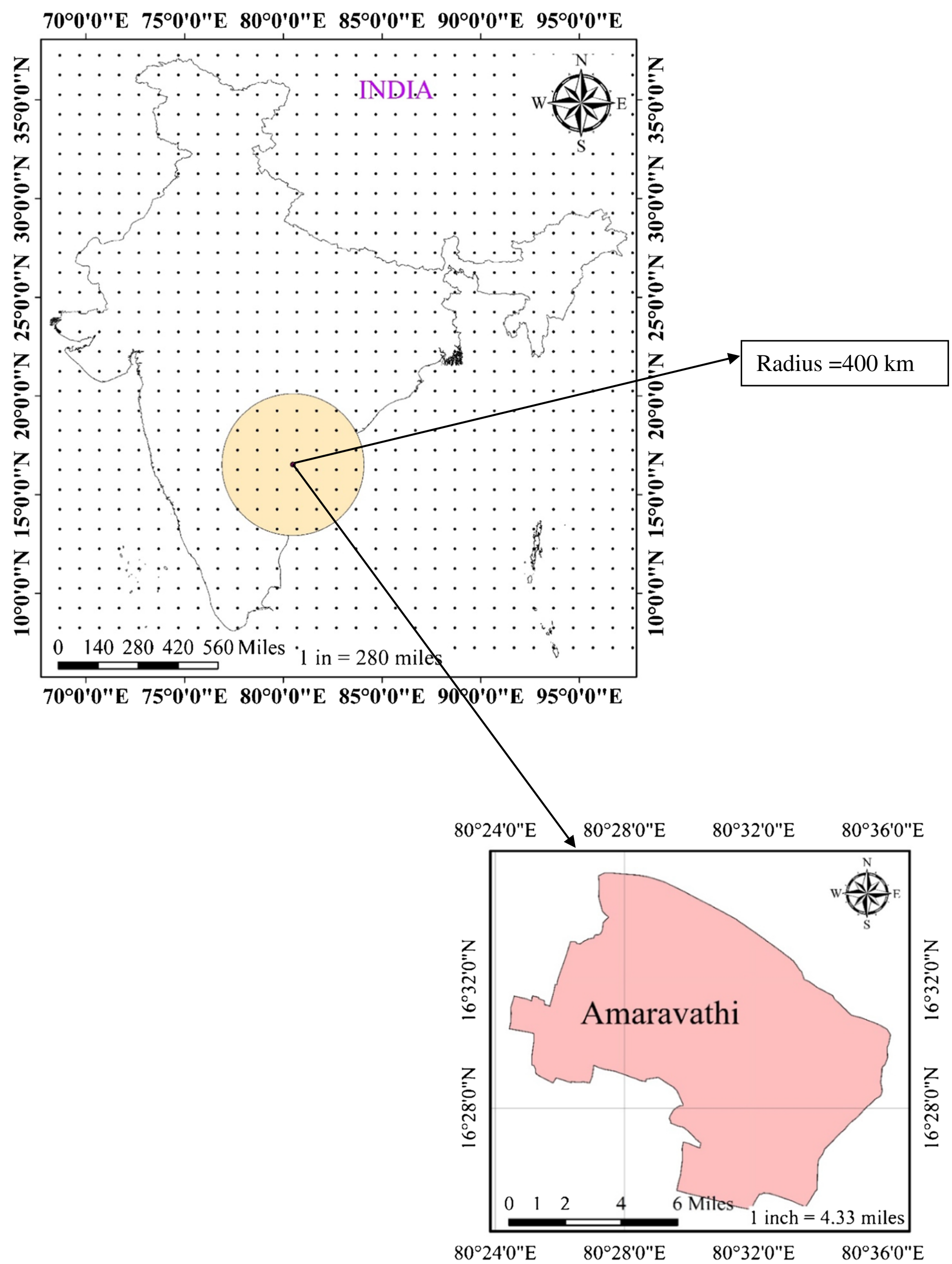


Fig. 1 Layout of study area, Amaravati, Andhra Pradesh, India

a microzonation study for the greater Delhi by considering a 300 km radius with the center as India Gate. The author has conducted Probabilistic Seismic Hazard Analysis (PSHA) and reported a Peak Ground Acceleration (PGA) of 0.2 g. This study has not used the areal source models and volume source models in the analysis.

Anbazghan et al. (2017) developed a seismotectonic map for Kanpur city, India. The linear seismogenic sources within a radius of 500 km are considered in the analysis. The author has divided Kanpur city into two zones. The Gutenberg-Richter relation is used and the *b* values are reported as 0.87 and 0.97. The author has conducted ground response analysis for Kanpur city. Puri and Jain (2016) attempted to evaluate the seismicity parameters of Haryana state for the catalog data of January 1505 to June 2013. A seismotectonic map for the Haryana state was developed by considering the seismogenic sources within a radius of 300 km. The authors have conducted deterministic seismic hazard analysis (DSHA) for Haryana state. The maximum Peak Ground Acceleration obtained for the Haryana state is in the range of 0.023 to 0.514 g. Only a single attenuation equation was used and the logic tree approach was not adopted. Anbazghan et al. (2019) developed a seismotectonic map for Patna district (which is in the Bihar state of India) by considering the linear seismogenic sources within a boundary of 500 km around Patna district. Also, the seismicity parameters were estimated. Chandra et al. (2018) attempted to estimate seismicity parameters of Kashmir valley by choosing the catalog data of a period 1902 to 2017. Patil et al. (2018). compiled an earthquake catalog for the study area of Vijayapura (Part of South India), considering Gol Gumbaz (archeological site) as a center, and developed a seismotectonic map for Vijayapura. Ramakrishnan et al. (2019) evaluated seismicity parameters for Mangalore city (Karnataka state in India) by considering catalog data for 1828–2008. To date, no study had presented the seismotectonic map for Amaravati and determined seismicity parameters. For the new capital city like Amarvati, seismic hazard studies are essential for proper urban planning and infrastructure that minimize earthquake risk. The initial step in the seismic hazard assessment is to prepare the seismotectonic map and estimate the seismicity parameters. Hence, in the present study, an effort has been made to develop the seismotectonic map of the Amaravati region and evaluate seismicity parameters for the Amaravati region, which are essential for seismic hazard assessment.

Study region and tectonic setting

Amaravati region, Andhra Pradesh, is considered as a study area in the present research. Figure 1 represents the layout of the study area digitized using the (ArcGIS 10.7.1 2020) software. Amaravati is one of the most important geological heritage sites of India. Amaravati is having the oldest Precambrian rocks, such as Khondalites and Charnockites (3000 million years old), trending north-east and south-west directions followed by Proterozoic Kadapa rocks (600 million years old) in the south (Ramaswamy and Murty 1973). Some of the significant earthquake epicenters close to the present study area are Jaggayyapeta of magnitude (M_W) 4.4 in 2020, Ongole earthquake of magnitude (M_W) 4.6 in 1987, and Bhadrachalam earthquake of magnitude (M_W) 5.7 in 1969 has sent alarm signals that need a seismic hazard assessment in the region. For seismic hazard analysis of any region, a

Table 1 Important faults surrounding Amaravati area, Andhra Pradesh

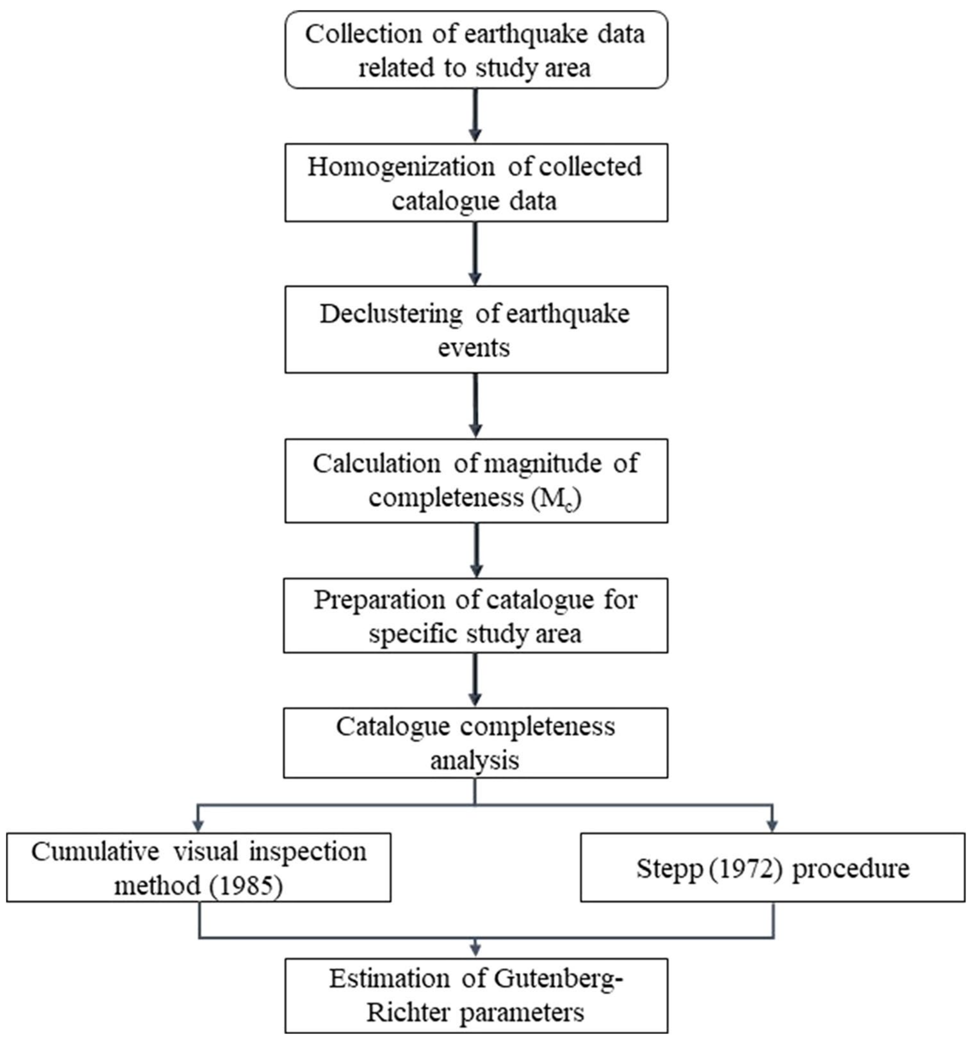
S. no	Name of the fault	Type of fault
1	Tirumala Fault	Fault involving basement and cover
2	Karkambudi-Swarnamukhi Fault	Fault involving basement and cover
3	Badvel Fault	Fault involving basement and cover
4	Gani-Kalva Fault	Fault involving basement and cover
5	Bhavani River Fault	Fault involving basement and cover
6	Nallavagu Fault	Fault involving basement and cover
7	Nekkantivagu Fault	Fault involving basement and cover
8	Krishna River Fault	Fault involving basement and cover
9	Bukkapatnam Fault	Fault involving basement
10	Raichur-Nagar Kurnool Fault	Fault involving basement
11	Gulcheru Fault	Fault involving basement
12	Kadiri Fault	Fault involving basement
13	Atmakuru Fault	Fault involving cover
14	Rudravagu Fault	Fault involving cover
15	Kolleru Lake Fault	Neotectonic fault
16	Vasista Godavari Fault	Neotectonic fault
17	Nizampatnam-Nagayalanka Fault	Neotectonic fault

seismic influence zone should be considered a minimum of 350 km radius as per the United States Nuclear Regulatory Guide (USNRG 1997). Andhra Pradesh High Court as a center bearing latitude and longitude of 16.5195° N and 80.4856° E with a 400 km radius is considered as a seismic influence zone for the present study. The seismic events that fall under this seismic influence zone were considered for the preparation of the catalog. In the current study, various types of faults were identified within the influence zone such as neotectinic faults, subsurface fault, strike-slip fault, and fault involving with basement and cover, etc. are listed in Table 1.

Methodology

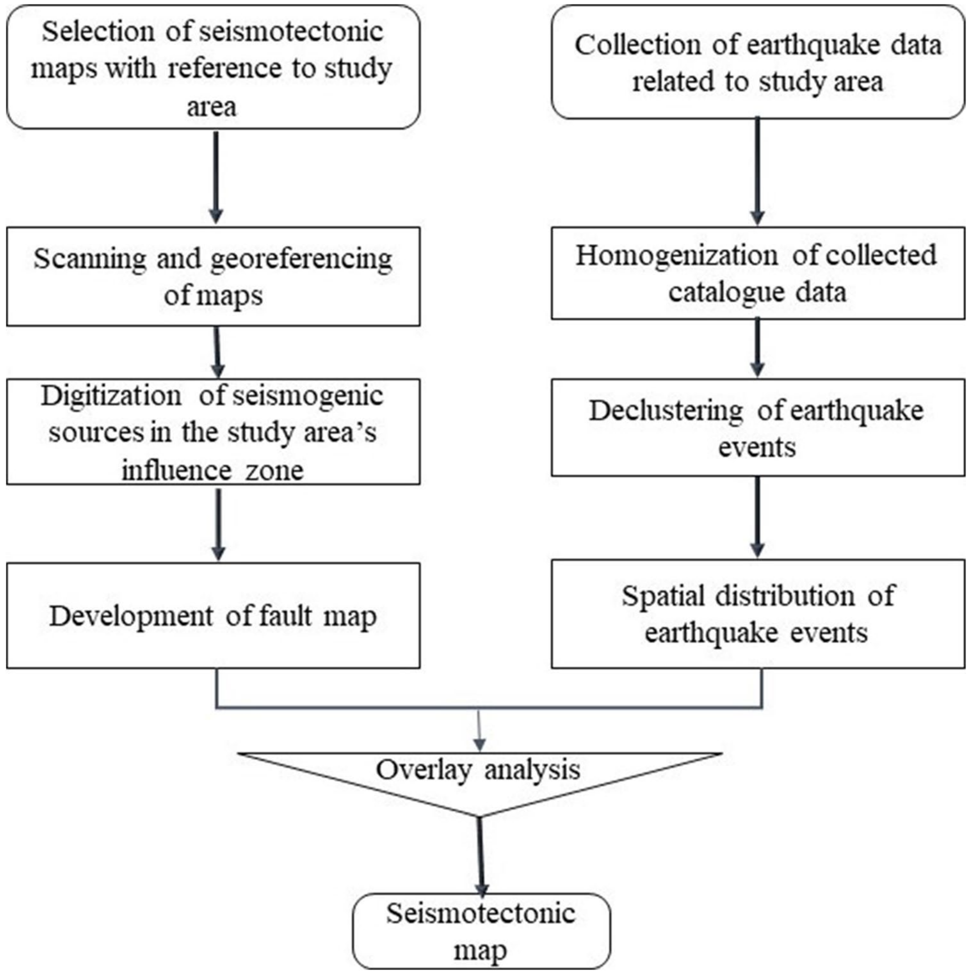
Past earthquake data in a control region of 400 km has been compiled to estimate the seismicity parameters for the current study area. The collected catalog data is converted to well established moment magnitude (M_W) scale. The catalog contains clusters such as aftershocks, foreshocks which can be removed using different approaches, which were discussed in the "Identification of main shocks" section. To estimate seismic hazard parameters, a detailed completeness analysis of catalog data is required. The completeness analysis for the present catalog data was discussed in the "Data completeness" section. The seismic sources within the influence zone were identified, georeferenced, and digitized to develop a fault map. For seismotectonic map of current study, epicenters of magnitude of $M_W \geq 3.5$ events were superimposed on the fault map. The detailed method of analysis is discussed in the following subsections. The methodology detailed below related to the determination of seismicity parameters is also shown as a simple flowchart in Fig. 2(a). Also, the methodology explained below corresponding to the development of a seismotectonic map is presented as a simple flowchart in Fig. 2(b).

Fig. 2 **a** Methodology for the determination of seismicity parameters. **b** Methodology for the development of seismotectonic map



(a) Methodology for the determination of seismicity parameters

Fig. 2 (continued)



(b) Methodology for the development of seismotectonic map

Data sources

Until date, there is no specific catalog data available for Amaravati, a new capital city of Andhra Pradesh. The earthquake catalog was prepared by incorporating the catalog data from different sources such as the National Earthquake Information Centre National Earthquake Information Centre (NEIC), United States Geological Survey (USGS), Advanced National Seismic System (ANSS), International Seismological Centre (ISC) NEIC, USGS, ISC (2011), and from other research works in literature on seismic hazard assessments of India (Kolathayar et al. 2012; Jaiswal and Sinha 2007;Schulte and Mooney 2005; Rao and Rao 1984; Chandra 1977; Oldham 1883). A total of 919 earthquake events with all ranges of magnitudes are reported from 1801–2021 (220 years) for Amaravati region. Earthquakes of magnitude greater than or equal to 4.0 have considerable engineering significance, and minor tremors may not have much engineering significance. In the present study, earthquake events with a magnitude greater than or equal to 3.5 are considered for seismicity analysis.

Magnitude conversion

The earthquake data collected from different sources are in different magnitude scales such as body wave magnitude (m_b), surface-wave magnitude (M_s), local magnitude (M_L), moment magnitude (M_W), and earthquake intensity scale (I). A complete and homogenized earthquake catalog is needed for the seismic hazard analysis. Unluckily, saturation restricts the use of certain magnitude scales for major earthquakes with $m_b > 6.0$, $M_L > 6.5$, and $M_S > 8.0$. Moment magnitude (M_W) does not saturate, and it is based on a seismic moment, which represents reliable earthquake magnitude (Scordilis 2006). Before the instrumental era, the shaking was measured based on damage caused by earthquakes in terms of Modified Mercalli Intensity scale (I). Based on 23 Peninsular India (PI) earthquakes from 1969 to 2001 with

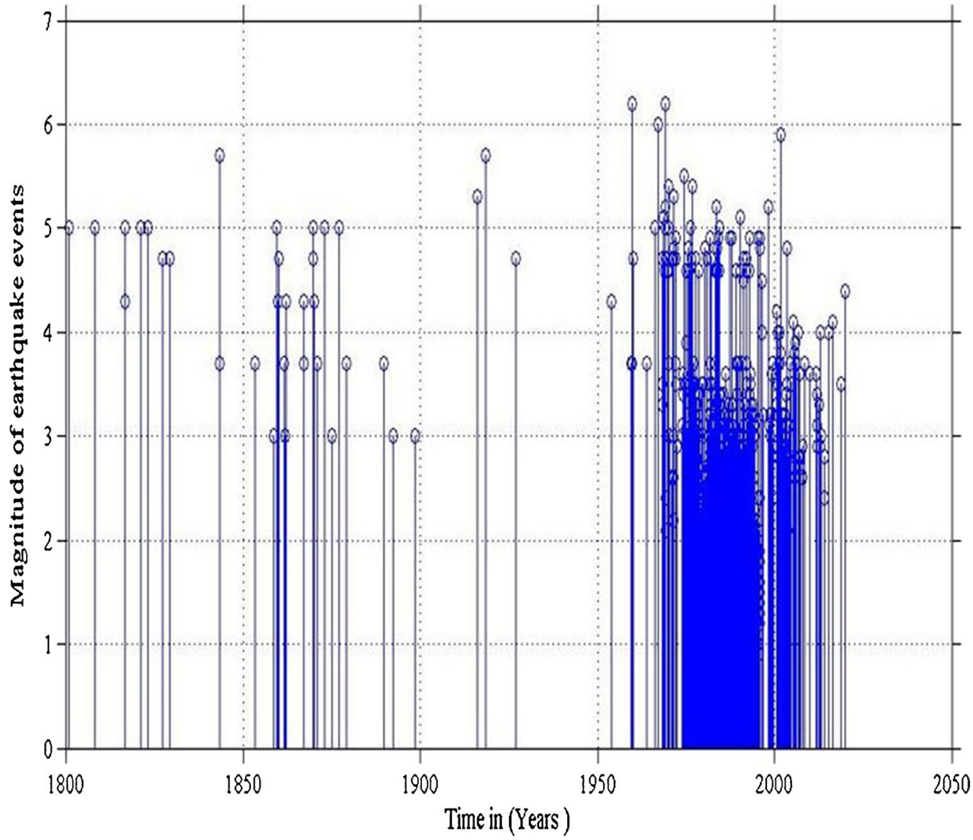


Fig. 3 Earthquake magnitude with time for the period 1801–2020

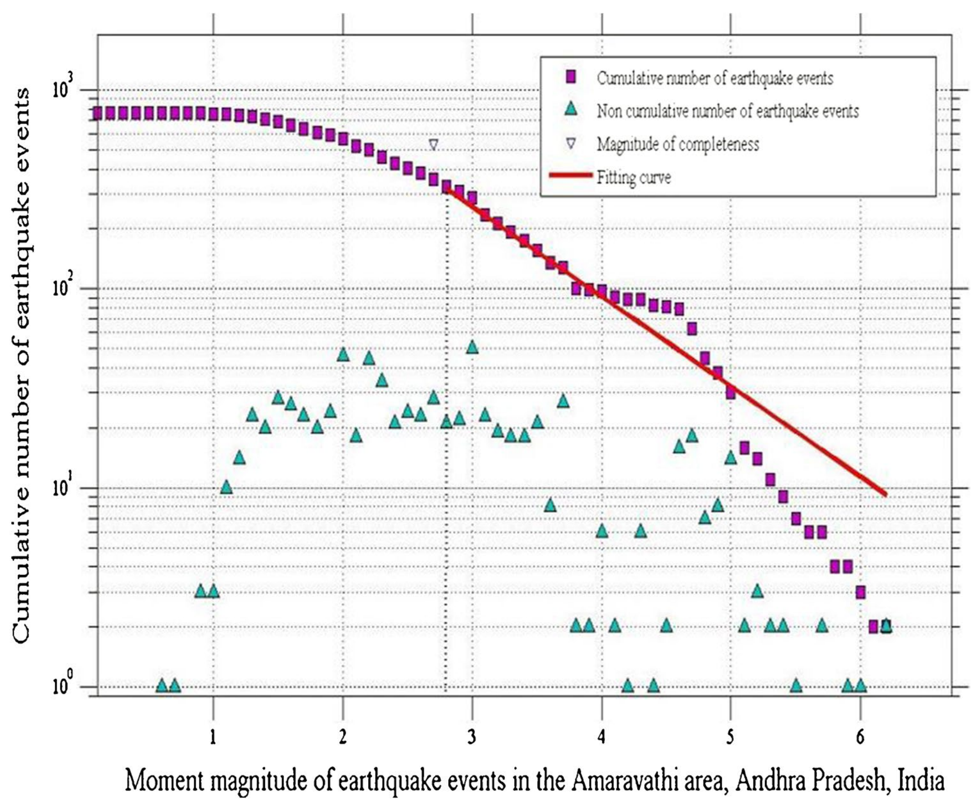


Fig. 4 Magnitude of completeness by EMR method

independent measures of Modified Mercalli Intensity scale (I) and magnitude (M_W) from different sources, a magnitude-intensity relationship was proposed by Lai et al. (2009). In the present study, M_W is determined using the following expression proposed by Lai et al. (2009).

$$M_W = 0.45I + 2.38 \quad (1)$$

Also, the earthquake magnitudes are converted to moment wave magnitude by the following regression equations proposed by Kolathayar and Sitharam (2018).

$$M_W = 1.08(\pm 0.0152)m_b - 0.325(\pm 0.081)4 \le m_b \le 7.2 \quad (2)$$

$$M_W = 0.815(\pm 0.04)M_L - 0.767(\pm 0.174)3.3 \le M_L \le 7 \quad (3)$$

$$M_W = 0693(\pm 0.006)M_S + 1.922(\pm 0.035)3.7 \le M_S \le 8.8 \quad (4)$$

Identification of main shocks

Minor tremors before seismic network development are unnoticeable. Incomplete reporting of the earthquake catalog leads to the recurrence rate of large earthquakes being overestimated and the recurrence rate of smaller earthquakes being underestimated. It is difficult to fit the Gutenberg Richter (G-R) equation for incomplete earthquake catalog data. Hence, one must check the completeness of the catalog before the calculation of G-R parameters. De clustering is a process of removing foreshocks and aftershocks from the raw catalog. There are several approaches proposed by various researchers available declustering catalog such as Gardner and Knopoff (1974), Reasenberg (1985). Gardner and Knopoff (1974) developed a declustering algorithm that claims that foreshocks and aftershocks are dependent on the size of the main event. Therefore, the time and distance window parameters vary depending on the magnitude of the main shock. In the current study, declustering was done using an algorithm developed by Gardner and Knopoff (1974) and modified by Uhrhammer (1986). Total earthquake events of all ranges of magnitude with latitude, longitude, and time are uploaded in the text format into a ZMAP tool. By giving proper input details such as the catalog data's beginning and ending year, and bin length ZMAP for Amaravti capital city was established. After that, the decluster algorithm must be specified. The decluster algorithm used in the present study was proposed by Gardner and Knopoff (1974) which is based on the following relation.

$$D = e^{-1.024+0.804M} \quad t = e^{-2.87+1.235*M} \quad (5)$$

where D = distance in kilometers, t = time in days.

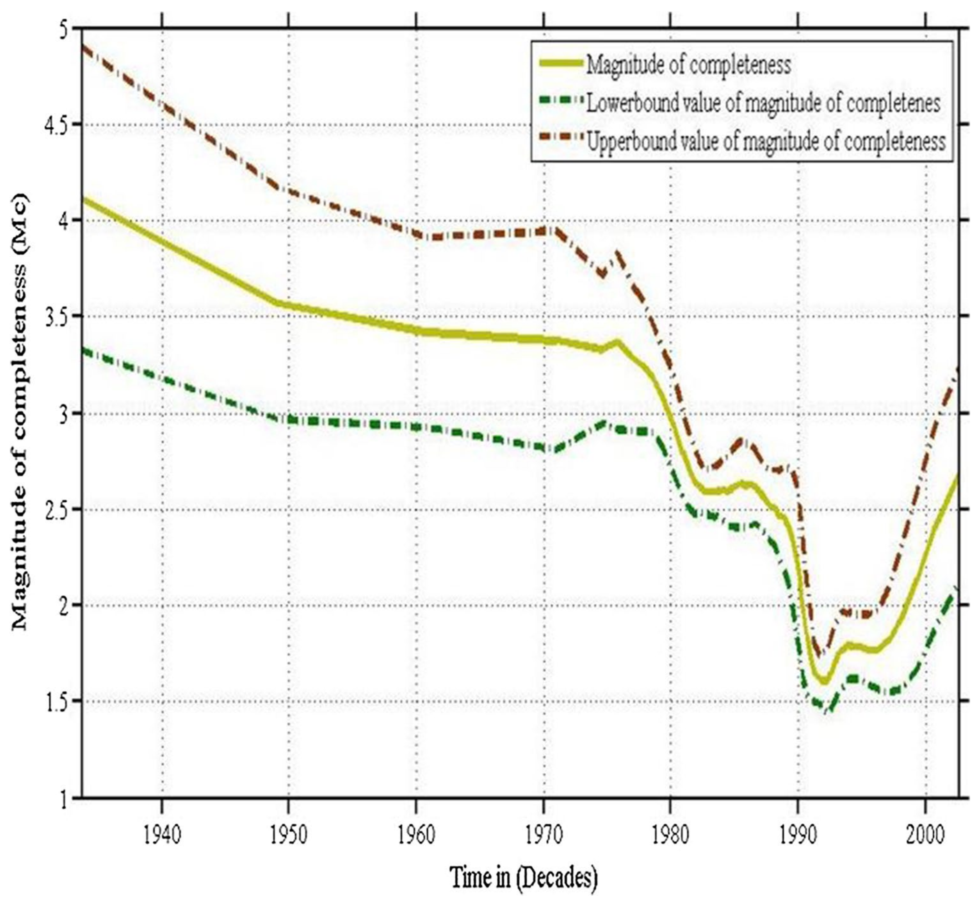


Fig. 5 Temporal variation of magnitude of completeness (M_c) for Amaravati region, India

After removing the foreshocks and aftershocks, 753 earthquake events are present in the study area.

Data completeness

Data completeness with respect to magnitude (M_c)

Minimum magnitude (M_{th}) should be considered for a well-constrained catalog in order to prevent errors caused by earthquakes of low magnitude. It is common practice to use the minimum magnitude of completeness as a threshold for any study that uses a well-constrained earthquake catalog, as this prevents error due to the presence of low magnitude earthquakes in the region. The magnitude of completeness (M_c) is the lowest magnitude above which all magnitude of earthquakes are detected by network stations (Rydelek and Sacks 1989). Magnitude of completeness plays a significant role in the estimation of seismicity parameters. If the assumed threshold magnitude (M_{th}) is less than the magnitude of completeness of a catalog, estimated seismicity parameters may be erroneous. Hence, the events below this magnitude are skipped by the network because they are too small to be identified by enough stations.

To estimate the magnitude of completeness of the catalog, the following two methods are popular in the literature.

1) Waveform based technique (Rydelk and Sacks 1989)
2) Catalog-based methods (Wiemer and Wyss 2000)

In the present study, catalog-based approach is considered for estimation of magnitude of completeness. These methods are developed based on the Gutenberg-Richter frequency magnitude curve. From the collected earthquake data, it is observed that small to medium range of magnitude events are occurred more compared to greater magnitude earthquakes. Also, in all the events, the earthquake magnitude is less than the moment magnitude of 7 (Fig. 3). Accordingly, the maximum possible earthquake for the present study area can be considered as 7. It can be noticed from Fig. 3 that more number of earthquakes are identified after the year 1964. The seismic network was well established after 1964; hence, recording events are more compared to before the 1960s. The magnitude completeness obtained by the *b* value stability approach is optimal in dealing with network-reported catalogs, whose detection is progressively enhanced with magnitude (Cao and Gao 2002). The best fit method and maximum curvature method underestimate the value of M_c (Wiemer and Wyss 2000). Stable and moderate M_c value is given by Entire Magnitude Spectrum system (EMR) (Woessner and Wiemer 2005). When the number of events is not too many and the missed events are in high number, the approach of EMR is recommended Yi lei et al. (2016). In the present study, M_c obtained by EMR method is considered to choose the catalog's threshold magnitude. From

Table 2 Number of earthquakes per each decade

Time in years	3.5–3.99	4–4.49	4.5–4.99	5–5.49	5.5–5.99	$M_W \geq 6$	Total
2011–2020	2	4	0	0	0	0	6
2001–2010	14	3	1	0	1	0	19
1991–2000	7	3	13	1	0	0	24
1981–1990	8	0	14	3	0	0	25
1971–1980	15	0	13	3	1	0	32
1961–1970	3	0	9	8	0	2	22
1951–1960	2	1	2	0	0	1	6
1941–1950	0	0	0	0	0	0	0
1931–1940	0	0	0	0	0	0	0
1921–1930	0	0	1	0	0	0	1
1911–1920	0	0	0	1	1	0	2
1901–1910	0	0	0	0	0	0	0
1891–1900	0	0	0	0	0	0	0
1881–1890	1	0	0	0	0	0	1
1871–1880	1	0	0	2	0	0	3
1861–1870	2	3	1	1	0	0	7
1851–1860	2	1	1	1	0	0	5
1841–1850	1	0	0	0	1	0	2
1831–1840	0	0	0	0	0	0	0
1821–1830	0	0	2	1	0	0	3
1811–1820	0	0	0	2	0	0	2
1801–1810	0	0	0	2	0	0	2
Total							162

Fig. 4, it is observed that the magnitude of completeness for the present catalog data is about 2.7 (M_W). The moment magnitude of $M_W = 3.5$ is considered threshold magnitude for the seismicity analysis of the present study area. The magnitude of completeness is varying with time because the number of seismograms recorded is also varying with time. These variations in M_c are shown in Fig. 5. The main catalog consisting of 162 events with M_W greater than or equal to 3.5 is presented in Table 2.

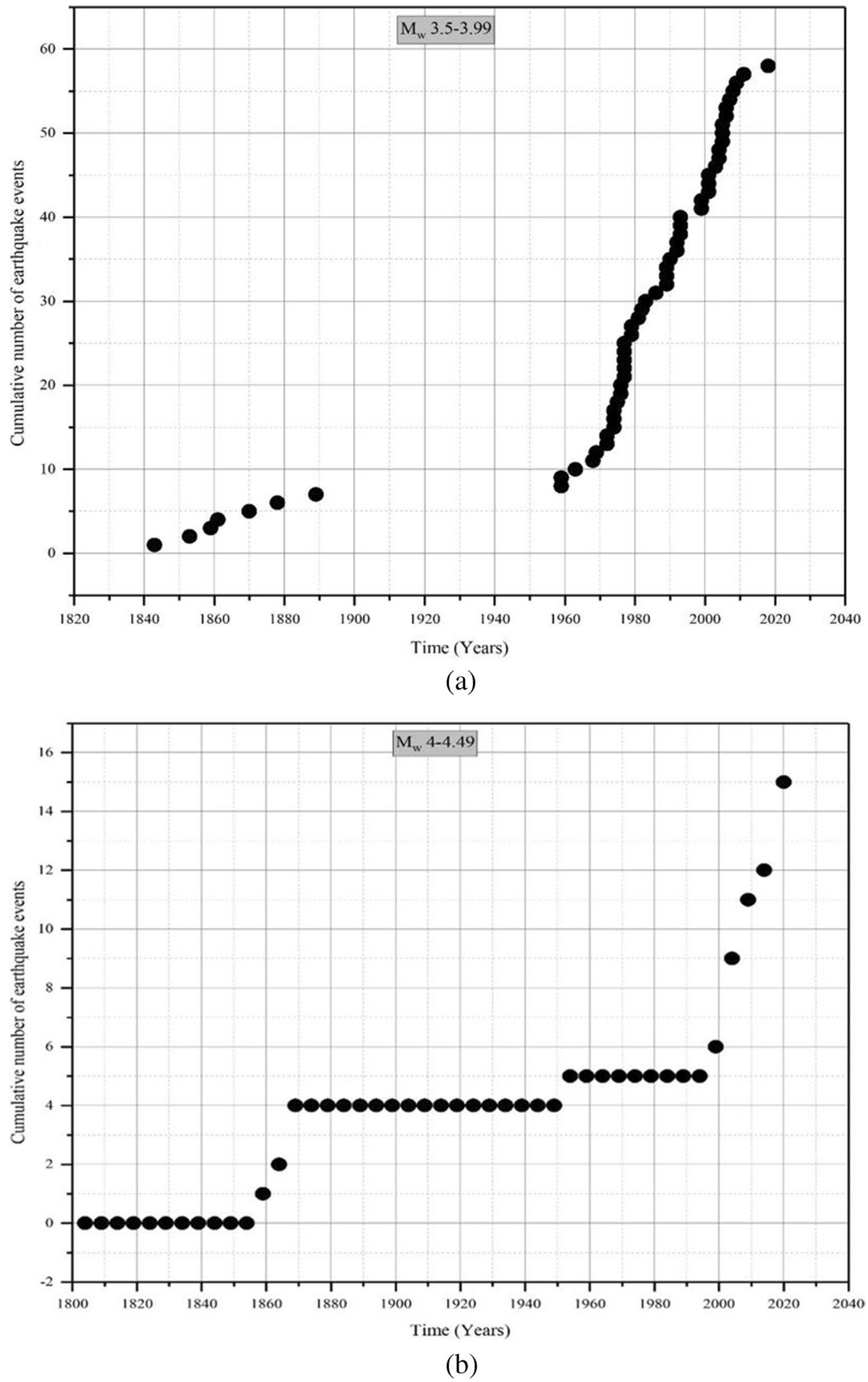


Fig. 6 Catalog completeness analysis by CUVI method

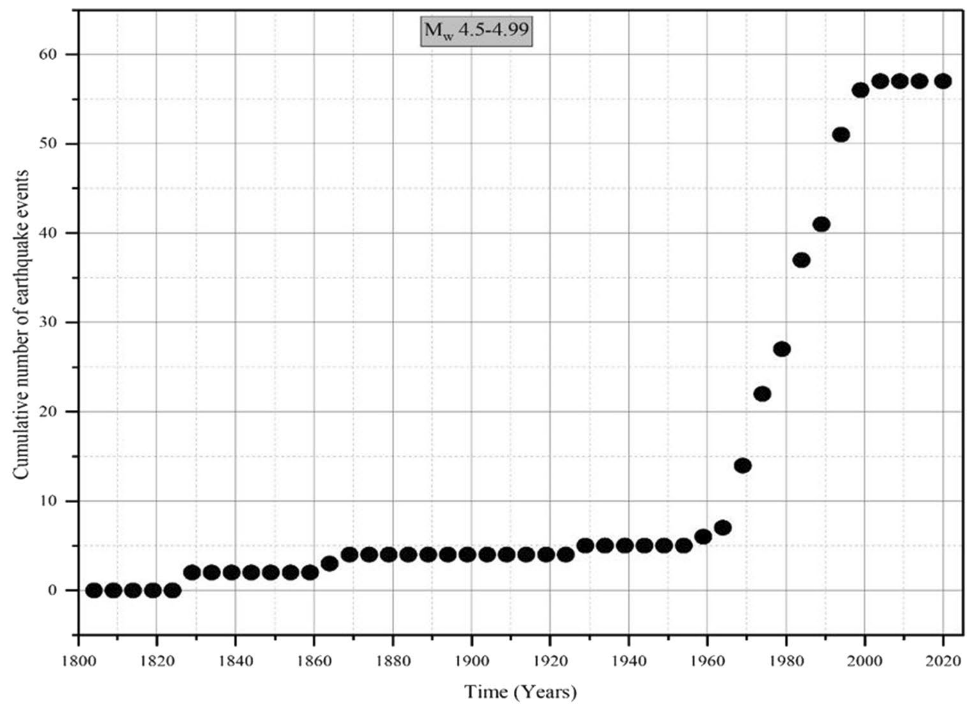
Data completeness with respect to time

In the present study, a catalog completeness analysis was done by using the following two methods and the results obtained were compared.

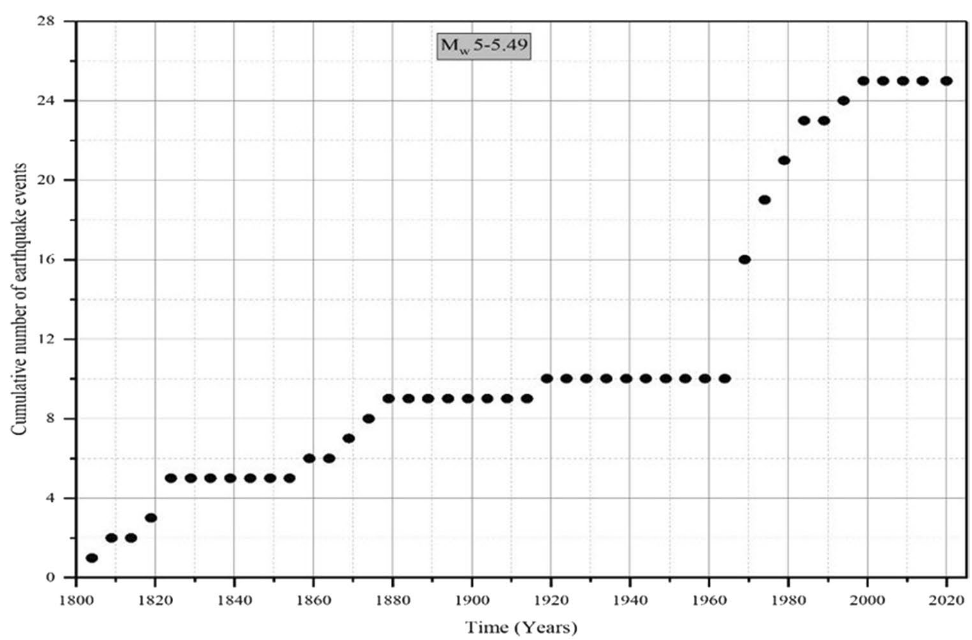
1. Cumulative visual inspection method (Mulargia and Tinti 1985)
2. Stepp procedure (1972)

Cumulative visual inspection method In the present study, all the earthquake events that occurred in the span of 220 years were subdivided into six magnitude classes viz. ($3.5 \leq M_W < 4$), ($4.0 \leq M_W < 4.49$), ($5.0 \leq M_W < 5.49$), ($5.5 \leq M_W < 5.99$), ($M_W \geq 6$). For different magnitude classes,

Fig. 6 (continued)



(c)

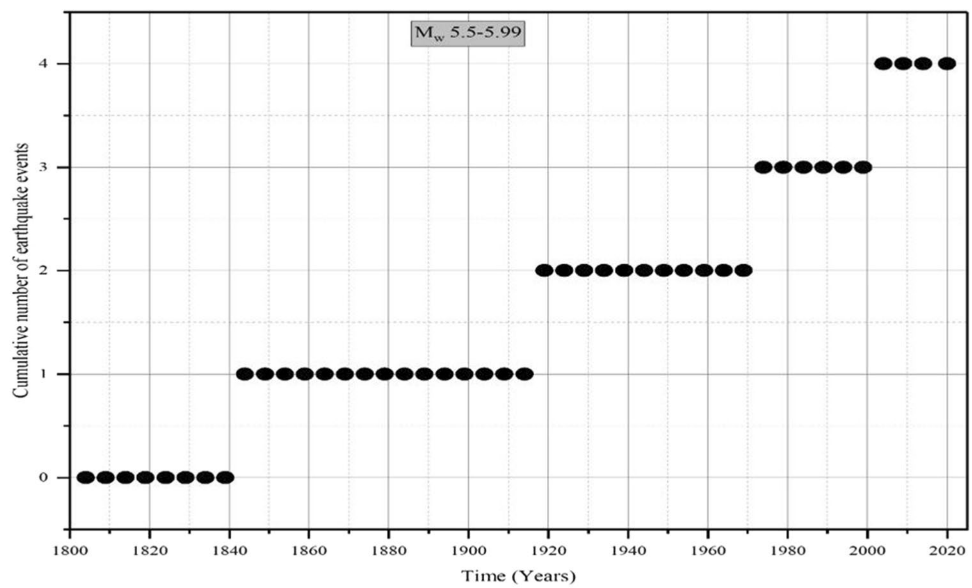


(d)

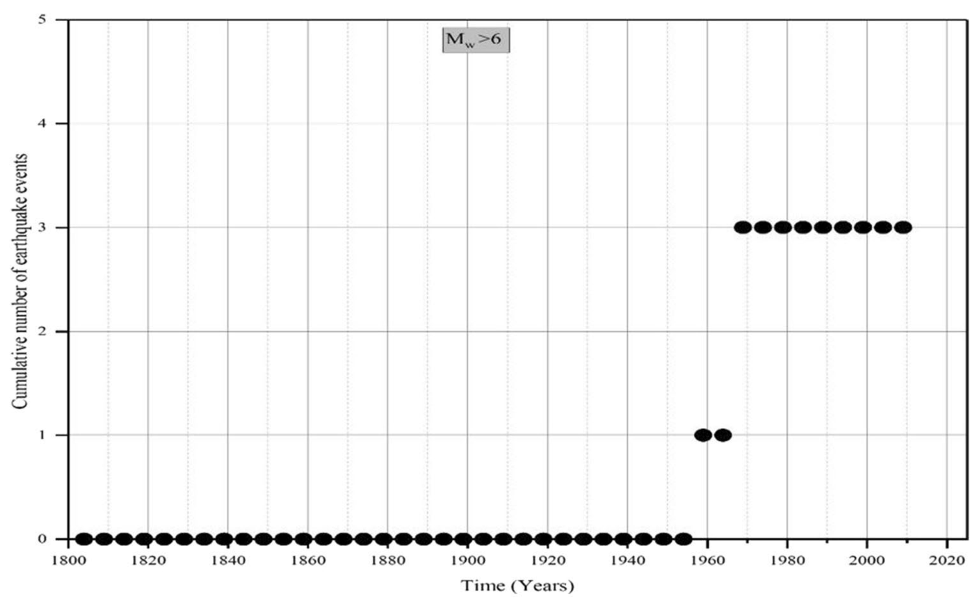
the number of earthquake events per decade is presented in Table 2. For a given magnitude class, the completeness period is considered to begin when a straight line approximates the slope of the fitting curve. It can be observed from Fig. 6(a) that for the magnitude range 3.5–3.99, the catalog is completed for the last 50 years (1971–2021). From Fig. 6(b), it can be noticed that for the magnitude range 4.0–4.49, the catalog is completed for the last 60 years (1961–2021); similarly from Fig. 6(c), (d), (e), and 6(f), for the magnitude ranges 4.5–4.99, 5.0–5.49, 5.5–5.99, and 6 and above, the catalog is completed for 60 years (1961–2021), 65 years (1956–2021), 220 years (1801–2021), and 220 years (1801–2021) respectively.

Stepp procedure (1972) To estimate the completeness period for given catalog, the standard deviation for different magnitude classes was calculated. The logarithmic graph was plotted between standard deviation and time. Each class of plotted points represents a straight path as long as the dataset is complete in that magnitude interval. The unbiased mean rate per unit time interval can be calculated using the following equation

Fig. 6 (continued)



(e)



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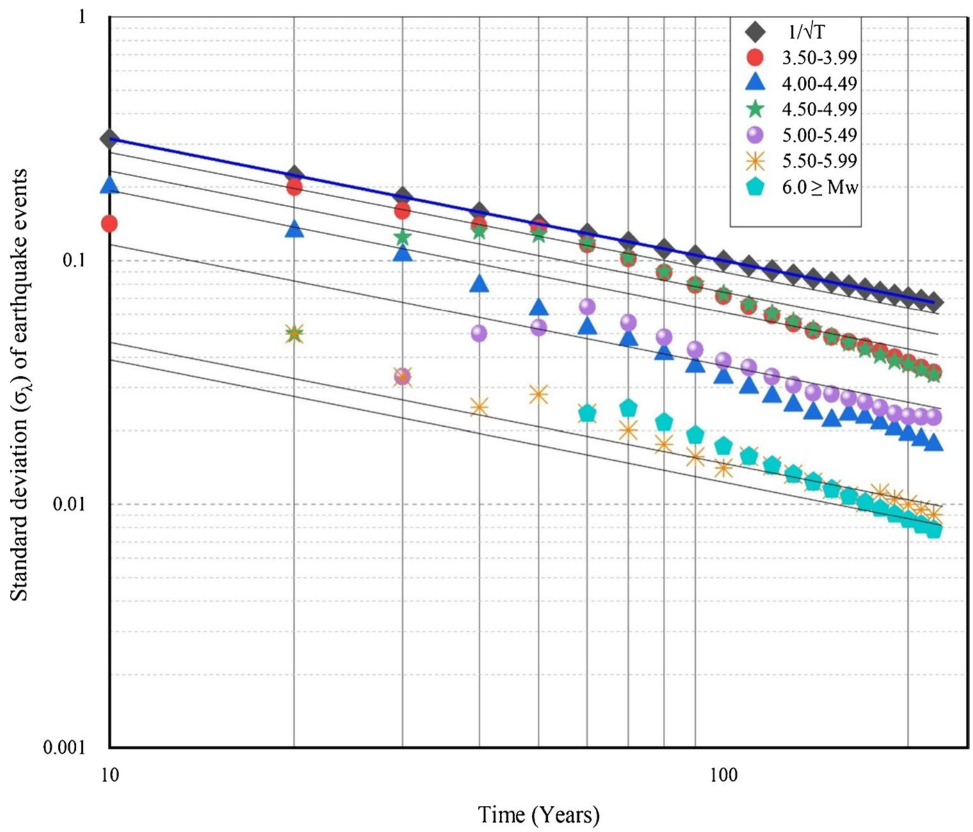


Fig. 7 Catalog completeness analysis by Stepp (1972) procedure

Table 3 Catalog completeness period by CUVI and Stepp (1972) methods

Method	3.50–3.99	4.0–4.49	4.5–4.99	5.0–5.49	5.5–5.99	$M_W \geq 6$
CUVI	50 years (1970–2020)	60 years (1960–2020)	60 years (1960–2020)	65 years (1955–2020)	220 years (1801–2020)	220 years (1801–2020)
Stepp's	50 years (1970–2020)	50 years (1970–2020)	80 years (1940–2020)	160 years (1860–2020)	220 years (1801–2020)	220 years (1801–2020)

Table 4 Seismicity parameters by least square and maximum likelihood method

Seismic hazard parameter	Least squares method (CUVI)	Least squares method (Stepp, 1972)	Maximum likelihood estimate
a value	2.400 ± 0.177	2.50 ± 0.190	3.43
b value	0.825 ± 0.033	0.71 ± 0.039	0.86 ± 0.38

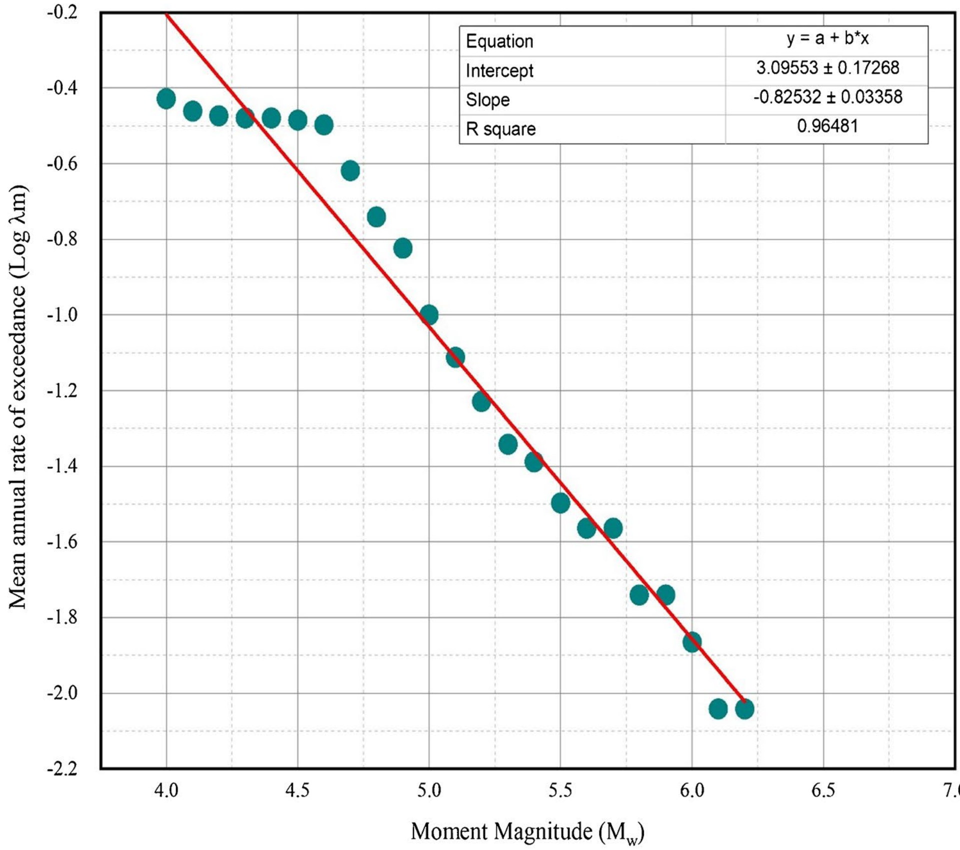
$$\lambda = \frac{1}{n}\sum_{i=1}^{n} X_i \tag{6}$$

where λ = mean rate per unit time interval,

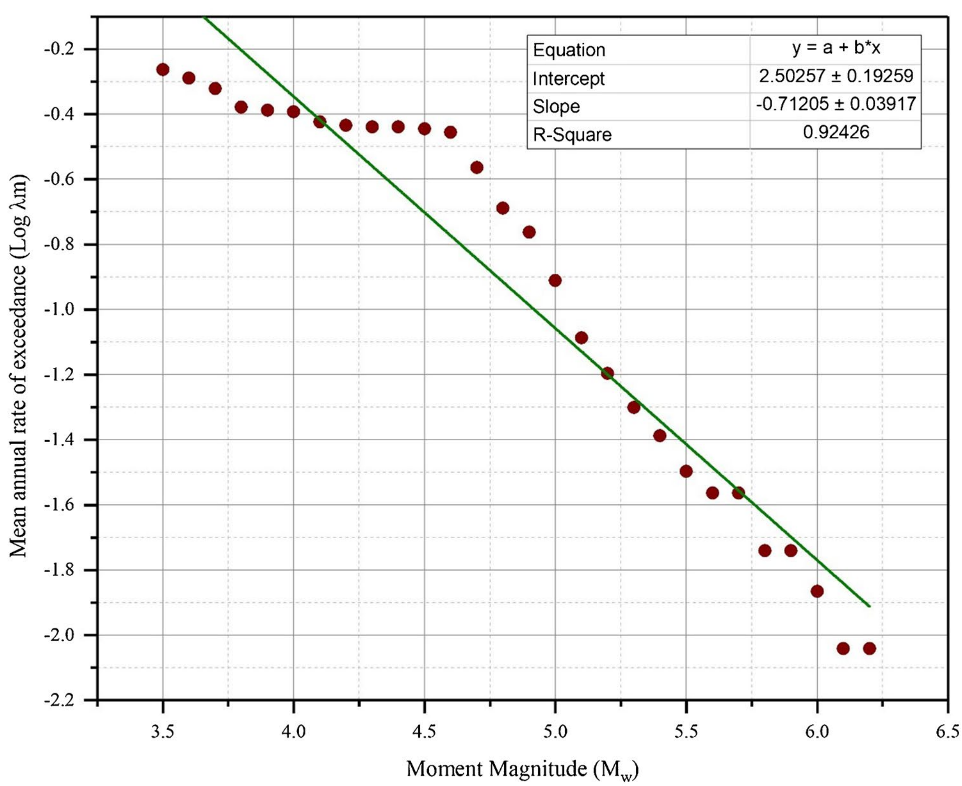
X_1, X_2……X_n are number of earthquake events reported per unit time interval and.

$n = T$ = number of unit time intervals or sample length.

Variance is given by $\sigma_\lambda^2 = (\lambda/n)$, where "*n*" is the number of unit time intervals; for the present study, $n = T = 10$ years. When unit time interval is taken as 1 year, then the standard deviation becomes $\sigma_\lambda = \sqrt{\lambda}/\sqrt{T}$. As long as data is complete, the standard deviation is proportional to $1/\sqrt{T}$. Figure 7 presents the standard deviation versus time plot for every range of magnitude class. It can be observed from Fig. 7 that for a specific region, all the range of magnitudes has the same slope of $1/\sqrt{T}$. The period from the beginning to the point where the slope of magnitude class deviates from $1/\sqrt{T}$ line is the completeness period for that specified class of magnitude. It is also noticed from Fig. 7 that the catalog completeness period for the different range of magnitudes such as 3.5–3.99, 4.0–4.49, 5.0–5.49, 5.5–6.0, and above magnitude 6 is 50 years, 50 years, 80 years, 160 years, and 220 years respectively. The catalog is completed for the



(a)



(b)

Fig. 8 **a** Frequency magnitude distribution curve for Amaravati region using CUVI method. **b** Frequency magnitude distribution curve for Amaravati region using the approach of Stepp (1972) completeness period by both the methods was reported in Table 3.

Earthquake recurrence

Several researchers are focused on estimation of seismicity parameters for different regions in India from both historical as well as instrumental catalog data (Joshi et al. 2020; Anbazhagan and Abraham 2020; Keshri et al. 2020; Khan and Kumar 2020; Mehta and Thaker 2020; Naik and Choudhury 2015; Shukla et al. 2015; Desai and Choudhury 2014). In the present study, the seismicity parameters of Amaravati region are calculated by least square method of regression analysis. The commonly used expression for earthquake size distribution of a region is the Gutenberg-Richter earthquake recurrence law (Gutenberg and Richter 1944) i.e.,

$$Log_{10}N = a - bM_W \tag{7}$$

where N is the number of earthquake events in a year, which are greater than or equal to the specified magnitude. The parameter a represents the logarithm of total number of earthquakes with magnitude greater than or equal to threshold magnitude and b represents a particular region's seismicity rate or the average size distribution of the earthquakes. The higher b value indicates that the smaller magnitude of earthquakes dominates in the region; similarly, the lower b value means the dominance of greater magnitude of earthquakes in that specified region. It is to be noted that the value of b depends upon the space, time, faulting style, and magnitude (Gulia and Wiemer, 2019). However, the present study did not consider these aspects in the analysis, which is a limitation of the study.

The seismicity parameters are estimated by using Gutenberg-Richter recurrence law for completed catalog data obtained from cumulative visual inspection (CUVI) method and Stepp (1972) method (Table 4). The frequency magnitude distribution curves for Amaravathi region using CUVI and Stepp approach are presented in Fig. 8(a) and Fig. 8(b) respectively. The seismicity parameters for Amaravati region are also estimated based on maximum likelihood method (Aki 1965). The estimation of b value through maximum likelihood method is carried out using the seismic tool ZMAP (Wiemer 2001).

Figure 9 presents the calculation of b-values using the maximum likelihood method. In Fig. 9, the cumulative number of earthquake events is represented by square and

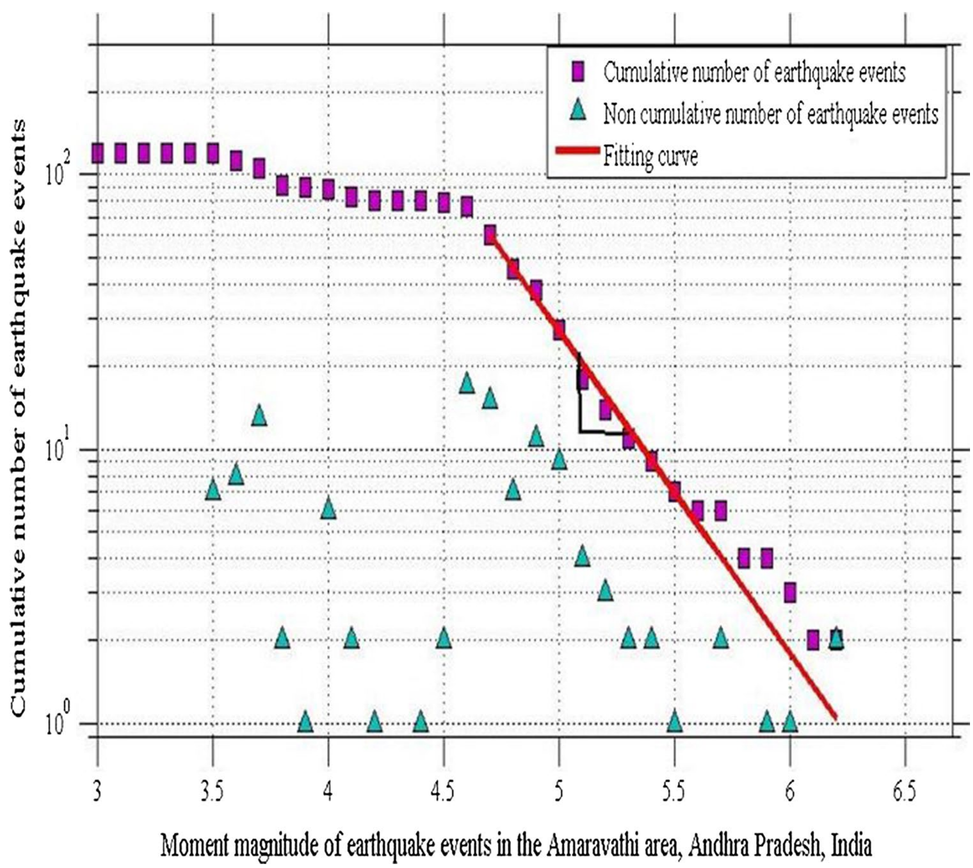


Fig. 9 Estimation of b value by Maximum likelihood estimation method

noncumulative events are represented by triangles. The slope of the linear fitting curve will give the *b* value for the given catalog data.

Maximum earthquake magnitude (M_{max}) estimation

The proper estimation of maximum magnitude (M_{max}) of a seismic source is crucial for seismic hazard analysis. There are several methods available in the literature to estimate the maximum magnitude such as Wells and Coppersmith (1994), Bonilla et al. (1984), Nowroozi (1985), Slemmons et al. (1989), and Guptha (2002).

In the present study, M_{max} value is calculated by using Guptha (2002) method. It is a popular conventional method of applying an increment of 0.5 units to the maximum observed magnitude of a specified source. The estimated maximum magnitude values for different sources in the Amaravati region are presented in Table 5.

Development of seismotectonic map

To quantify seismic hazard and seismic risk of any region, one must have knowledge of the active faults, lineaments, and any other active seismogenic sources present in the study area. In the present study, a fault map was developed by considering the faults with in the radius of 400 km with Andhra Pradesh High Court, Thulluru, Amaravati as a center. The fault map of Amaravati was developed by digitizing the eight sheets which are relevant to our study area from Seismotectonic atlas – 2000 (Geological Survey of India). A total of 49 faults, four major lineaments, and nine shear zones were identified with in the study area. In identificating seismogenic sources, the sources which are extended beyond the influence zone are also taken into consideration for preparation of seismotectonic map. The fault map of Amaravati area is presented in Fig. 10. The color of the fault represents the type of faults which are present in the influence zone of current study area.

Figure 11 presents the spatial distribution of earthquake events with in the influence zone of Amaravati region. The scale chosen for constructing these maps (Figs. 10 and 11) was 1 cm = 54.58 km. It is prepared by considering the events of magnitude $M_W \geq 3.5$ for a span of 220 years (1801–2021). The events are grouped in to three magnitude categories such as 3.5–4.2, 4.3–5.1, and 5.2–6.2 and are represented as circles in Fig. 11. The larger the size of the circle, the larger is the magnitude of earthquake. The seismotectonic map of Amaravati area is presented in Fig. 12. It is developed by superimposing both the fault data and seismic events using *ArcGIS10.7.1* software.

Table 5 Estimation of maximum magnitude for different sources using the Gupta (2002) method

Name of the fault	Observed maximum magnitude (M_{obs})	Estimated M_{max}
F1	5	5.5
F2	5	5.5
F3	6.2	6.7
F4	6.2	6.7
F5	4.8	5.3
F6	4.8	5.3
Nizampatnam-Nagayalanka Fault	6.2	6.7
Kolleru Lake Fault	5.1	5.6
Vasista Godavari Fault	5	5.5
F10	6.2	6.7
F11	6.2	6.7
F12	5.2	5.7
F14	5.9	6.4
Tirumala fault	5.7	6.2
Karkambudi-Swarnamukhi fault	5.7	6.2
Badvel fault	5.4	5.9
F15	5	5.5
Gani-Kalva fault	5.2	5.7
Bhavani river fault	5.2	5.7
F16	5.2	5.7
Nallavagu fault	5.2	5.7
Nekkantivagu fault	5.2	5.7
F17	5.2	5.7
F18	4.9	5.4
F19	5.2	5.7
F20	5.2	5.7
Bukkapatnam fault	4.8	5.3
F23	5.7	6.2
Gulcheru fault	4.8	5.3
Kadiri fault	4.8	5.3
Raichur-nagarkurnool fault	5.2	5.7
Addanki-Nuzividu fault	6.2	6.7
F24	6.2	6.7
F25	5.7	6.2
Papaghani fault	5.2	5.7
F26	5.2	5.7
Atmakuru fault	5.2	5.7
F27	5.2	5.7
F28	5.2	5.7
Rudravagu fault	5.2	5.7
Gundlakamma fault	6.2	6.7

Results and discussions

The prepared earthquake catalog of magnitude $M_W \geq 3.5$ for Amaravati region is presented in Appendix Table7. The magnitude of completeness was obtained as 2.7 by Entire Magnitude Range method. The completeness analysis by CUVI reveals that the data is complete for the last 50, 60, 60, 65, 220, and 220 years for magnitude classes (3.5–3.99), (4.0–4.49), (4.5–4.99), (5.0–5.49), (5.5–5.99), and ($M_W \geq 6.0$) respectively. The completeness analysis by Stepp (1972) procedure reveals that the data is complete for the last 50, 50, 80,160, and 220 years for different classes of magnitude (3.5–3.99), (4.0–4.49), (4.5–4.99), (5.0–5.49), (5.5–5.99), and ($M_W \geq 6.0$) respectively. The calculated *b* value for Amaravati region by least square method is varied from 0.70 to 0.85, whereas the *b* value calculated using the maximum likelihood method is found to be 0.88. The estimated *b* value for the Amaravati region in the present study is compared with the *b* values obtained in the earlier studies of Indian cities that are having similar seismotectonic setups (Table 6). It is observed that the obtained *b* value of 0.7–0.85 for the present study area compares well with the study of Khan et al. (2020). Also, the *b* value of 0.88 obtained by the maximum likelihood method is very close to the Karnataka region's (which is also a part of Peninsular India) *b* value reported by Anbazhagan and Sitharam. (2008). Furthermore, the Working Committee Experts National Disaster Management Authority (WCE NDMA 2010) recommended a *b* value of 0.85 ± 0.09, specifically for the Godavari Graben region in which the present study area belongs.

The estimated maximum possible earthquake moment magnitude (M_W) for Amaravati region is found to be 6.7. The seismotectonic map (Fig. 12) shows that the maximum number of

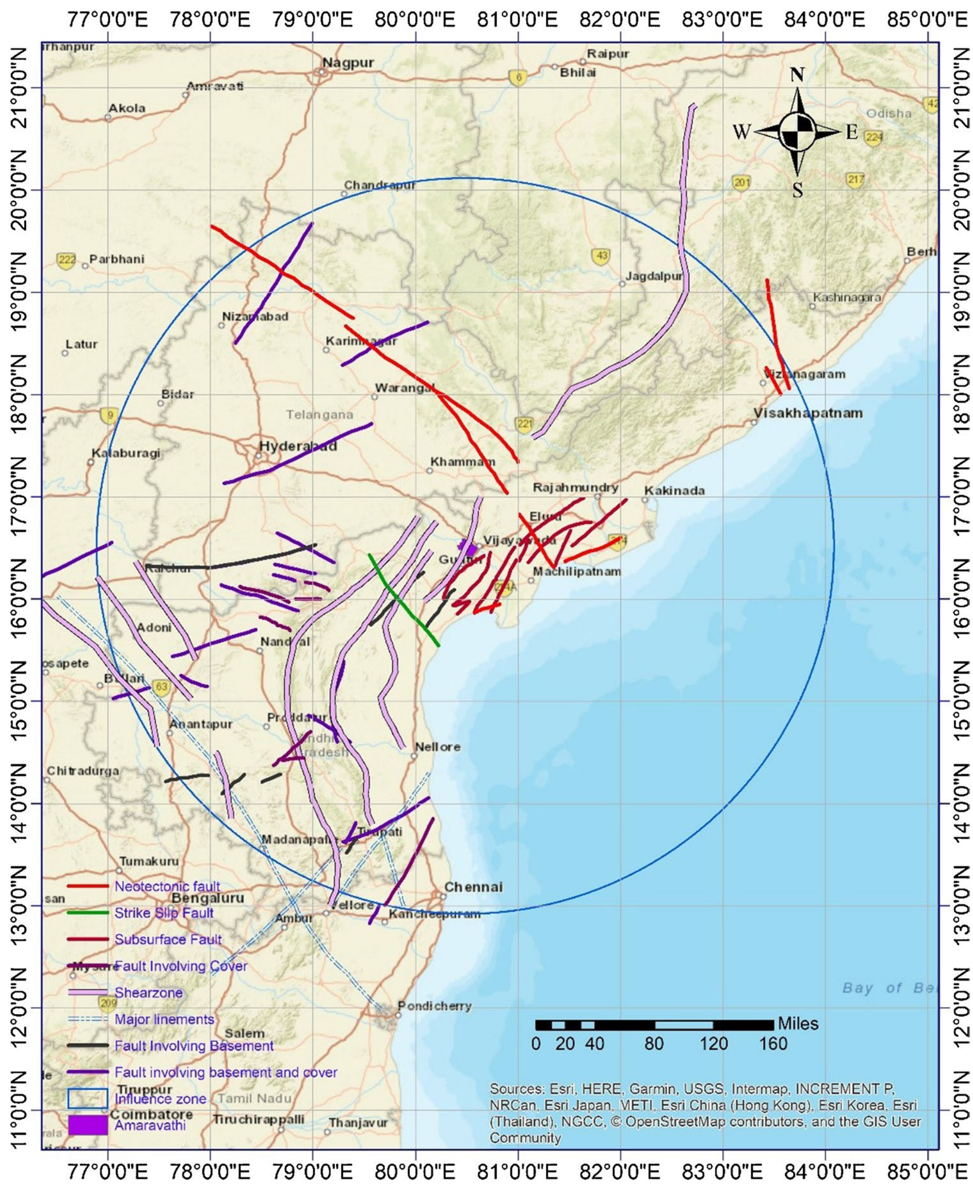


Fig. 10 Fault map of Amaravati area, Andhra Pradesh, India

earthquake epicenters is the nearest to the faults. This information is useful for estimating the maximum potential magnitude of faults. It is also observed that no earthquakes with $M_W \geq 5.5$ have their epicenters with in the geographical area of Amaravati region. It can also be seen that most of the subsurface faults and neotectonic faults are located at a distance of 10 km and 50 km to the Amaravati respectively. It can be noticed that most of the moderate earthquakes with M_W lies between 4.2 and 5.2 are in Southern Amaravati region. The proposed map serves as a basis for seismic hazard analysis of Amaravati region, India.

Conclusions

An attempt has been made in the present study to quantify seismic hazard parameters for the area of Amaravati, Andhra Pradesh, India. In the present study, an earthquake catalog of magnitude $M_W \geq 3.5$ related to Amaravati region, for a period of 220 years, has been created by incorporating historically and instrumentally recorded events. The magnitude of completeness for the present catalog data is found to be moment magnitude of $M_W = 3.10$. Catalog completeness analysis reveals that the data is complete for last 60 years from present for moderate magnitude of earthquakes. In the case of $M_W \geq 5.5$, the data is not complete even for the entire time period. The seismic hazard parameters for the Amaravati region were calculated using the least squares method and the maximum likelihood estimate method. The obtained *a* value varies from 2.6 to 3.5 and the obtained *b* value varies from 0.63 to 1.10. Seismotectonic map of Amaravati area is developed. The maximum possible earthquake of magnitude produced by any seismogenic source within the Amaravati influence zone is estimated as $M_W = 6.7$.

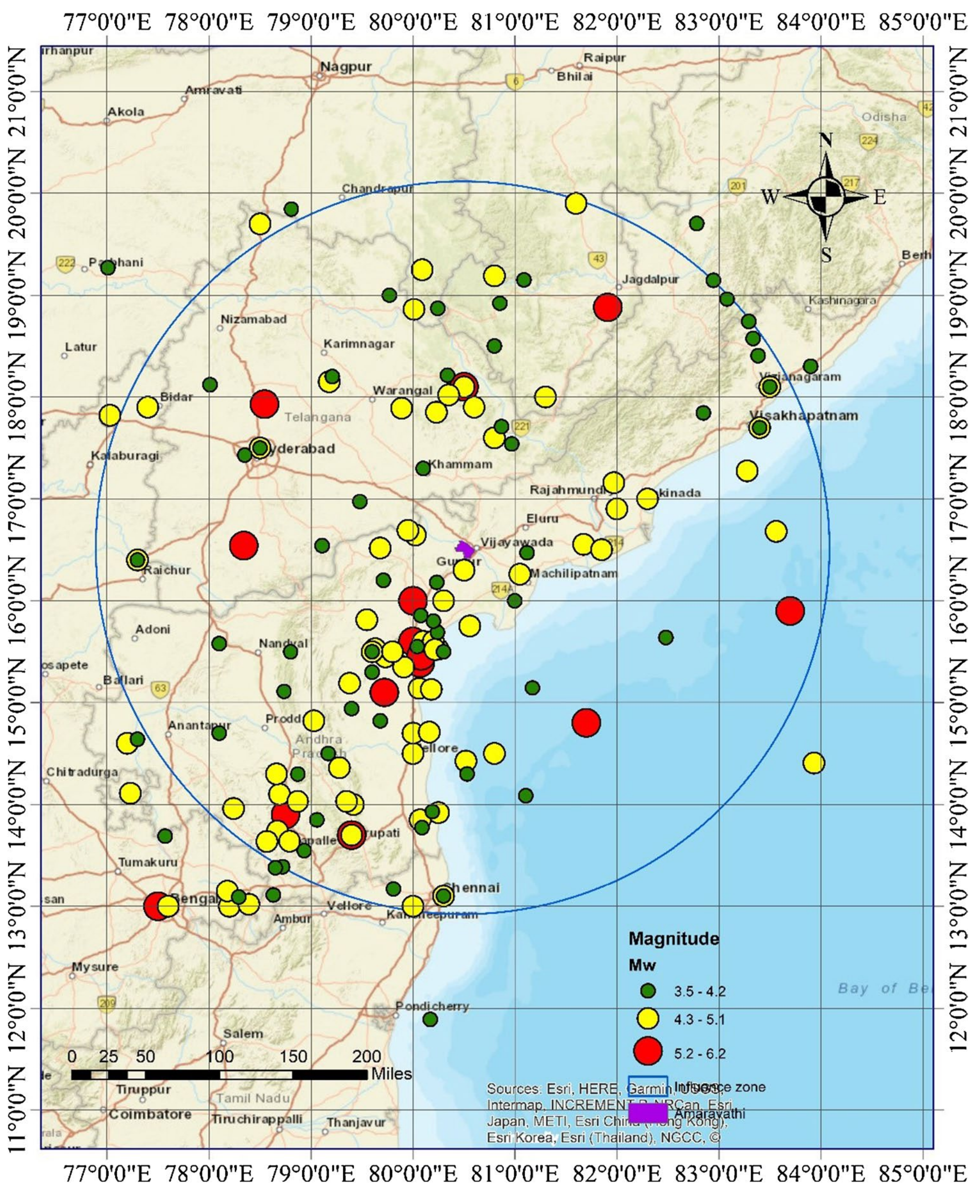


Fig. 11 Spatial distribution of earthquake events ($M_W \geq 3.5$) around Amaravati region, Andhra Pradesh India

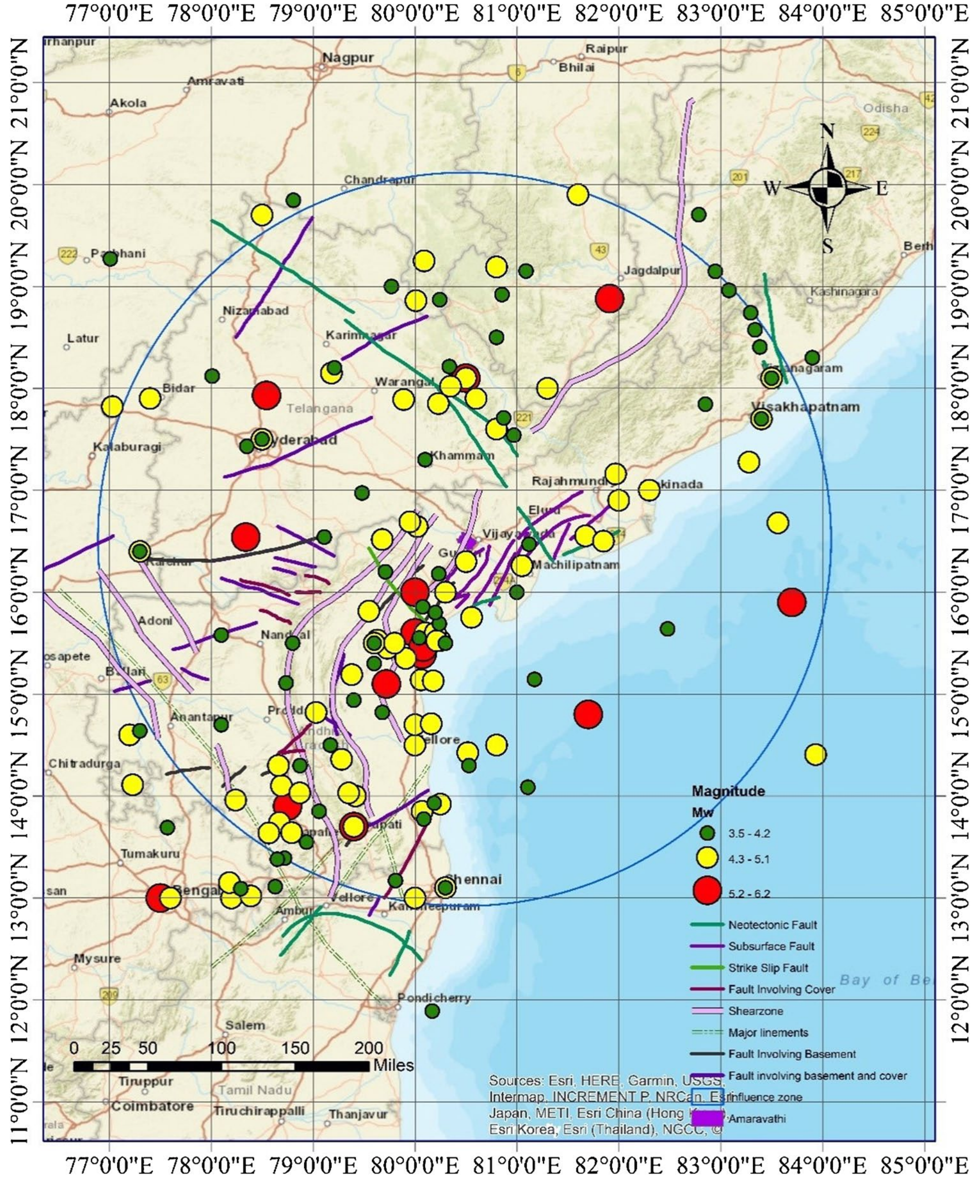


Fig. 12 Seismotectonic map of Amaravati region, Andhra Pradesh, India

Table 6 Comparison of *b* values with the existing literature

S. no	Authors	Study area	*b* value	Data considered in years
1	Khan(2020)	Warangal	0.72 to 0.97	220
2	Bahuguna and Sil (2020)	Assam	0.5–2.5	255
3	Anbazhagan and Sitharam (2020)	Karnataka	0.95	120
4	Sinha and Sarkar (2020)	Dhanbad	0.77	85
5	Naik and Choudhury (2015)	Goa	0.91	213
6	Desai and Choudary (2014)	Mumbai	0.83	418
7	Kumar et al. (2013)	Lucknow	0.86 (Region I) 0.80 (Region II)	170
8	Shukla and Choudhury (2012)	Gujarath	0.51	190
9	Menon et al. (2010)	South India	1.13	501
10	Vipin et al. (2009)	South India	0.89	400
11	Jaiswal and Sinha (2007)	South India	0.92	160
12	Raghukant and Iyengar (2006)	Mumbai	0.86	408
13	Kaila et al. (1972)	South India	0.7	70
14	Ram and Rathor (1970)	South India	0.81	70
15	Present study	Amaravati	0.75–0.88	220

Appendix

Table 7 Earthquake catalog of $M_W \geq 3.5$ for Amarvati region, Andhra Pradesh, India

Longitude	Latitude	Year	Month	Date	M_W
80.17	11.89	1968	5	3	3.5
78.1	15.58	1972	1	5	3.5
78.65	13.38	1974	5	13	3.5
79.06	13.85	1974	10	3	3.5
78.8	15.5	1976	10	25	3.5
78.1	14.7	1976	1	9	3.5
78.1	14.7	1976	2	9	3.5
79.6	15.5	1977	1	25	3.5
79.6	15.5	1977	5	25	3.5
80.26	13.09	1977	9	11	3.5
79.01	13.54	1977	1	8	3.5
78.93	13.54	1977	10	23	3.5
80.8	18.5	1979	4	22	3.5
79.48	16.97	1979	10	10	3.5
78.8	15.5	1981	11	2	3.5
78.35	17.43	1982	3	30	3.5
81.12	16.47	1992	2	29	3.5
79.77	19	1993	2	10	3.5
78.01	18.12	1993	3	30	3.5
79.91	15.33	2000	12	9	3.5
82.48	15.63	2003	5	7	3.5
83.33	18.57	2004	8	26	3.5
81.1	15	2006	12	16	3.5
80.87	17.71	2018	8	14	3.5
79.81	13.17	1974	2	3	3.6
80.23	16.18	1986	3	31	3.6
81.09	19.15	1993	4	4	3.6
80.338	18.21	1999	2	3	3.6
82.94	19.14	2005	3	14	3.6
81.17	15.14	2006	12	16	3.6
80.24	18.86	2007	1	28	3.6
80.53	14.30	2009	12	11	3.6
79.11	16.54	2011	10	20	3.6
78.5	17.5	1843	3	12	3.7
83.4	17.7	1853	2	21	3.7
80.5	16.29	1859	8	9	3.7
83.5	18.1	1859	8	24	3.7
77.3	16.4	1861	7	24	3.7
79.6	16.1	1867	1	3	3.7
79.8	16.1	1867	1	6	3.7
82.3	17.9	1869	12	1	3.7
82.3	17.9	1869	12	19	3.7
83.4	17.7	1870	12	19	3.7
83.9	18.3	1878	12	10	3.7
80.3	13.1	1889	8	12	3.7
83.5	18.1	1959	8	9	3.7
80.2	15.8	1959	8	21	3.7

Table 7 (continued)

Longitude	Latitude	Year	Month	Date	M_W
80.1	17.3	1963	12	5	3.7
77.3	14.64	1969	11	26	3.7
78.63	13.11	1972	3	16	3.7
79.17	14.5	1977	1	6	3.7
78.83	14.15	1977	2	5	3.7
78.72	13.39	1977	8	4	3.7
78.38	13.51	1977	10	23	3.7
80.07	15.85	1981	11	16	3.7
80.3	15.5	1983	4	24	3.7
80.97	17.54	1989	10	24	3.7
77.01	19.27	1989	6	11	3.7
77.57	13.69	1989	3	26	3.7
80.19	13.93	1990	10	9	3.7
79.21	18.2	1992	1	18	3.7
78.87	14.29	1999	5	2	3.7
83.29	18.74	2001	3	26	3.7
80.08	13.77	2001	6	8	3.7
80.85	18.92	2004	7	6	3.7
80.04	15.55	2006	1	4	3.7
82.85	17.84	2008	5	29	3.7
82.78	19.70	2001	11	3	3.8
83.38	18.40	2005	7	21	3.8
79.6	15.3	1975	2	25	3.9
78.29	13.09	2005	11	2	3.9
79.68	14.82	1996	8	4	4
81	16	2000	10	16	4
78.73	15.10	2001	6	15	4
81.10	14.08	2006	8	4	4
79.71	16.20	2012	10	29	4
80.24	15.69	2015	2	25	4
79.32	14.95	2016	5	28	4
83.08	18.96	2005	3	14	4.1
79.40	14.94	2016	5	28	4.1
78.808	19.84	2000	6	22	4.2
80.3	13.1	1816	7	1	4.3
80.3	13.1	1816	8	1	4.3
83.4	17.7	1859	8	24	4.3
77.3	16.4	1862	1	13	4.3
80.3	16.00	1867	3	11	4.3
82.3	17.00	1869	12	19	4.3
81.30	18	1954	1	5	4.3
79.95	16.69	2020	1	25	4.4
81.85	16.5	1991	2	3	4.5
80.023	16.64	1996	8	4	4.5
79.85	16.00	1996	8	4	4.5
79.03	14.82	1968	5	12	4.6
79.28	14.36	1968	12	9	4.6
79.35	14.03	1969	9	8	4.6
77.20	14.6	1970	2	20	4.6
79.91	15.35	1972	3	11	4.6
80.20	15.60	1974	11	28	4.6

Table 7 (continued)

Longitude	Latitude	Year	Month	Date	M_W
79.60	15.50	1975	11	25	4.6
80.18	15.13	1977	1	26	4.6
78.76	13.45	1977	8	12	4.6
77.80	13.4	1978	8	8	4.6
80.55	15.75	1983	9	24	4.6
79.8	15.50	1983	5	20	4.6
80.21	15.52	1983	6	10	4.6
81.6	19.9	1984	7	21	4.6
78.39	13.02	1989	4	6	4.6
81.05	16.26	1990	2	25	4.6
80.8	19.19	1992	12	13	4.6
80.09	19.25	1992	2	7	4.6
79.18	18.15	1992	12	5	4.6
79.89	17.89	1993	1	14	4.6
80.10	13.10	1807	12	9	4.7
83.40	17.70	1827	1	6	4.7
77.60	13.00	1829	3	13	4.7
80.50	16.29	1859	7	21	4.7
79.40	13.70	1860	2	2	4.7
80.80	14.50	1869	9	1	4.7
83.40	17.70	1927	1	1	4.7
83.50	18.10	1959	12	23	4.7
80.30	16	1960	10	8	4.7
78.87	14.03	1968	4	13	4.7
78.79	13.64	1969	11	10	4.7
77.23	14.11	1969	2	5	4.7
80.6	17.90	1970	7	28	4.7
79.6	15.50	1971	7	28	4.7
78.63	13.68	1971	5	10	4.7
80.07	13.85	1972	3	23	4.7
79.41	14.00	1976	8	7	4.7
78.56	13.63	1977	8	16	4.7
82.00	16.90	1980	10	2	4.7
78.20	13.00	1982	3	13	4.7
80.50	18.10	1990	6	9	4.7
78.18	13.15	1991	4	19	4.7
80.35	18.02	1992	2	25	4.7
78.24	13.96	1971	5	22	4.8
79.60	15.50	1975	7	31	4.8
81.97	17.16	1980	3	30	4.8
77.40	17.90	1983	9	25	4.8
80.51	14.42	1988	3	21	4.8
77.03	17.82	1995	12	14	4.8
81.67	16.55	2003	5	7	4.8
82.10	16.20	2003	5	7	4.8
80.16	14.71	1968	4	25	4.9
78.40	14.53	1969	7	4	4.9
79.63	15.53	1971	12	31	4.9
78.67	13.74	1976	5	18	4.9
83.56	16.68	1981	10	13	4.9
78.76	17.50	1983	7	5	4.9

Table 7 (continued)

Longitude	Latitude	Year	Month	Date	M_W
83.27	17.27	1984	3	28	4.9
78.50	19.7	1987	4	18	4.9
80.24	15.52	1987	12	3	4.9
80.06	15.14	1992	11	14	4.9
79.67	16.51	1995	5	24	4.9
79.54	15.81	1995	5	24	4.9
79.73	15.45	1995	10	21	4.9
80.1	15.60	1800	10	19	5
80.3	13.10	1807	12	10	5
80.3	13.10	1816	9	16	5
80	14.50	1820	12	13	5
80	13.00	1823	3	2	5
80.5	16.30	1859	6	21	5
80	14.50	1869	9	1	5
80.01	18.86	1872	11	12	5
78.50	17.5	1876	11	22	5
80.00	14.7	1966	4	10	5
80.25	13.92	1969	3	12	5
79.38	15.19	1970	1	12	5
78.66	14.30	1976	2	9	5
83.93	14.40	1984	4	14	5
80.80	17.60	1968	7	20	5.1
80.60	17.90	1969	8	30	5.1
78.69	14.10	1969	7	1	5.1
80.23	17.85	1990	5	9	5.1
78.75	13.9	1969	1	16	5.2
78.54	17.93	1983	6	30	5.2
78.50	17.9	1983	9	14	5.2
78.34	16.54	1998	4	9	5.2
77.50	13	1916	1	7	5.3
80.08	15.46	1971	7	28	5.3
79.72	15.1	1970	1	16	5.4
80.07	15.39	1976	10	25	5.4
81.70	14.8	1974	7	5	5.5
79.40	13.7	1843	4	1	5.7
83.70	15.9	1918	5	19	5.7
81.91	18.88	2001	11	3	5.9
80.00	15.6	1967	3	27	6
80.00	16	1959	10	12	6.2
80.50	18.1	1969	4	14	6.2

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Declarations

Conflict of interest The authors declare no competing interests.

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