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ORIGINAL ARTICLE

Maximum magnitude estimation considering the regional rupture character

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Abstract The main objective of the paper is to develop a new method to estimate the maximum magnitude (M_{max}) considering the regional rupture character. The proposed method has been explained in detail and examined for both intraplate and active regions. Seismotectonic data has been collected for both the regions, and seismic study area (SSA) map was generated for radii of 150, 300, and 500 km. The regional rupture character was established by considering percentage fault rupture (PFR), which is the ratio of subsurface rupture length (RLD) to total fault length (TFL). PFR is used to arrive RLD and is further used for the estimation of maximum magnitude for each seismic source. Maximum magnitude for both the regions was estimated and compared with the existing methods for determining M_{max} values. The proposed method gives similar M_{max} value irrespective of SSA radius and seismicity. Further seismicity parameters such as magnitude of completeness (M_c), "a" and "b" parameters and maximum observed magnitude (M_{max}^{obs}) were determined for each SSA and used to estimate M_{max} by considering all the existing methods. It is observed from the study that existing deterministic and probabilistic M_{max} estimation methods are sensitive to SSA radius, M_c, a and b parameters and M_{max}^{obs} values. However, M_{max} determined from the proposed method is a function of rupture character instead of the seismicity parameters. It was also observed that intraplate region has less PFR when compared to active seismic region.

Keywords Maximum earthquake magnitude (M_{max}) · Regional rupture characteristics · "a" and "b" G-R parameters · Magnitude of completeness · Maximum observed magnitude (M_{max}^{obs})

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1 Introduction

Seismic hazard analysis describes the potential for earthquake-related ground shaking at a site. The maximum possible earthquake magnitude (M_{max}) estimation is indispensable in many seismic/engineering applications. It is obligatory for use in earthquake engineering community, disaster management agencies, and the insurance industry. However, there is no universally accepted practice for estimating the value of M_{max} (Kijko 2004; Kijko and Singh 2011). The maximum magnitude is defined as the upper limit of earthquake magnitude for a given region and is synonymous with the magnitude of the largest credible earthquake (EERI Committee on Seismic Risk 1984; WGCEP (Working Group on

Central California Earthquake Probabilities) (1995)). It assumes a sharp cutoff magnitude at a maximum magnitude, so that by definition, no earthquakes are expected with magnitude exceeding M_{max} (Joshi and Sharma 2008). Presently, deterministic- and probabilistic-based approaches are used for M_{max} estimation. The deterministic approaches are based on the empirical relationship between magnitude and various tectonic and fault parameters such as rupture length, rupture width, slip rate, rupture area, and surface displacement. These relationships are different for the different seismic regions and fault parameters (Singh et al. 1980; Nowroozi 1985; Wells and Coppersmith 1994; Anderson et al. 1996). Short historical data of small source zones produce small samples of seismicity, which can be very few to show clearly long-term spatial relations between observed seismicity and geologic features (Wheeler 2009). Jin and Aki (1988) had developed a spatial correlation for the determination of M_{max} which correlates the logarithm of coda Q at 1 Hz (Q_0) and largest earthquake magnitude observed in China, but M_{max} estimated from this process shows inconsistency (Wheeler 2009). M_{max} is widely estimated by taking up the largest observed earthquake magnitude (M_{max}^{obs}), with or without an added increment. In most of the deterministic procedures, the value of the M_{max} often reached an increment of half unit on the magnitude scale, which leads to an increase in the energy release of 5.62 times the maximum energy released in the considered region. Anbazhagan et al. (2013) highlighted that 5.62 times energy increment is less and it should be region specific to estimate the maximum possible earthquake. In the probabilistic approach, the determination of M_{max} is based on the seismological history of the area and is calculated using the appropriate statistical estimation procedure and seismicity catalogues. These probabilistic methods are mainly based on the extrapolation of the classical, frequency-magnitude relation (Gutenberg and Richter 1942, 1956). Several statistical procedures were also defined by Kijko and Singh (2011) for the estimation of the M_{max} for both parametric and nonparametric data. Probabilistic-based methods require the earthquakes that have a magnitude greater than or equal to the magnitude of completeness (M_c). Wiemer and Wyss (2000) proposed different methods for the determination of M_c , which was implemented by Joshi and Sharma (2008) in the seismicity catalogues.

The objective of this paper is to establish an alternate method for estimating the largest possible magnitude considering the regional rupture character. Kalpakkam (low to moderate seismicity region) in Southern India and Patna (moderate to high seismicity region) in the Indo Gangetic Basin (IGB) were selected as the study areas. A seismic study area was defined for a radius of 150 km, 300 km as per conventional practice, and 500 km based on maximum damage distance considering the past earthquakes in both the regions (Anbazhagan et al. 2014). The detailed earthquake catalogue has been generated for each seismic study area. Seismic parameters such as M_c, "a" and "b" parameters and maximum reported earthquake magnitude has been identified for each area. These data were used to estimate the maximum magnitude for both the sites considering all available existing procedures. In each seismic study area, damaging earthquake magnitudes of 5 and above were identified and subsurface rupture lengths (RLD) were estimated using the well-recognized relation proposed by Wells and Coppersmith (1994). The calculated RLD was divided by the respective source total length, and the normalized subsurface rupture factor was calculated. The plotting of the normalized subsurface rupture factor with the total length of the source showed a unique trend, and this was called as a regional rupture character (Anbazhagan et al. 2014) for the corresponding seismic study area. The regional rupture character has been estimated for each seismic study area (SSA). Based on the observed trend, maximum possible subsurface rupture in terms of percentage of the total length of source was determined and called subsurface rupture character. Subsurface rupture character was further used to estimate maximum possible earthquake for each source. It was found that the maximum magnitude from regional rupture character is a unique value that represents the rupture phenomenon in the region. Maximum magnitude estimated by considering the regional rupture character does not vary with seismic study area and is based on the regional tectonic feature, i.e., rupture of the seismic source.

2 Methods of M_{max} estimation

The M_{max} of any region reflects the potential of seismic strain which is expected to be released in the region (Anbazhagan et al. 2013). M_{max} is generally estimated using two approaches namely deterministic and probabilistic methods. M_{max} is determined deterministically by various methods such as adding an increment value to maximum magnitude observed (M_{max}^{obs}) in the region. This method is simple and can be applied to any seismotectonic setting. The maximum magnitude is most likely equal to maximum magnitude observed (M_{max}^{obs}) if the historical seismological record is long compared to the recurrence interval of M_{max}, or if the seismicity rate is high (Wheeler 2009). It provides the lower bound of M_{max} (Wheeler 2009), whereas M_{max} estimated from incremental method is inconsistent (Wheeler 2009). According to Risk Engineering Inc. et al. (1988) and Budnitz et al. (1997), an increment of 0.5 to M_{max}^{obs} for the site having b value range from −0.9 to −1. Nuttli (1981) proposed that M_{max} is an event that would recur in 1000 years in a region and can be predicted by extrapolating the magnitude frequency graph of seismic study area's seismicity. The M_{max} value computed from the extrapolation method is consistent with the size of the study area, whereas inconsistent with recurrence intervals of large earthquakes (Wheeler 2009). Maximum magnitude can also be evaluated from historic data by taking the arithmetic mean of large earthquakes (having magnitudes seven and above) reported in SSA. The estimated seismic rate could be considered a valid indicator of M_{max}, but paleoseismic and instrumental seismicity suggest that the utility of seismicity rate is restricted to approximately moment magnitude M_w 7 and above (Wheeler 2009). Jin and Aki (1988) proposed an inverse relation between coda (Q_0) and M_{max} that could be helpful for hazard assessments of a region. Areas of active or recently active tectonics have low Q_0, whereas most continental areas have higher Q_0 (Mitchell and Cong 1998). Few of the stable continental regions (SCR) experienced earthquakes large enough to be taken as M_{max} from Q_0 (Wheeler 2009). Markropoulos and Burton (1983, 1985) and Bayliss and Paul (2013) have proposed an analytical method for maximum magnitude estimation of a region using strain energy released. Three magnitudes have been defined which correspond to (i) the most probable annual maximum earthquake which depends upon the Gutenberg-Richter relationship and equals $^{a}/_{b}$ (ME_1), (ii) magnitude resembling mean annual rate of energy released (ME_2), and (iii) the analytical upper bound for the earthquake magnitude (ME_3). These magnitudes are shown graphically in the next sections. Mark (1977) postulates a recurrence relation between magnitude and total fault length. The author recommended that the RLD might be assumed as 1/3 to 1/2 of the total fault length (TFL) based on the worldwide record data. Kijko and Singh (2011) proposed several procedures for statistical estimation of the M_{max} based on seismic data of a particular region. These methods can be applied when no information about the nature of the earthquake magnitude distribution is available and when the earthquake catalogue is incomplete. Kijko and Singh (2011) proposed 12 procedures for the determination of M_{max}, which are summarized in Table 1. The estimation of maximum magnitude has been divided into three categories, i.e., parametric, nonparametric, and fit to the cumulative density function of earthquake magnitude. These methods depend upon the time interval, number of earthquakes occurred which have magnitude greater than or equal to the threshold of completeness of the specific study area. These methodologies assume that the magnitudes are independent, identically distributed, random values with probability density function and the cumulative distribution function (Kijko and Singh2011).

3 New method M_{max} estimation

The above discussion clearly shows that the prevalent maximum magnitude estimation methods are based on M_{max}^{obs}, frequency magnitude distribution (FMD), and seismic data. It is known that the amount of energy released, i.e., magnitude is directly related to the rupture phenomena of the region. Most of the existing methods do not account for the regional rupture phenomena. The maximum earthquake magnitude depends upon tectonic features where future seismicity is supposed to occur (Gupta 2006). Therefore, the incorporation of regional tectonic features in the form of rupture character in the estimation of maximum magnitude has been attempted in this study. The source criterion that influence fault rupture is density and shear wave velocity of the crustal rock at rupture. These parameters are directly related to the shear strength of rupture rock and are considered uniform throughout the region in many seismological models based on the geology and deep geophysical data. In that case, rupture phenomena can also be assumed uniform in the region if deep geology does not vary much and can be captured from past earthquake rupture.

Table 1 Summary of Kijko's maximum magnitude estimation procedures

S. no.	Kijko's method	Highlight of each method
Parametric approach—parametric models of frequency–magnitude distribution are known		
1	Tate–Pisarenko procedure (T-P) (K1)	It is a very straight forward method and does not require extensive calculations, but it fails to provide an estimator having a smaller mean-squared error
2	Kijko–Sellevoll procedure (Cramér's approximation) (K-S-approx) (K2)	It is better than T-P procedure, but it requires integration and based on Cramér's approximation. This procedure is capable of providing a correct approximation of M_{max} only for a large number of data
3	Kijko–Sellevoll procedure (exact solution) (K-S-exact) (K3)	This procedure is the exact estimator of M_{max}, when the magnitudes are distributed according to the Gutenberg–Richter relation
4	Tate–Pisarenko–Bayes procedure (TPB) (K4)	The M_{max} is presented when the uncertainty of the Gutenberg–Richter parameter b is taken into account.
5	Kijko–Sellevoll–Bayes procedure (KSB) (K5)	It is capable of dealing with cases of complex empirical distributions, but it requires the knowledge of all the earthquake events less than the magnitude of completeness
Nonparametric approach—the empirical distributions of earthquake magnitudes are of bimodal or multimodal character and the log-frequency magnitude relation has a strong nonlinear component		
6	Nonparametric with Gaussian kernel procedure (N-P-G) (K6)	The M_{max} can be determined without the nature of the magnitude distributions or their empirical counterparts.
7	Robson–Whitlock procedure (R-W) (K7)	This procedure is used when the analytical form of the magnitude distribution is not known. It can be applied in cases of limited and/or doubtful seismic data, when quick results, without going into sophisticated analysis, are required. Unfortunately, the reduction of bias of the R-W estimator can be achieved only at the expense of a high value of its mean squared error
8	Robson–Whitlock–Cooke procedure (R-W-C) (K8)	Reduction in the value of mean squared error and performs better as compared to the R-W method
9	Nonparametric procedure based on order statistics (OS) (K9)	Earthquakes magnitude arranged in increasing order, but it requires the knowledge of all the earthquake events less than the magnitude of completeness
10	Procedure based on a few largest earthquakes (K10)	It is used when no information on the analytical form of the magnitude distribution is available and only several largest earthquake magnitudes are available.
Fit of cumulative distribution function (CDF) of earthquake magnitude—they are based on the fit of a CDF for earthquake magnitudes		
11	Procedure based on L1-norm fit of CDF of earthquake magnitudes (K11)	Especially useful when the data are unreliable, contain significant outliers, come from different sources and are a mixture of uncertain historic and recent instrumental observations
12	Procedure based on L2-norm fit of CDF of earthquake magnitudes (K12)	It is same as L1-norm fit except the absolute values of CDF residuals are replaced by respective residuals taken to the power 2.

Rupture character of the region is defined considering damageable earthquakes, i.e., moment magnitude (M_w) of 5 and above and associated RLD. Anbazhagan et al. (2013) found that the regional rupture character is unique and does not change with seismic study area. The regional rupture characteristic can be determined by considering the RLD of each past earthquake and associated seismic source in SSA. RLD of each damaging earthquake was estimated using the well-known magnitude and the source parameter relation presented by Wells and Coppersmith (1994). The relationship between moment magnitude and RLD was developed using reliable source parameters. This relation is applicable for all types of faults, shallow earthquakes, and interplate or intraplate earthquakes (Wells and Coppersmith 1994). This relation is valid for the magnitude range of 4.8–8.1 and length/width range of 1.1–350 km (Wells and Coppersmith 1994). The relation is represented mathematically as follows:

$$\log(\mathrm{RLD}) = 0.59M_w - 2.44 \quad (1)$$

Wells and Coppersmith (1994) have also considered the magnitude and source parameters from Indian earthquake data. RLD values arrived from past earthquakes are divided by the total length of source associated and plotted against the total length of the source. The ratio of RLD to TFL expressed in percentage is defined as percentage fault rupture (PFR). PFR follows a unique trend with total length of source and has been found to be similar in the region for different SSA and referred as the rupture character of the region. Figure 1 shows a typical plot of PFR with respect to the total fault length, which is mainly governed by the rupture characteristics of a region and follows a unique trend. Based on the trend, maximum and average PFR values can be estimated and further used to derive RLD; thereby, maximum magnitude for each seismic source can be calculated. Based on the observed trend, the typical curve can be divided into three segments, considering the maximum percentage of fault rupture and total length of the fault. The rupture values of each segment can be considered as an average rupture character. For example, in Fig. 1, maximum PFR is 7.54 % and minimum is 4.82 % which corresponds to the segment having TFL within 150 km, so rupture value (solid line) developed using power law is the average rupture characteristic for the segment corresponding to different TFL. The average/maximum rupture values can be increased based on the importance of the structure or level of safety and can be used to estimate the maximum magnitude of a particular region. This unique trend has to be established for each study area. In this study, low to moderate seismicity region of Kalpakkam in Southern India and moderate to high seismicity region of Patna in the Indo Gangetic Basin was selected to estimate maximum magnitude using this approach.

4 SSA for M_{max} estimation

The maximum magnitude estimation by existing methods requires seismicity data, and the proposed method requires details of damaging earthquakes and associated source data. These data are presented for both the study areas in this section. Kalpakkam in Tamil Nadu in the intraplate region and Patna in Bihar in an active seismic region have been selected as the study areas to demonstrate the newly proposed method and for comparison with the existing methods. The area around the site where seismotectonic data is used to estimate seismic hazard is called as the SSA. In this study, three radii of SSAs have been adopted to show the sensitivity of the existing and proposed methods. Generally shorter radius SSA, i.e., around 100- to 150-km radius, is routinely used in the deterministic seismic hazard analysis (Boominathan et al. 2008). A seismic study area of 300 to 350 km (around 200 mi.) is being adopted in many of seismic hazard analysis based on the Regulatory Guide of US Nuclear Regulatory Commission (NUREG-0800 2007). Anbazhagan et al. (2013) suggested that seismic study area must be selected based on the region specific past earthquake damage distribution (intensity) map. In this study, short, medium, and larger seismic study areas, corresponding to radius of 150, 300, and 500 km, respectively, have been considered to prepare a seismotectonic map for both the sites. In order to prepare three seismotectonic maps, seismic data from the Bhabha Atomic Research Centre (BARC), Indian Meteorological Department (IMD), Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam and National Geophysical Research Institute (NGRI), Hyderabad, International Seismological Centre (ISC), Amateur Seismic Centre (ASC), the US Geological Survey/National Earthquake Information Center (NEIC), Anbazhagan et al. (2013), and Sreevalsa et al. (2012) have been considered. The whole catalogue of Kalpakkam and Patna region has been homogenized to the moment magnitude (M_w) and declustered as per Gardner and Knopoff (1974) modified by Uhrhammer (1986). Seismic source information was compiled from SEISAT (2000) and recent seismogenic sources mapped by Ramasamy (2006) and Gupta (2006). Seismic data and sources have been used to generate a seismotectonic map for a radius of 150, 300, and 500 km for both the regions.

Kalpakkam is located in South India, a part of Peninsular India at 12.558° N, 80.175° E, where more than 12 earthquakes of magnitude moment above 5.5 have been recorded. Kalpakkam is located in the stable continental region of the peninsular India, which is a part of Gondwanaland and is located on top of a thin lithosphere and fast moving plate (Kumar et al. 2007). The complete earthquake catalogue of Kalpakkam consisted of 1238 events with a maximum magnitude of 6.3 recorded until November 2013. The catalogue

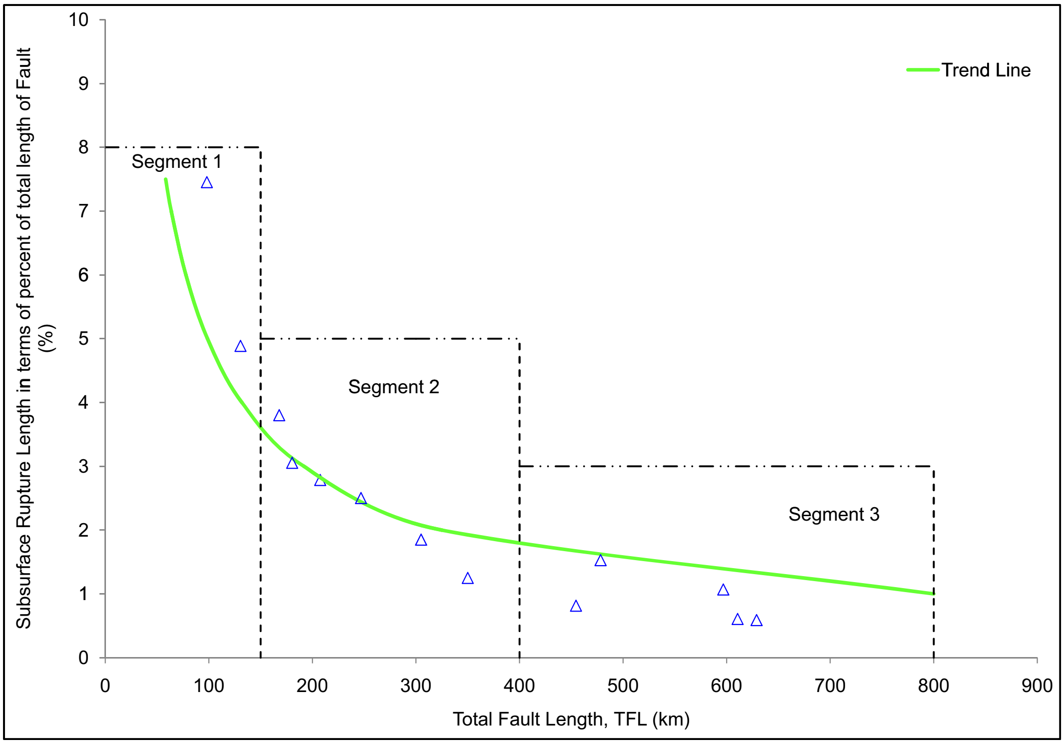


Fig. 1 Typical regional rupture character

contains 823 events of M_w less than 3.0 and 415 events M_w above 3.0. The region consists of about 51 seismic sources, viz., the shortest length of seismic source is about 50 km and the longest length is about 610 km. Maximum observed moment magnitude is found to be 6.3 for the fault, having length of 391.092 km. Total 37 seismic sources possess magnitude 4 to 5 and 13 sources with magnitude above 5; only one source with moment magnitude 6.3, which is the maximum observed magnitude in South India. Most of the sources were aligned toward the western part of the region, and small sources have been found near Kalpakkam region. These sources are densely placed on land area and few in the ocean region (Anbazhagan et al. 2013). Seismotectonic map of Kalpakkam (KLP) has been generated for three seismic study area circles and shown in Fig. 2.

Patna is located in North India, a part of the Indo Gangetic Basin at 25.611° N, 85.144° E, where more than 15 earthquakes of magnitude moment above 6.0 have been recorded. Patna lies in IGB that is close to the seismically active Himalayan belt and vulnerable to greater earthquakes. In case of Patna, the data comprises 1257 events with a maximum magnitude of 7.0 until November 2013. The catalogue contains only 25 events of M_w less than 3.0 and 1232 events with M_w above 3.0. The region consists of about 176 seismic sources; the shortest length of source is about 5.14 km, and the longest length is about 374 km. Maximum observed magnitude is found to be M_w of 7 for the fault having length of 220.63 km. Total 70 seismic sources possess magnitude moment 4 to 5 and 105 sources with magnitude moment above 5, and only one source has magnitude moment 7 which is the maximum observed magnitude in Patna region. Seismotectonic map has been generated considering three seismic study area circles and shown in Fig. 3 for Patna (PTN). Data from both the regions have been plotted and the seismic study areas divided considering radius of 150, 300, and 500 km. A summary of seismic data and source information for each seismic study has been given in Table 2.

5 M_{max} using proposed method

The region-specific rupture characteristic is a prerequisite for the proposed maximum magnitude estimation method. The region-specific rupture character has been established for both the SSA by considering the past

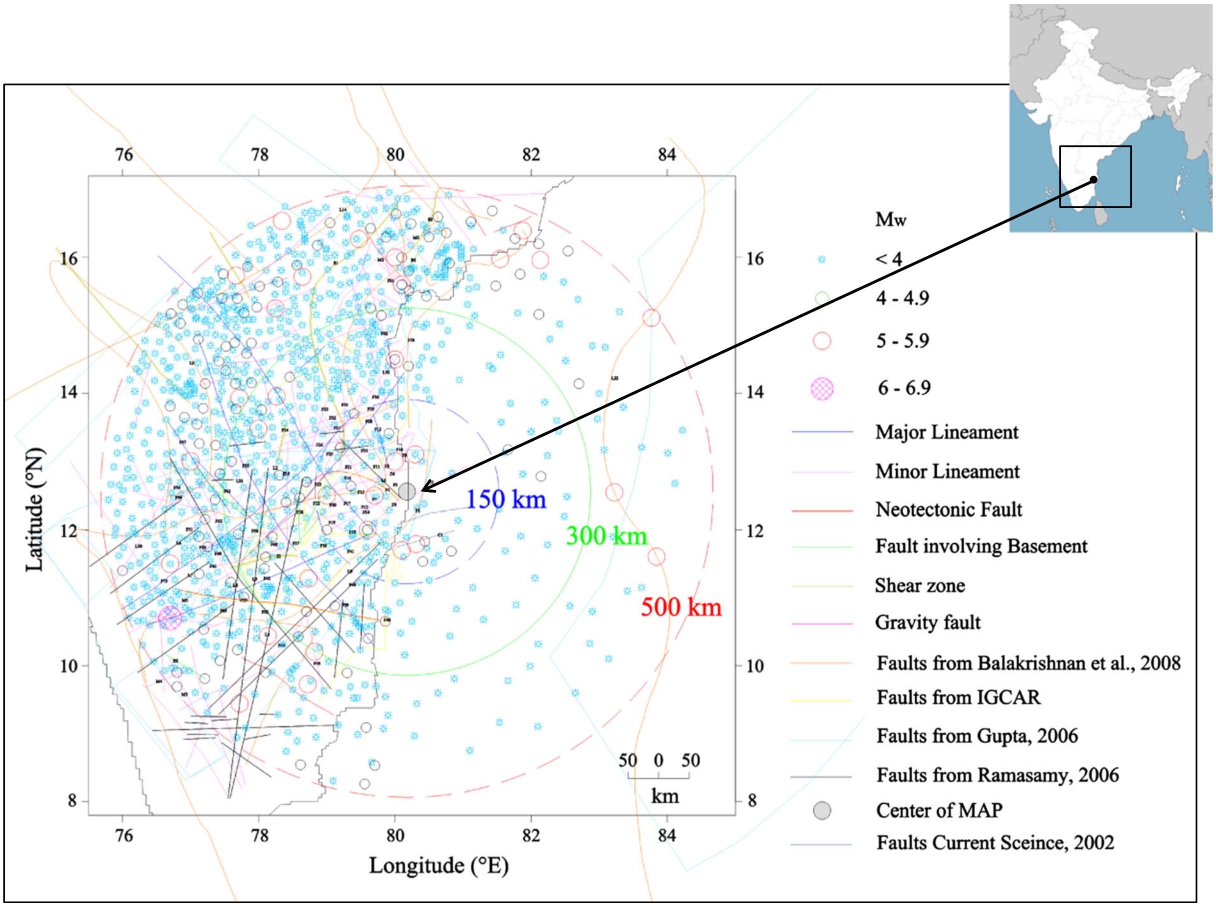


Fig. 2 Seismotectonic map of Kalpakkam

earthquakes of magnitude 5 and above. Each earthquake and associated source has been identified and subsurface rupture length due to past earthquake has been estimated using Wells and Coppersmith (1994) relation. The RLD was divided by the total length of the source and called as a percentage of fault rupture. The rupture character of the region has been established by considering PFR versus total fault/source length plot as per Fig. 1. Figures 4 and 5 show the plot of subsurface length in terms of PFR and TFL for Kalpakkam and Patna region, respectively, for three SSA generated via three radii. It can be noticed that PFR follows a unique trend with total source length. It can also be observed from Figs. 4 and 5 that the percentage of the total fault ruptured for shorter faults are more when compared to that of longer faults and shows a decreasing trend with an increase in the fault length. This indicates that most of the damaging earthquakes in the region follow some trend. It has also been noticed that active region of Patna has higher PFR when compared to stable region of Kalpakkam. Figures 4 and 5 also show that the trend of PFR does not vary with SSA radius, only the fitness becomes better due to increase in the SSA radius. Based on the observed trend for both SSA, the curve was divided into three segments, considering the average percentage of fault ruptured and total length of the fault. This PFR can be used to estimate potential subsurface rupture length of each source, which can be again converted as the maximum magnitude for the respective source. Possible worst scenario PFR has been established by considering minimum, maximum, and average PFR in three length bins and given in Table 3 for Kalpakkam and Patna, respectively. In case of Kalpakkam segment I consist of faults having TFL less than 200 km, segment II has TFL between 200 and 500 km, and segment III has TFL greater than 500 km (Fig. 4). The respective worst scenarios PFR for these three segments are 10, 7, and 2 %, shown as horizontal line in Fig. 4. In case of Patna

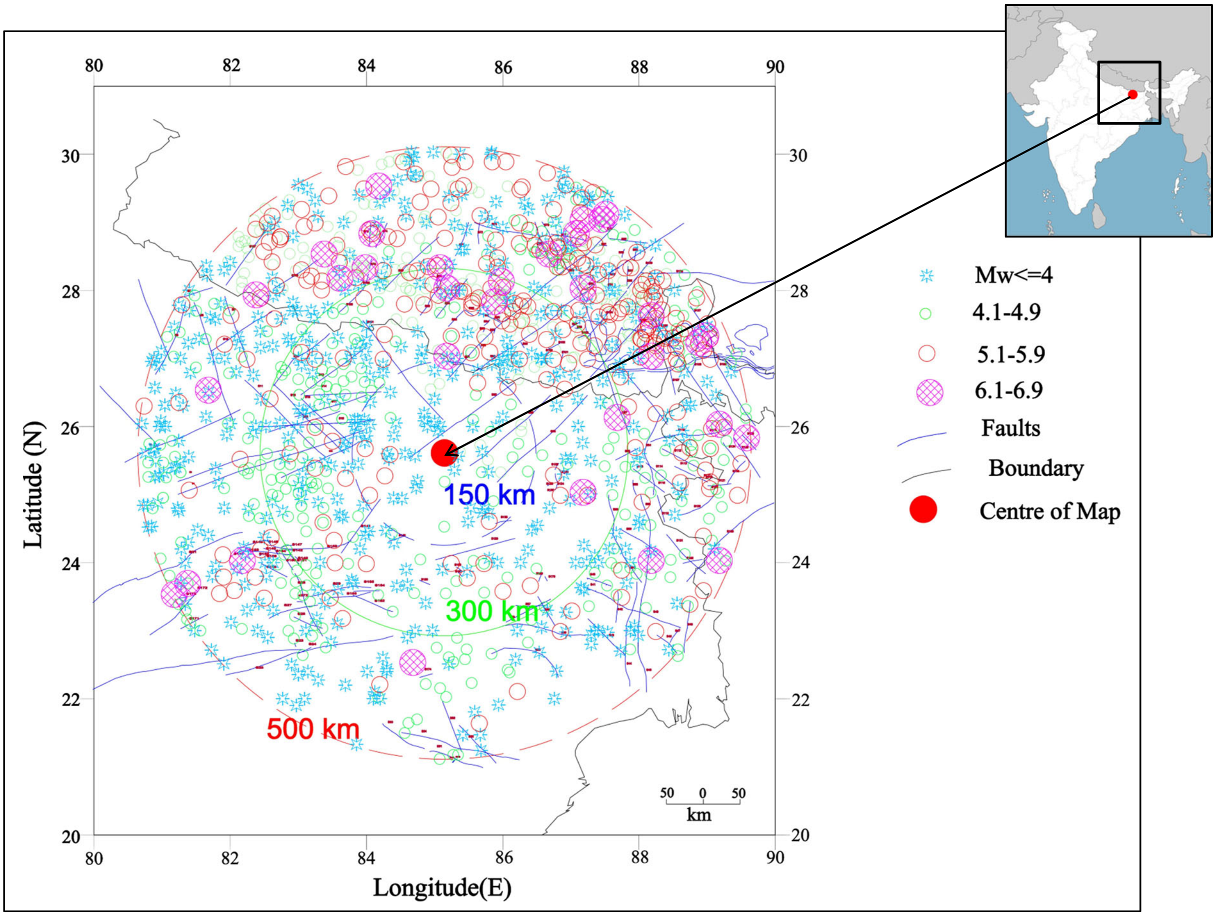


Fig. 3 Seismotectonic map of Patna

SSA, the segment I consist of faults having TFL less than 100 km, segment II has TFL between 100 and 300 km, and segment III has TFL greater than 300 km. The respective maximum PFR for the worst-case scenario for these three segments are 33, 30, and 5.5 %, shown as horizontal line in Fig. 5. For each length bin, PFR for the worst scenario earthquake has been taken as five times the average PFR, which is also more than the maximum reported PFR. PFR for the worst scenario (Table 3) has been taken as the regional rupture character of the seismic study area. It has been observed that 64 % of the total faults for Kalpakkam SSA have PFR of

Table 2 Summary of seismic data and source information for Kalpakkam (KLP) and Patna (PTN)

Study area radius	150 km		300 km		500 km	
Description	KLP	PTN	KLP	PTN	KLP	PTN
Total number of events	92	72	685	377	1238	1257
Minimum observed magnitude (M_w)	1.6	2.4	1	1.7	0.6	1.7
Maximum observed magnitude (M_w)	5.9	5.8	5.9	6.5	6.3	7.0
Number of events$<M_w$ 3	51	9	457	11	823	25
Number of events$\geq M_w$ 3	41	63	228	366	415	1232
Number of seismic source	11	12	25	71	51	176
Data period (years)	201	52	205	152	213	205

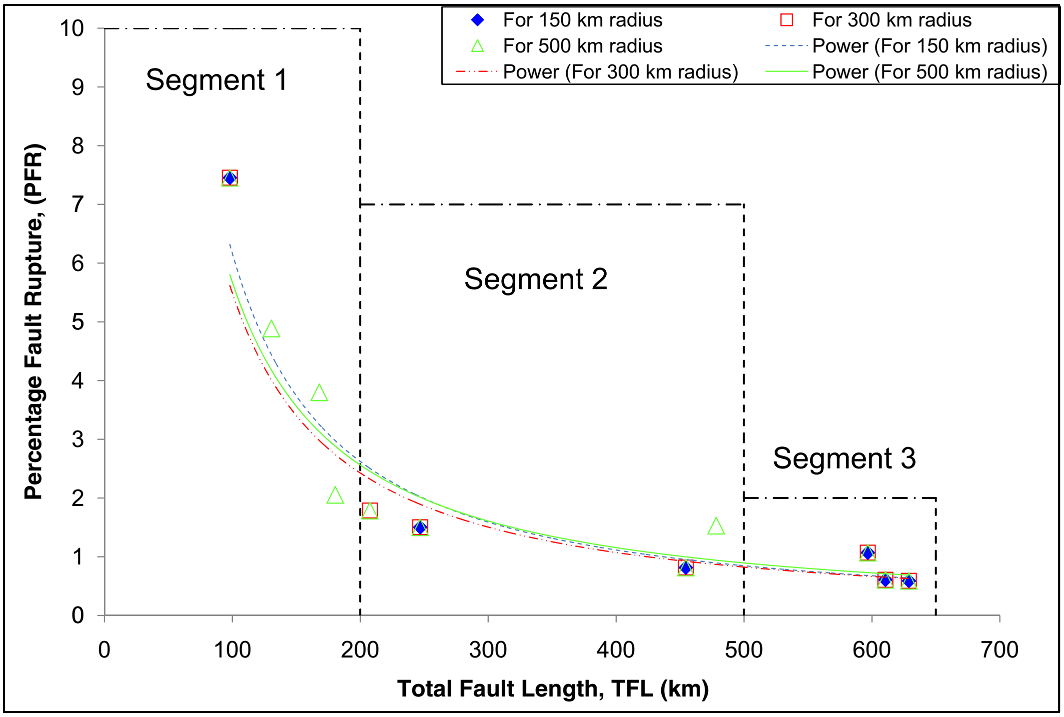


Fig. 4 Regional rupture character for subsurface rupture length in terms of percent of total length of fault versus total length of fault for Kalpakkam (*horizontal line* shows PFR for worst-case scenario as per Table 3)

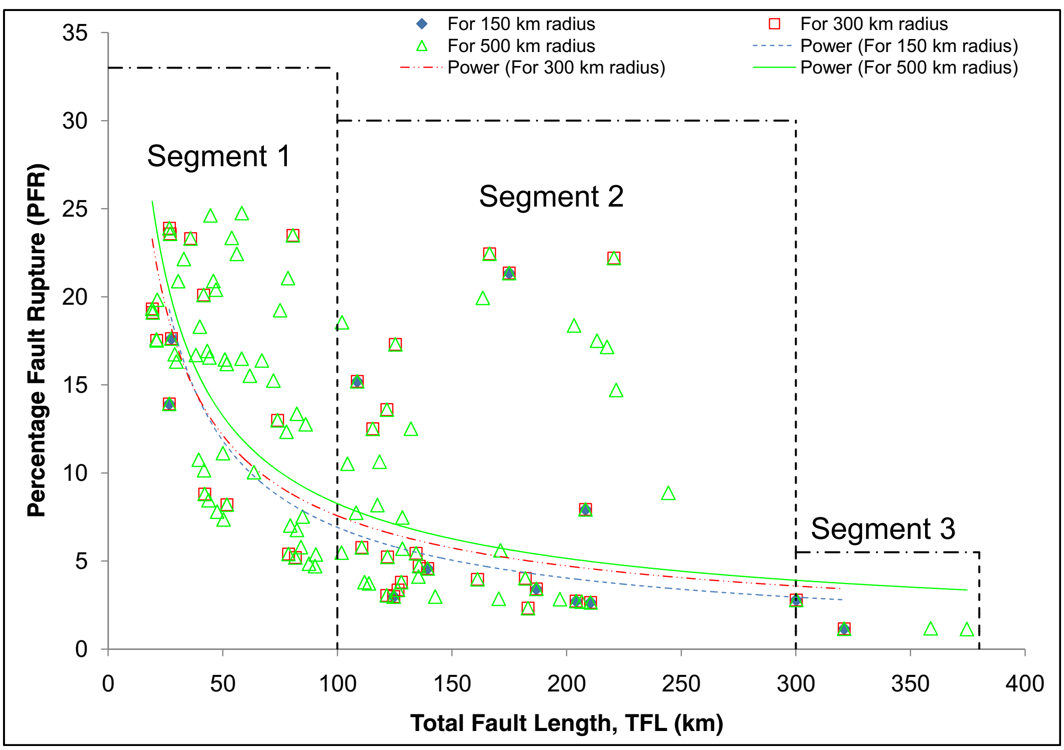


Fig. 5 Regional rupture character for subsurface rupture length in terms of percent of total length of fault versus total length of fault for Patna (*horizontal line* shows PFR for worst-case scenario as per Table 3)

Table 3 Regional rupture character for various length bins

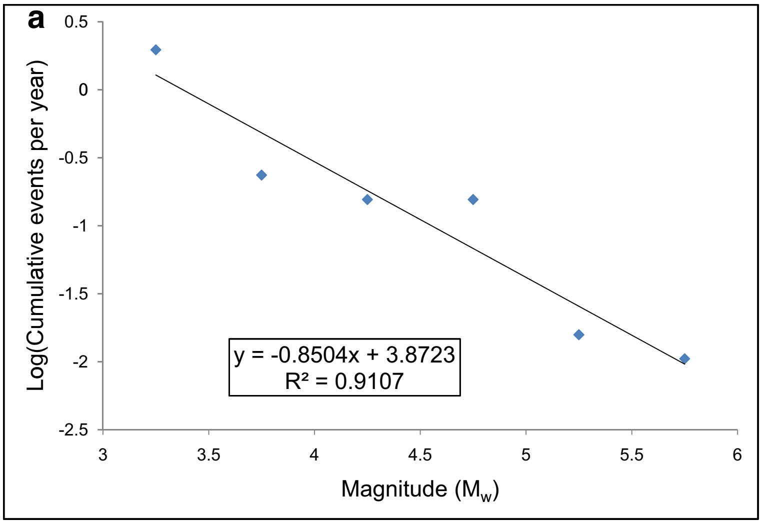
Length bins	PFR (%TFL)			PFR (% TFL) for worst scenario (WS)	Ratio of PFR for WS to maximum PFR
	Maximum	Minimum	Average		
Kalpakkam					
<200	7.45	1.786	3.99	10	1.34
200–500	4.83	0.815	2.16	7	1.44
>500	1.06	0.589	0.722	2	1.88
Patna					
<100	25	4.71	15.06	33	1.32
100–300	22.2	2.32	8.74	30	1.35
>300	3	1.13	1.56	5.5	1.83

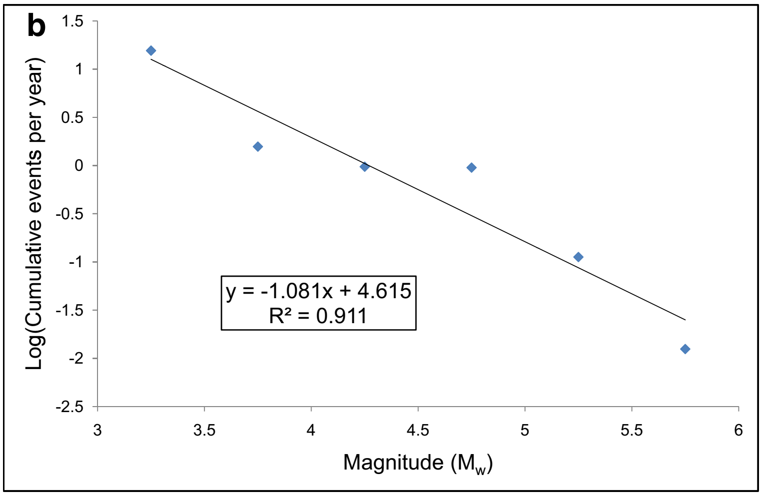
10 % whereas in case of Patna SSA, approximately 70 % of the total faults have PFR of 33 %. The subsurface rupture length was calculated based on the length of each source and the regional rupture character, which was further used to estimate the M_{max} corresponding to each source in the region. The range of maximum magnitude estimated from regional rupture characteristic for Kalpakkam site for three different radii are 5.8 to 6.7 for 150 km, 5.8 to 6.7 for 300 km, and 5.3 to 6.7 for 500 km, respectively. For Patna site, maximum magnitude range varies from 5.7 to 7.5 for 150 km, 4.5 to 7.5 for 300 km, and from 4.5 to 7.5 for 500 km radius of consideration. It has been found that the range of maximum magnitude in each study area is almost a constant irrespective of the radius of consideration. This method gives a constant value of M_{max} as it depends upon the rupture characteristic, which is a constant for a particular region. This method does not require seismic parameters of M_c, a and b parameters and $M_{max.}^{obs}$. Detailed estimation of maximum magnitude from each source for the respective study area, viz., Kalpakkam and Patna, using regional rupture characteristic are submitted as electronic material (Table EM1 and EM2).

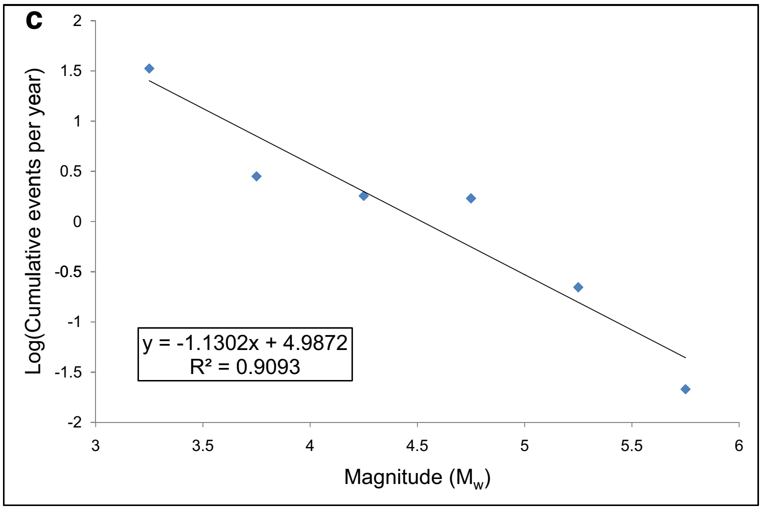
6 Seismic parameters for SSA

The seismic parameters of M_c, a and b parameters, and M_{max}^{obs} estimation are a prerequisite and are necessary for the maximum magnitude calculation by existing methods. The a and b parameters can be estimated by standard Gutenberg- Richter (G-R) recurrence relationship (Gutenberg and Richter 1956) using data from completed period or using the magnitude of completeness by Wiemer and Wyss (2000). G-R relationship hypothesizes the existence of an exponential correlation between the mean annual rate of exceedance of an earthquake of specified magnitude and the magnitude for the period of completeness. The seismic recurrence rate has to be determined correctly if the collected data of the earthquake events are complete. The data completeness for the catalogue has been estimated by adopting Stepp (1972) procedure. For evaluating the duration of completeness, the homogenized and declustered catalogue has been divided into smaller bins considering the variance of each bin as same (Stepp 1972). The compiled catalogue of Kalpakkam study area is available for a period from 1807 to 2008 (201 years), from 1807 to 2012 (205 years), and from 1800 to 2013 (213 years) for 150-, 300-, and 500-km radii, respectively. All the three catalogues were examined separately for the evaluation of a and b parameters for Kalpakkam. It has been seen that earthquake having M_w less than 5.5 is complete for 50 years for all the three radii, whereas above 5.5 M_w is complete for 190, 160, and 140 years for 150-, 300-, and 500-km radii, respectively. For this complete catalogue, a and b parameters have been calculated. Figure 6a–c shows the G-R relationship for 150-, 300-, and 500-km radii, respectively, for Kalpakkam. The "b" value for Kalpakkam is 0.85, 1.08, and 1.13 for three respective radii of consideration (Table 4). The a and b parameters estimated here were comparable with previous studies by Kaila and Sarkar (1978), Rao and Rao (1984), Boominathan et al. (2008), Boominathan (2011), Ramanna and Dodagoudar (2012), and Anbazhagan et al. (2013). The compiled catalogue of Patna study area is available for a period from 1958 to 2010

Fig. 6 **a** Gutenberg-Richter relationship for 150-km radius of Kalpakkam SSA. **b** Gutenberg-Richter relationship for 300-km radius of Kalpakkam SSA. **c** Gutenberg-Richter relationship for 500-km radius of Kalpakkam SSA







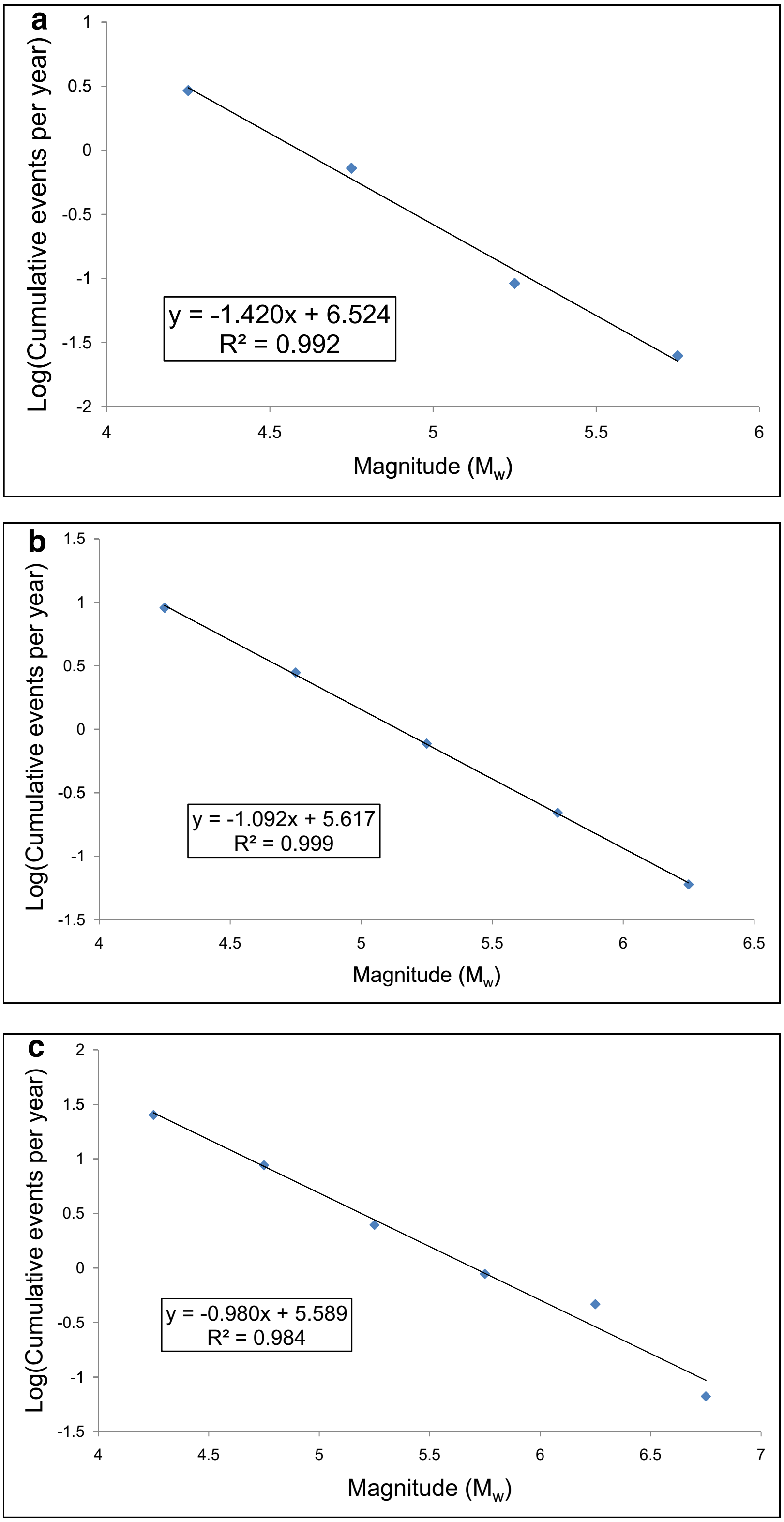


Fig. 7 **a** Gutenberg-Richter relationship for 150-km radius of Patna SSA. **b** Gutenberg-Richter relationship for 300-km radius of Patna SSA. **c** Gutenberg-Richter relationship for 500-km radius of Patna SSA

Table 4 Seismic parameters for Kalpakkam and Patna

S. no.	Description		150 km				300 km				500 km			
SSA			KLP		PTN		KLP		PTN		KLP		PTN	
1	Guttenberg–Richter parameter	a	3.87		6.524		4.62		5.617		4.98		5.589	
		b	0.85		1.42		1.08		1.09		1.13		0.98	
2	Woessner and Stefan (2005)		M_c	a and b	M_c	a and b	M_c	a and b	M_c	a and b	M_c	a and b	M_c	a and b
		M1	2.4	2.78–0.44 M_w	4.7	12.2–2.31 M_w	2	3.6–0.44 M_w	5.8	8.04–1.28 M_w	2.2	4.03–0.49 M_w	4.7	8.23–1.21 M_w
		M2	1.6	2.38–0.27 M_w	2.4	3.24–0.71 M_w	1	3.08–0.23 M_w	1.7	2.79–0.18 M_w	0.6	3.29–0.22 M_w	1.7	3.24–0.71 M_w
		M3	NA	NA	NA	NA	2	3.6–0.44 M_w	4.8	7.06–1.08 M_w	1.8	3.8–0.41 M_w	4.6	7.35–1.03 M_w
		M5	2.4	2.78–0.44 M_w	4.7	12.2–2.31 M_w	2	3.6–0.44 M_w	4.8	7.06–1.08 M_w	2.2	4.03–0.49 M_w	4.6	7.35–1.03 M_w
		M6	2.4	2.78–0.44 M_w	4.6	9.11–1.68 M_w	2.2	3.65–0.45 M_w	5.8	8.04–1.28 M_w	2.4	3.87–0.44 M_w	5	7.8–1.12 M_w
		M7	1.7	2.56–0.33 M_w	2.5	2.78–0.33 M_w	2	3.6–0.44 M_w	2.5	2.97–0.22 M_w	2	3.96–0.49 M_w	4.8	7.76–1.12 M_w
		M8	1.7	2.56–0.33 M_w	2.5	2.78–0.33 M_w	2	3.6–0.44 M_w	1.8	2.79–0.18 M_w	2	3.96–0.49 M_w	1.8	3.3–0.18 M_w
		M9	1.8	2.56–0.33 M_w	2.6	2.78–0.33 M_w	2	3.6–0.44 M_w	1.9	2.97–0.22 M_w	0.6	3.29–0.22 M_w	1.8	3.3–0.18 M_w

NA not available

(52 years), from 1858 to 2010 (152 years), and from 1808 to 2013 (205 years) for 150-, 300-, and 500-km radii, respectively. It has been seen that earthquake having magnitude moment less than 5.5 is completed for 30 years for 150 km, 40 years for 300 km, and 50 years for 500 km radius, respectively, whereas for above 5.5 M_w, catalogue is completed for 80, 100, and 110 years for 150-, 300-, and 500-km radii, respectively. For this, completed catalogue a and b parameters have been calculated and shown in Figure 7a–c for 150-, 300-, and 500-km radii, respectively. The b value for Patna is 1.42, 1.09, and 0.98 for the respective three radii of consideration (Table 4). The a and b parameters obtained here were comparable with the previous study by NDMA (2010), Nath and Thingbaijam (2011), Sreevalsa et al. (2011), and Kumar et al. (2013).

Alternately, a and b parameters can be estimated by considering the magnitude of completeness. The magnitude of completeness is defined as the lowest magnitude at which 100 % of the events in a space–time volume are detected (Rydelek and Sacks 1989; Taylor et al. 1990; Wiemer and Wyss 2000). For estimation of the magnitude of completeness and a and b parameters for both the SSA, nine different methods are used. Maximum curvature method (M1) and minimum magnitude method (M2) are fast and reliable for estimation of M_c. M_c has been determined by computing the maximum value of the first derivative of the frequency–magnitude curve (Wiemer and Wyss 2000). The goodness-of-fit method (M3, M4, and M5) computes M_c by comparing the observed frequency–magnitude distribution with synthetic ones (Wiemer and Wyss 2000). A synthetic model found at R-value of 90 and 95 % was comparable with the observed magnitude–frequency distribution and is modeled by a straight line. The 95 % level has been rarely obtained for real catalogue; therefore, 90 % is a compromise as per Woessner and Wiemer 2005. Entire magnitude range method (M6) uses the entire data set for the determination of M_c using normal cumulative distribution function and the Gutenberg-Richter power law. This is stable under most conditions but time consuming for computing a comprehensive seismicity model (Woessner and Stefan 2005). Cao and Gao (2002) (M7) define M_c as the magnitude for which the change in b value, $\Delta b(M_{co})$ of two successive cutoff magnitude (M_{co}) is smaller than 0.03. However, this criterion is unstable, as the frequency of events in single magnitude bins can vary strongly. To base and stabilize the approach numerically, b value uncertainty according to Shi and Bolt (1982) (M8) is used. According to this, M_c is the magnitude at which $\Delta b=|b_{avg}-b|\leq\delta b$, where b_{avg} is calculated from $b-$ value of successive cutoff magnitude in half a magnitude range (Woessner and Stefan 2005). Bootstrap method (M9) is used to compare the performance of different methods of estimation of M_c. The bootstrap sample earthquake catalogue is generated by replacement with an equivalent amount of the events from the original catalogue for M_c calculation.

The magnitude of completeness along with a and b parameters for all three radii has been determined from the above mentioned nine methods. It has been observed that in the Kalpakkam region, the value of M_c varies from 0.8 to 2.4, 1 to 2.2, and 0.6 to 2.4 for the radius of 150, 300, and 500 km (indicated as arrows in Fig. 8). The calculated a and b values from these nine methods have been shown in Table 4 from the respective method. Figure 9 shows M_c, a and b values for Patna region for three SSA radii. It has observed from Fig. 9 that in the Patna region, the value of M_c varies from 2.4 to 4.7, 1.7 to 5.8, and 1.7 to 5.0 for the radius of 150, 300, and 500 km. The calculated a and b values from these nine methods have been given in Table 4 from the respective method.

A best-fit model has been found at an R-value of 95 % fit in percentage of the observed magnitude–frequency distribution for both study areas. It is observed from the study that G-R relation a and b parameters for the KPL intraplate region increased with increasing SSA (Table 4), whereas these parameters decreased with increasing SSA for an active region of PTN. The a and b parameters calculated using the magnitude of completeness by nine methods varies when compared to the G-R relationship for both the regions. The methods proposed by Woessner and Stefan (2005) considered all the earthquake events for a magnitude of completeness, whereas the G-R relationship considers all the earthquakes events from the period greater than or equal to the period of completeness (Table 4). These values are further used to estimate maximum magnitude of the study area considering existing methods.

7 Maximum magnitude ($M_{\max}$) estimation by existing methods

The maximum magnitude estimation by existing method for the study area has been presented in this section. Maximum magnitude for the Kalpakkam and Patna has been estimated by considering all existing methods described above for the three radii of consideration for both the seismic study areas. A first method of magnitude estimation (MM1) considered maximum observed magnitude ($M_{\max}^{\text{obs}}$) as the maximum magnitude for the study area (Wheeler 2009; Anbazhagan et al. 2013). According to this, Kalpakkam site has $M_{\max}$ of 5.9, 5.9, and 6.3 within the radius of 150, 300, and 500 km, respectively. Similarly, MM1 gives $M_{\max}$ for Patna as 5.8 for 150 km, 6.5 for 300 km, and 7.0 for 500 km radius. In the second method, maximum magnitude (MM2) can be estimated by incrementing $M_{\max}^{\text{obs}}$ with some factor based on Gutenberg-Richter b − value' (Wheeler 2009). The $b-$value was found to be close to 1 in all three considered radii, so a factor of 0.5 is added to observed magnitude, and the resulting $M_{\max}$ is 6.4, 6.4, and 6.8, respectively, for Kalpakkam and 6.3, 7.0, and 7.5 for Patna. This method is widely practiced in India without considering regional $b-$ value and adopting 0.5 increments equivalent to one increment of earthquake intensity value. Anbazhagan et al. (2013) highlighted this and suggested that an increment of 1 is for very important structures as the 0.5 magnitude increment adds up only ten times the energy released by $M_{\max}^{\text{obs}}$ earthquake. Considering the uncertainty in data and for the worst-case scenario incrementing $M_{\max}^{\text{obs}}$ with one magnitude, leads to energy release of 31.6 times the energy released by the same source for $M_{\max}^{\text{obs}}$. Therefore, $M_{\max}$ value results in 6.6, 6.6, and 7.3 for Kalpakkam and 6.8, 7.5, and 8.0 for Patna. In the third method, maximum magnitude (MM3) value is established by extrapolating the magnitude–frequency graph of area's seismicity (Nuttli 1981; Bollinger et al. 1989) by considering the recurrence interval of 1000 years. $M_{\max}$ values diverge as 6.4, 6.6, and 7.3 for the three different radii of the Kalpakkam and 6.7, 7.9, and 8.7 for Patna. Results obtained from one magnitude increment method (MM2) by Anbazhagan et al. (2013) are comparable with 1000-year return period method (MM3) by Nuttli (1981) and Bollinger et al. (1989). As per seismicity rate method, $M_{\max}$ can be calculated from historical data by taking mean of large earthquakes having magnitudes above 7 (Wheeler 2009). Observed magnitude for the

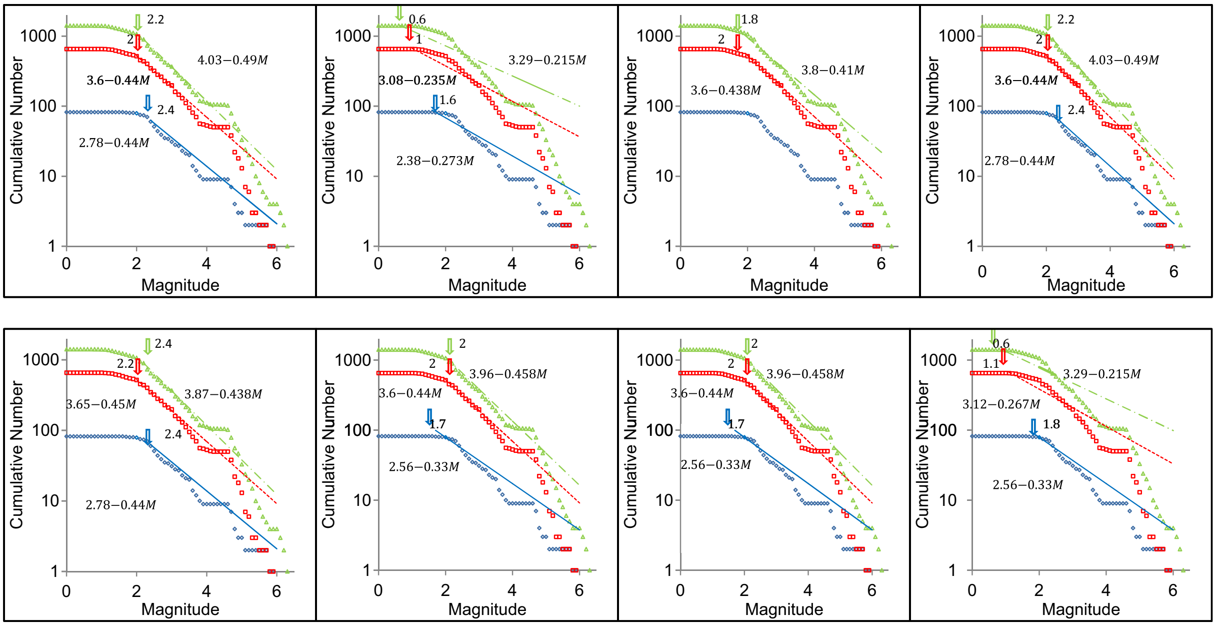


Fig. 8 Threshold magnitude for Kalpaakam using eight different methods (where *triangle* represents 500 km, *square* represents 300 km, and *diamond* represents 150 km)

Kalpakkam and Patna is found to be 6.3 and 7.0, respectively, so this method cannot be applied to these SSA. Maximum magnitude estimation by coda (Q_0) (MM4) is given in Tables 5 and 6; Q_0 value for South India is found to be 460 (Mandal and Rastogi 1998; Morozov et al. 2008), and it was concluded that South India is under the stable continental region in terms of Q_0. An estimated coda wave for Himalayan range is

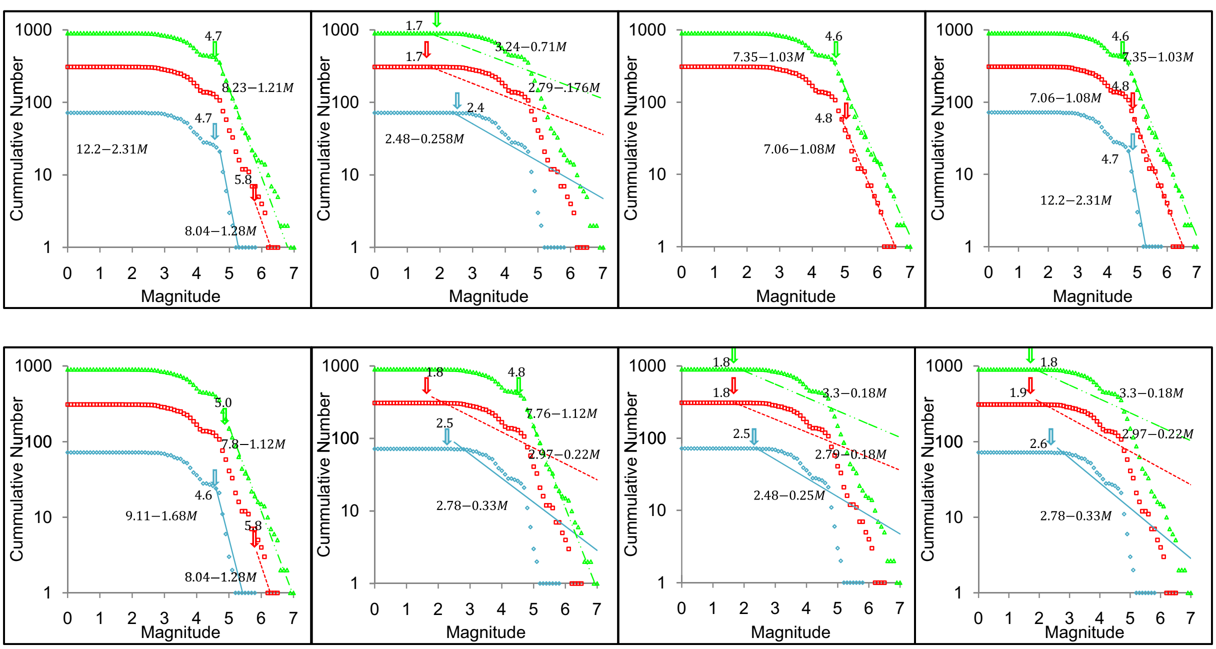


Fig. 9 Threshold magnitude for Patna using eight different methods (where *triangle* represents 500 km, *square* represents 300 km, and *diamond* represents 150 km)

Table 5 M_{max} on Kallpakam site using different methods

S. no.	Methods		M_{max} (calculated)													
			Radius of study													
			150 km					300 km				500 km				
MM1	$M_{max}=M_{max}^{obs}$		5.9					5.9				6.3				
MM2	$M_{max}=M_{max}^{obs}$ +incement	0.5	6.4					6.4				6.8				
		1	6.9					6.9				7.3				
MM3	Extrapolation of magnitude–frequency graph		6.42					6.66				7.29				
MM4	Coda method		6.4					6.4				6.4				
MM5	Mark (1977)		8.10					8.10				8.10				
MM6	Strain energy	ME_1	4.55					4.27				4.41				
		ME_2	4.04					4.74				6.11				
		ME_3	4.46					5.25				6.5				
MM7	Kijko's method[a]		M1, M5, M6	M2	M3	M7, M8	M9	M1, M3, M5, M7, M8	M2	M6	M9	M3, M5	M7, M8	M2, M9	M1	M6
	K1		6.43	6.13	NA	6.15	6.22	6.43	5.93	6.00	5.94	6.43	6.39	6.32	6.4	6.37
	K2		6.24	6.10	NA	6.11	6.15	6.10	5.93	5.99	5.94	6.36	6.38	6.32	6.39	6.37
	K3		6.24	6.10	NA	6.11	6.15	6.20	5.93	6.00	5.94	6.36	6.38	6.32	6.4	6.37
	K4		6.31	6.12	NA	6.13	6.18	6.20	5.93	5.98	5.94	6.35	6.36	6.32	6.37	6.36
	K5		6.20	6.09	NA	6.10	6.13	6.20	5.93	5.98	5.94	6.34	6.36	6.32	6.37	6.36
	K6		6.01	6.14	NA	6.14	6.12	6.12	6.13	6.10	6.13	6.42	6.41	6.43	6.4	6.41
	K7		6.08	6.08	NA	6.08	6.08	6.00	6.00	6.00	6.00	6.32	6.32	6.32	6.32	6.32
	K8		6.04	6.04	NA	6.04	6.04	6.10	5.99	5.99	5.99	6.32	6.32	6.32	6.32	6.32
	K9		6.10	6.10	NA	6.10	6.10	6.10	6.10	6.10	6.10	6.3	6.3	6.3	6.3	6.3
	K10		6.00	6.00	NA	6.00	6.00	6.00	6.00	6.00	6.00	6.3	6.3	6.3	6.3	6.3
	K11		6.06	5.98	NA	6.00	6.16	6.10	5.42	5.9	5.42	6.36	6.41	5.8	6.28	6.28
	K12		6.20	5.82	NA	5.94	6.32	6.10	5.4	6.14	5.4	6.56	6.4	5.8	7.06	6.38
MM8	Regional rupture characteristic		M_{max} varies from 5.8 to 6.7 for TFL diverges from 97.35 to 454.52 km					M_{max} varies from 5.8 to 6.7 for TFL diverges from 97.35 to 493.23 km				M_{max} varies from 5.3 to 6.7 for TFL diverges from 50.18 to 493.23 km				

NA not available

[a] As per Table 1

Table 6 $M_{\max}$ on Patna site using different methods

S. No.	Methods		M_{max} (calculated)												
			Radius of study												
			150 km					300 km			500 km				
MM1	$M_{\max}=M_{\max}^{\text{obs}}$		5.8					6.5			7.0				
MM2	$M_{\max}=M_{\max}^{\text{obs}}+$ incement	0.5	6.3					7.0			7.5				
		1	6.8					7.5			8.0				
MM3	Extrapolation of magnitude–frequency graph		6.7					7.9			8.7				
MM4	Coda method		7.3					7.3			7.3				
MM5	Mark (1977)		7.6					7.6			7.8				
MM6	Strain energy	ME_1	4.6					5.2			5.7				
		ME_2	4.9					5.6			5.8				
		ME_3	6.5					6.7			7.2				
MM7	Kijko's method[a]		M1, M5	M2, M8	M3	M6	M7, M9	M1, M6	M2, M7, M8, M9	M3, M5	M1	M2, M8, M9	M3, M5	M6	M7
	K1		6.8	5.94	NA	8.52	5.95	7.1	6.54	7.48	8.46	7.02	7.60	7.84	7.87
	K2		6.41	5.93	NA	6.27	5.94	6.77	6.54	6.87	7.45	7.02	7.30	7.35	7.36
	K3		6.4	5.92	NA	6.26	5.93	6.77	6.54	6.87	7.45	7.02	7.30	7.35	7.36
	K4		6.31	5.93	NA	7.39	5.94	7.04	6.54	7.11	7.57	7.02	7.30	7.48	7.43
	K5		6.35	5.92	NA	6.22	5.94	6.75	6.54	6.81	7.3	7.02	7.21	7.27	7.26
	K6		6.14	6.01	NA	6.2	6.02	6.62	6.67	6.7	7.16	7.15	7.17	7.17	7.16
	K7		6.5	6.5	NA	6.5	6.5	6.9	6.9	6.00	7.20	7.20	7.20	7.20	7.20
	K8		6.15	6.15	NA	6.15	6.15	6.7	6.7	5.99	7.10	7.10	7.10	7.10	7.10
	K9		6.08	6.08	NA	6.08	6.08	6.66	6.66	6.10	7.12	7.12	7.12	7.12	7.12
	K10		6.06	6.06	NA	6.06	6.06	6.64	6.64	6.00	7.12	7.12	7.12	7.12	7.12
	K11		9.00	5.54	NA	9.00	5.54	6.76	6.0	9.00	9.00	6.5	9.00	9.00	9.00
	K12		10.0	5.48	NA	10.0	5.48	6.72	6.0	10.0	10.0	6.5	10.0	10.0	10.0
MM8	Regional rupture characteristic		$M_{\max}$ varies from 5.7 to 7.5 for TFL diverges from 26.63 to 321.03 km					$M_{\max}$ varies from 4.5 to 7.5 for TFL diverges from 5.14 to 321.03 km			$M_{\max}$ varies from 4.5 to 7.5 for TFL diverges from 5.14 to 321.03 km				

NA not available

[a] As per Table 1

varied from 1100 to 1200 (Kumar et al. 2007). However, it does not involve study area considering 150 and 300 km radius. Due to lack of data for 150 and 300 km radii of study area, the above values have been considered same for three radii for Patna SSA. Resulting M_{max} for Kalpakkam and Patna sites is found to be 6.4 and 7.3 for the three radii of both the SSA, respectively. These M_{max} values are close to M_{max}^{obs} values, i.e., MM1 in the respective region. Maximum moment magnitude is calculated for the three radii considering RLD as 1/2 times of TFL as per Mark (1977) and called as method five (MM5). M_{max} by MM5 has been computed for each source/fault length, and these values are shown in electronic materials (EM1 and EM2). The maximum value of each SSA is given in Tables 4 and 5 for Kalpakkam and Patna, which is 8.1 and 7.8, respectively. M_{max} values determined using MM5 are very large and do not match with any of the above methods. The maximum magnitude corresponding to strain energy released (MM6) has been calculated as per Markropoulos and Burton (1983, 1985) and Bayliss and Paul (2013) for both the seismic study area considering 150-, 300-, and 500-km radii. A typical plot for 150, 300, and 500 km for Kalpakkam and Patna is shown in Figs. 10a–c and 11a–c. ME_1, ME_2, and ME_3 for Kalpakkam 500-km radius are 5.9, 6.1, and 6.5 and for Patna region is 5.7, 5.8, and 7.2. ME_1, ME_2, and ME_3 for 150- and 300-km radius are given in Table 5 for Kalpakkam and Table 6 for Patna. It can be observed from Table 5 that ME_1 has maximum value for 150-km radius, and ME_3 has maximum values for 300- and 500-km radii. These values are sensitive to *a* and *b* parameters of the region. Methods 1 to 6 (MM1 to MM6) is deterministic in nature and varies with seismicity of the SSA.

Kijko and Singh (2011) provide the several statistical techniques that depend upon the statistical distribution model and/or the information available about past seismicity. Kijko and Singh (2011) methods are probabilistic in nature and are called method 7 in this study constituting 12 submethods (K1 to K12). The magnitudes of completeness along with *a* and *b* values from Wiemer and Wyss (2000) as given in Table 4 have been used to estimate maximum magnitudes. Maximum magnitude for the Kalpakkam and Patna site is estimated by Kijko and other methods using MATLAB and is given in Tables 5 and 6 for Kalpakkam and Patna, respectively. In total, each SSA has 9×12 maximum magnitude values, which are grouped based on similarity. Maximum magnitude variation with respect to different *a* and *b* values are analyzed, and it is found that the methods having the same magnitude of completeness have almost equal maximum magnitude for both the study areas. The maximum magnitude of the newly proposed method is considered as method 8 (MM8), and values are given in Tables 5 and 6 for Kalpakkam and Patna, respectively. These maximum magnitude values are further discussed in the next section.

8 Results and discussion

The maximum magnitude from newly proposed method considering regional rupture characteristics and from different existing approaches are compared in this section for two regions. In both analyses, M_{max} was estimated considering seismic study area of 150-, 300-, and 500-km radii. M_{max} estimation for all approaches is given in Table 5 for Kalpakkam (intraplate region) and Table 6 for Patna (active region). The regional rupture characteristic analysis in this study shows that intraplate region of Kalpakkam has PFR of about 8 % of total length of the source and active region of Patna has PFR of about 25 % of total length of the source. The maximum PFR was noticed for shorter sources and these values decreased as the source length increased (see Figs. 4 and 5). These PFR values are incremented to find out the maximum magnitude for the worst scenario. The same data for three SSA of two regions has been further used to estimate the maximum magnitude as per the seven existing methods. It is observed from this study that most of the existing M_{max} methods are sensitive to the SSA and seismicity parameters of the region, i.e., number of events, M_{max}^{obs}, M_c, and *a* and *b* values. M_{max} from deterministic methods (MM1 to MM6), probabilistic methods, i.e., MM6 with K1 to K12, and newly proposed method (MM8) are plotted together for comparison. Figures 12 and 13 show the comparison of M_{max} by existing and newly proposed methods with M_{max}^{obs} (horizontal line) for Kalpakkam and Patna, respectively. In both the figures, diamond shape is used for 150-km radius, square is used for 300-km radius, and triangle is used for 500-km radius. In addition, error in the M_{max} estimation by both probabilistic and deterministic method has also been quantified. As the difference in the moment magnitude of any region can be ±0.3 irrespective of magnitude size and slip mechanism (Blaser et al. 2010), error of ±0.3 has been

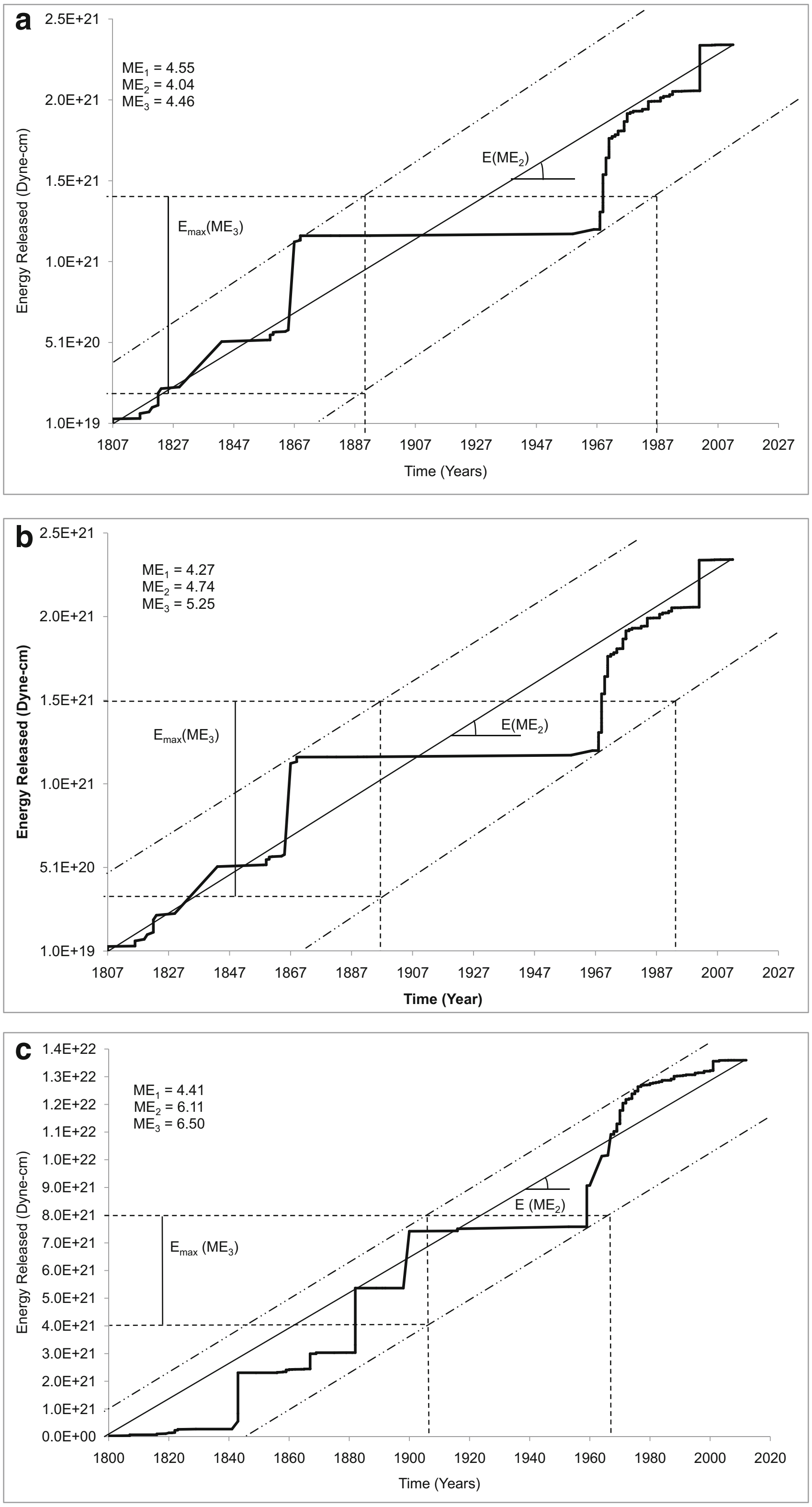


Fig. 10 **a** Schematic representation of energy-based maximum magnitude estimation for Kalpakkam (150-km radius). **b** Schematic representation of energy-based maximum magnitude estimation for Kalpakkam (300-km radius). **c** Schematic representation of energy-based maximum magnitude estimation for Kalpakkam (500-km radius)

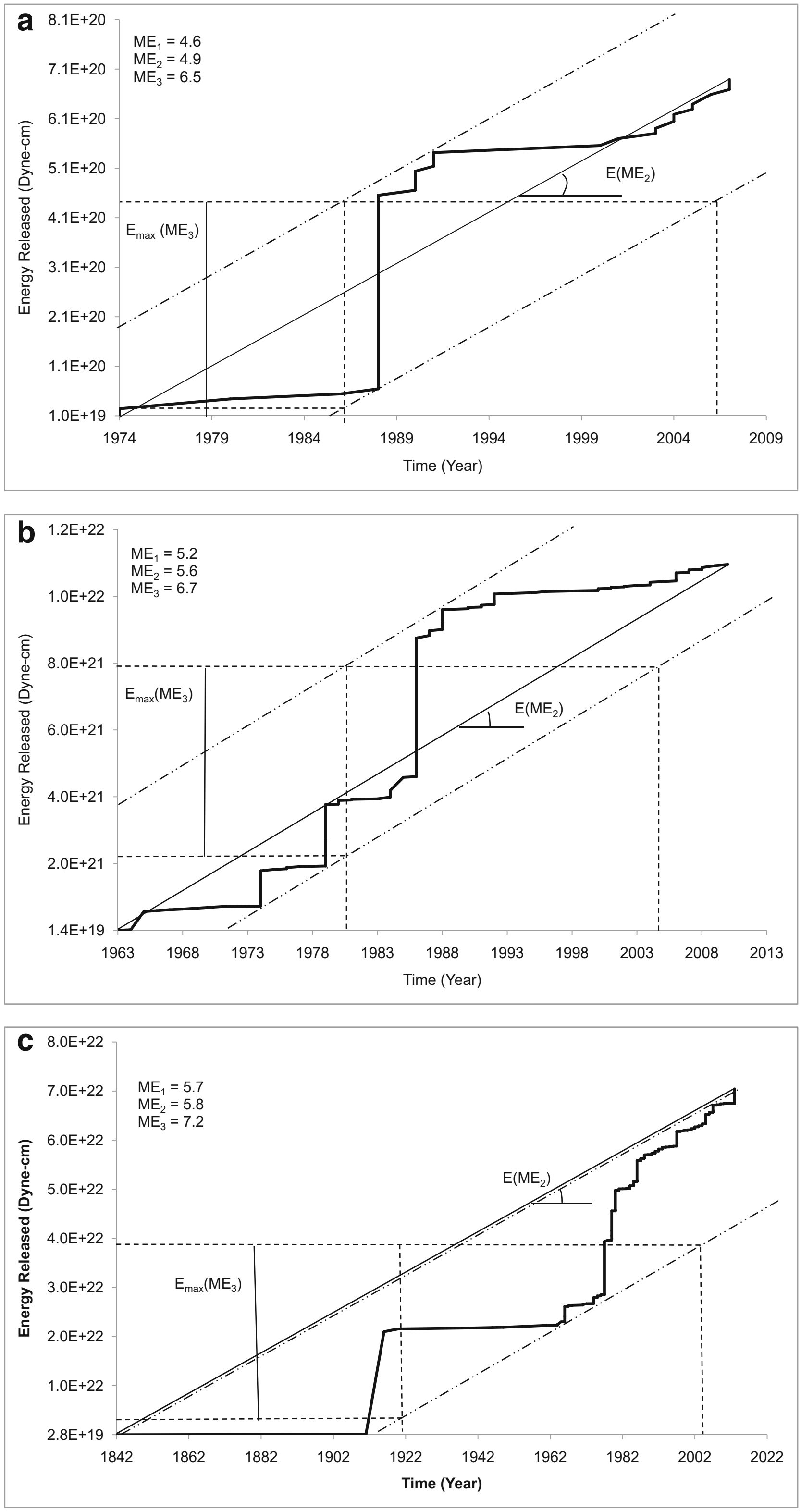


Fig. 11 **a** Schematic representation of energy-based maximum magnitude estimation for Patna (150-km radius). **b** Schematic representation of energy-based maximum magnitude estimation for Patna (300-km radius). **c** Schematic representation of energy-based maximum magnitude estimation for Patna (500-km radius)

accounted in deterministic method. In probabilistic methods, uncertainty has been determined by standard deviation. The error bars in terms of standard deviation are shown in Figs. 12 and 13. From figures, it can be noticed that most of the methods has higher error when compared to proposed method. It is observed from both figures that increase in SSA results in increase in $M_{\max}$ values in general for the region. The same $M_{\max}$ was predicted by coda wave method proposed by Jin and Aki (1988) (MM4) due to the assumption of the same Q_0 value for the three radii. It can be also noted that Wheelers (2009) had highlighted Q_0 method as inconsistent with paleoseismic data. The method proposed by Mark (1977) (MM5) does not vary with SSA and depends on the source length in the region. However, in this study, it is noticed that the $M_{\max}$ value by MM5 is approximately fourfold than $M_{\max}^{\text{obs}}$ (in case of Kalpakkam), which is unrealistic and inappropriate for intraplate region. The $M_{\max}$ values by MM5 for active regions of Patna is comparable with the proposed method and do not vary much with SSA.

Probabilistic methods for $M_{\max}$ estimation by Kijko and Singh (2011) (MM7) account uncertainty in estimating the $M_{\max}$ value and consider seismicity parameters a and b values and M_c of the study area. The estimated value of $M_{\max}$ using a probabilistic approach varies from 5.4 to 7.1 for Kalpakkam and for Patna 5.9 to 10. This study shows that $M_{\max}$ value as determined by the probabilistic approaches are sensitive to SSA, M_c and a and b values and most of the $M_{\max}$ values are close to the $M_{\max}^{\text{obs}}$ in the region. However, for Patna region, K11 and K12 methods are giving the same $M_{\max}$ values irrespective of the SSA. However, these $M_{\max}$ values are very high when compared to maximum magnitude observed in the region (Fig. 13) and uncertainty in $M_{\max}$ value in terms of standard deviation was found to be more than 2 for methods K11 and K12. It is observed that no particular trend was followed by any approach with different radius of study as either these depend upon the number of events or maximum observed earthquake magnitude that changes with alteration in seismic areas. The $M_{\max}$ values from a newly proposed method in this study (MM8) considering regional rupture characteristic are also shown in Figs. 12 and 13 for Kalpakkam and Patna regions. It can be observed from the figures that $M_{\max}$ is same for three SSA and does not depend on $M_{\max}^{\text{obs}}$ values and seismicity parameters of M_c and a and b values and error is less for the different radii considered. MM8 is a function of fault/source length and regional rupture characteristics. Furthermore, uncertainty in $M_{\max}$ value is epicentric in nature as it all depends on the well-defined seismic source. The regional rupture characteristics can be established by estimating the RLD for the past earthquakes using well-established correlation between the magnitude and subsurface rupture length (Wells and Coppersmith 1994). This proposed method deals with estimation of $M_{\max}$ considering the seismic source and its rupture length that is more reliable and not same for the whole region of seismic site.

As estimation of $M_{\max}$ is useful for determination of seismic hazard in term of peak ground acceleration (PGA) or spectral acceleration. Therefore, to quantify the applicability of the new method over existing methods, a typical seismic source (F4, see Fig. 2) which is near to Kalpakkam SSA has been selected to calculate the PGA value. $M_{\max}$ is determined by $M_{\max}=M_{\max}^{\text{obs}}$, Kijko method (K3), Mark (1977) and regional rupture characteristics (proposed method) for the seismic source F4 and used to enumerate the distribution of PGA value for Kalpakkam SSA. Seismic source F4 is having $M_{\max}^{\text{obs}}$ of 4.6 M_w and 150 km SSA has $M_{\max}^{\text{obs}}$ of 5.9 M_w, considering both $M_{\max}$ as per MM1 method is taken as 5.9. The maximum magnitude estimated using Kijko method and Mark (1977) method for seismic source F4 is 5.6 M_w and 7.4 M_w. It can be noted here that $M_{\max}$ estimated by MM1 and Kijko methods are more than source observed magnitude of 4.6 and less than regional maximum magnitude of 6.3. Gangopadhyay and Talwani (2003) highlighted that $M_{\max}^{\text{obs}}$ for Indian Stable continental region, which are associated with rift is 7.5 M_w and for a Narmada Rift basin (where the present study area is located), maximum observed magnitude is 6.3 M_w. Therefore, $M_{\max}$ determined from Kijko method and $M_{\max}= M_{\max}^{\text{obs}}$ under predict the hazard value, whereas Mark (1977) over predict as compared to previous studies. A simple deterministic seismic hazard analysis has been performed to compute the PGA using ground motion prediction equation proposed by Atkinson and Boore (2006) as per Anbazhagan et al. (2013) and is given in Fig. 14. It can be observed from four maps that PGA values are considerably different from proposed and existing methods. In the proposed method, $M_{\max}$ can be estimated for an individual fault instead of assigning one $M_{\max}$ to the seismic study area irrespective of source length and

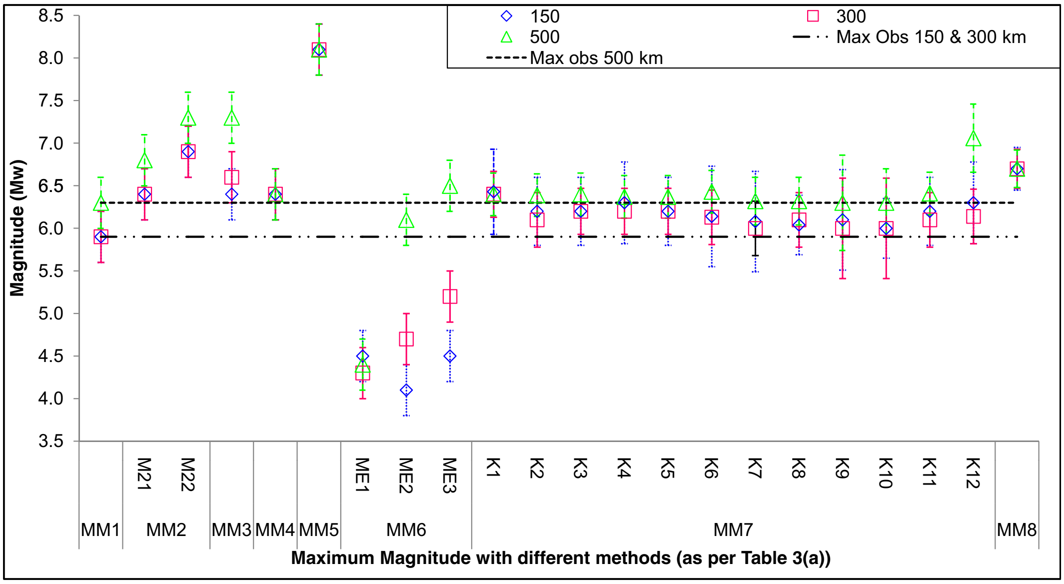


Fig. 12 Comparison of different maximum earthquake magnitude (M_{max}) method with the maximum observed magnitude (M_{max}^{obs}) of Kalpakkam region

it takes care of uncertainty in the magnitude as a function of source dimension. Hence, M_{max} estimates using proposed method correspond to less improbability in hazard values and are more reliable when compared to other methods for SSA which has well-defined seismic sources.

9 Conclusion

In this study, a new approach is proposed for estimation of maximum earthquake magnitude considering regional rupture characteristics. The regional rupture characteristic is established by accounting the rupture length

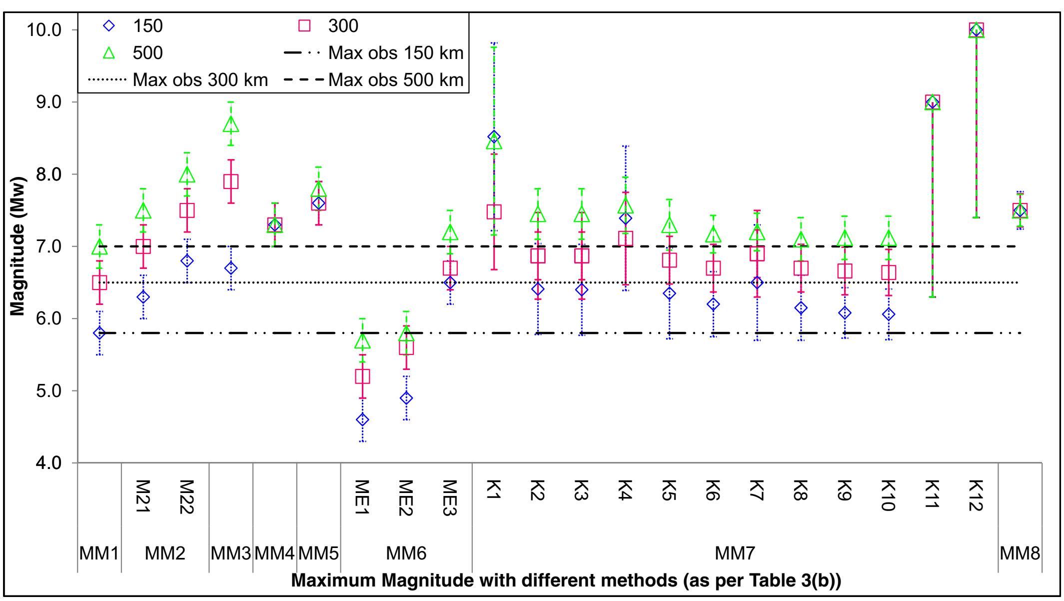


Fig. 13 Comparison of different maximum earthquake magnitude (M_{max}) method with the maximum observed magnitude (M_{max}^{obs}) of Patna region

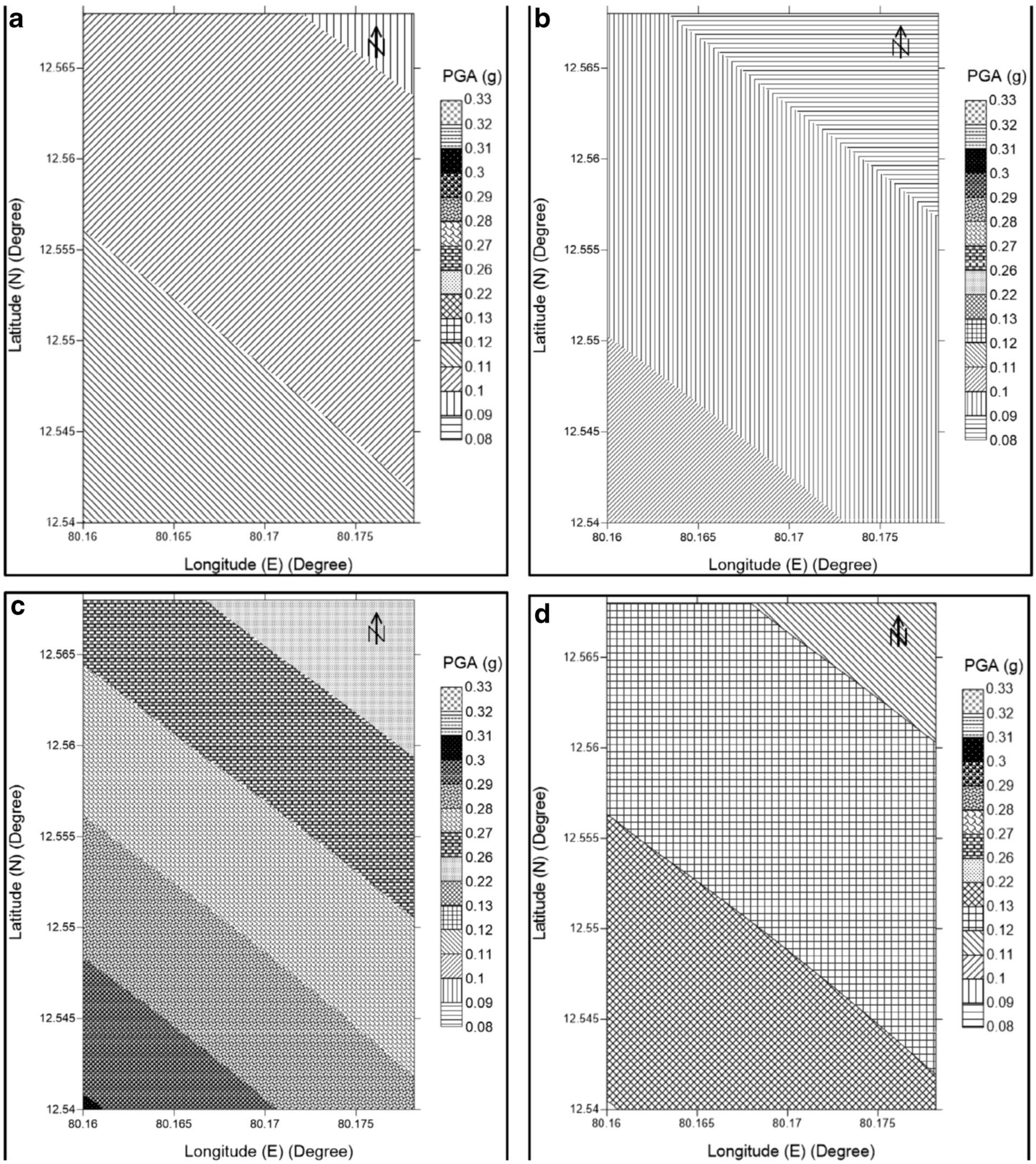


Fig. 14 Hazard values in terms of PGA corresponding to fault F4 and M_{max} is determined using **a** $M_{max}=M_{max}^{obs}$, **b** Kijko method, **c** Mark 1977, and **d** regional rupture characteristic

from the past earthquakes and associated fault/source length. The study area of Kalpakkam (intraplate region) and Patna (active region) were considered to show the maximum magnitude by the newly proposed method and from existing methods. This study shows that most of the existing methods for maximum magnitude estimation mainly depends on the radius of seismic study area, cutoff magnitude, and *a* and *b* values of the region. The proposed method is more consistent when compared to the existing methods for both intraplate and active regions. The proposed method depends upon the seismic sources and does not depend on maximum observed magnitude which corresponds to the particular seismic source or in the seismic study area and follows the same trend irrespective of seismic study area radius. The regional rupture characteristic can be precisely determined for the SSA having well-defined seismic sources. Furthermore, the correlation coefficient between the seismic source length and percentage fault rupture will be high and will follow an accurate trend for region with clear and precise seismic source information, which reduces the error in estimation of $M_{\max}$ by proposed method. In addition, variability in seismic hazard value in terms of PGA value is also computed for a typical seismic source. PGA estimated considering proposed $M_{\max}$ is different from conventional methods. Maximum magnitude determined using the new method has less standard error when compared to other existing methods.

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