



Seismic hazard curves for Warangal city in Peninsular India

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Abstract

A site-specific probabilistic seismic hazard analysis (PSHA) has been carried out for the heritage city Warangal in Telangana state of Peninsular India. The Cornell–McGuire approach of PSHA has been considered to estimate the hazard. The area of influence is taken as 500 km radius. A homogeneous and updated earthquake catalogue was compiled for the considered area which was later categorized into four seismic sources (zones) considering the earthquake epicentre and geology. The seismic parameters a and b were estimated and the b value of the for the four seismic zones ranges from 0.72 to 0.97, whereas the a value ranges from 2.45 to 3.20. The results obtained are shown as uniform hazard curves and hazard maps showing the spatial variation peak ground acceleration (PGA) considering 2% and 10% probability of exceedance in 50 years. The PGA and PSA values were compared with NDMA (Development of probabilistic seismic hazard map of India, technical report of the Working Committee of Experts (WCE), National Disaster Management Authority (NDMA), Govt. of India, New Delhi, 2010) and IS 1893-1 (Criteria for earthquake resistant design of structures, part 1: general provisions and buildings, 6th edition, Bureau of Indian Standards, New Delhi, 2016). The study focussed on understanding the possibility of seismic hazard at the heritage city Warangal in Peninsular India.

Keywords Uniform hazard spectrum · Peak ground acceleration · Probabilistic seismic hazard analysis · Warangal

Introduction

Earthquakes are the natural geophysical hazards that have an adverse effect on humans and the environment. Earthquakes were initially assumed to occur only at the tectonic plate boundaries, but some of the earthquakes at Koyna (10th December 1967), Jabalpur (21st May 1997), Latur (29th September 1993), Ongole (3rd December 1987) and Bhadrachalam (13th April 1969) emphasized that the intra-plate region is also prone to deadly earthquakes. The devastating effect of any seismic event can be decreased considerably

by evaluating the seismic hazard at the area of interest and designing the buildings accordingly. Some of the seismic hazard studies in India have considered entire India as the study region (NDMA 2010; Sitharam et al. 2015) encompassed broad seismic zones and coarse grid size; hence the hazard values may not be suggestive for local site-specific hazard assessment. Site-specific seismic hazard assessment has also been performed at micro level for some important places within Peninsular India region, such as Bangalore (Anbazhagan et al. 2009), Tamil Nadu (Menon et al. 2010), Kancheepuram (Corigliano et al. 2012), Visakhapatnam (Kumar et al. 2012), Chennai (Ramanna and Dodagoudar 2012), Mumbai (Desai and Choudhury 2014), Koyna (Dev and Nagarajan 2017) and Vijayapura (Patil et al. 2018). It is noteworthy that the Peninsular India (PI) region is vulnerable to moderate magnitude earthquakes and it is suggested that there be the site-specific hazard studies considering the local seismicity. Though Peninsular India has witnessed some of the catastrophic earthquakes, understanding of seismic hazard seems limited.

The objective of this paper was to perform a probabilistic seismic hazard analysis (PSHA) to evaluate the ground shaking elements and produce the hazard curves for the

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heritage city of Warangal. It is an ancient city which was ruled by the Kakatiya rulers from 1163 AD. The Kakatiyas have constructed many historical structures like Thousand Pillar Temple, Warangal Fort and Ramalingeswara temple. The presence of such historical structures in Warangal favoured its inclusion in “National Heritage City Development and Augmentation Yojana (HRIDAY)” scheme by the Govt. of India with the aim of bringing together the economic growth, urban planning and heritage conservation. Warangal was also selected for the Smart Cities Mission (2016) program by Government of India to make it a citizen-friendly and sustainable city. It is the second-most populous city after the capital city, Hyderabad, which is at a distance of about 130 km from Warangal, Telangana. IS 1893-1 (2016) divided the country into four zones (zones II–V) based on the earthquake intensity. Warangal falls within zone III, which is a moderate seismic region with a PGA value of 0.08 g. Peninsular India comprises many active faults and lineaments. Some important faults and lineaments featured in the influence region are Kinnerasani–Godavari fault, Kaddam fault and Musi lineament. Conservation of the ancient historical structures from earthquake hazard is essential for the future generation to understand the culture and the history of the region. Any seismic activity in such a historical and populous city will have an adverse impact on the tourism industry, employment and rapid development of the area. These aspects have made the author realize the importance and the need for seismic exposure studies of Warangal district.

The probabilistic approach of seismic hazard assessment is preferable than the deterministic method for places with moderate seismicity (Patil and Tande 2018). In this article, PSHA has been performed to estimate the earthquake hazard at Warangal region due to subsequent earthquakes in a particular time frame at a grid interval of 0.05° by the classical Cornell–McGuire (Cornell 1968; McGuire 1976) approach. The circular study region of 500 km radius with National Institute of Technology Warangal (NITW) as the centre was divided into four seismic sources considering the geology and earthquake epicentre. The Gutenberg and Richter recurrence relationship has been evaluated after the completeness analysis of the compiled homogeneous earthquake catalogue. The maximum magnitude was calculated from Kijko method (Kijko 2004). The ground motion prediction equation provided exclusively for Peninsular India by NDMA (2010) was selected to determine the ground motion parameters. The earthquake hazard values were computed for a return period of 475 years and 2475 years. Furthermore, the uniform hazard spectrum has also been developed for the considered return periods. The obtained values were compared with NDMA (2010) and Indian Standard, IS 1893-1 (2016). The seismic hazard assessment for Warangal region helps in safeguarding existing

buildings, heritage structures from earthquake hazard and to build new structures including earthquake resistant design.

Tectonic setting

Peninsular India (PI) was anticipated as a stable continental region (SCR) with low seismicity; however, Johnston and Kanter (1990) have expressed that potentially damaging earthquakes are possible in SCRs with maximum damage to life and property since the earthquake resistance design is reluctantly followed in SCRs. The Kutch, Bhuj, Koyna and Latur earthquakes are some of the examples of the earthquakes in SCRs. These earthquakes occurred because of the stresses generated in the intraplate region of PI due to the collision of Indian plate and the Eurasian plate (Kumar et al. 2007). Bilham et al. (2003) illustrated that the striking of the Indian plate with Tibet plate developed flexure in the Indian plate that produces sufficient stresses to trigger earthquakes. The 2001 Bhuj earthquake is an example of a high-stress concentrated region earthquake (Singh and Singh 2005). Vita-Finzi (2004) stated that the spatial distribution of earthquakes in PI is due to the buckling of the lithosphere. A number of sedimentary basins are present in Peninsular India. The sedimentary basins present in the study area are the Godavari Graben, Cuddapah basin and some parts of Eastern Ghats. These areas are well known and are classified as moderate seismic regions from past seismicity history (Gupta 2006). The earthquakes are comparatively fewer in Peninsular India due to the intraplate setting than at near-plate boundaries of the Himalayan region, but there is a possibility of earthquakes due to the stresses developed by the impact of the Indian plate and the presence of geological faults and lineaments. The sources for earthquakes are mostly the rupture of geological faults where the strain energy is built up over time and released along the fault plane.

The study region in this investigation is taken as 500 km radius with NITW as centre. The lineaments and faults that existed in the considered region were recognized from the Seismotectonic Atlas of India and its environs. These faults and lineaments were digitized as layers in the ArcGIS software for seismic source characterization. It is observed from the seismotectonic map that the WNW–ESE trending Kinnerasani–Godavari neo-tectonic fault is just 45 km away from Warangal city. The Musi lineament, Kolleru Lake Fault and the Godavari valley fault are propagated at 69 km, 74 km and 115 km, respectively, from the Warangal city.

Earthquake catalogue

An earthquake catalogue of a particular area features past earthquake details such as the location, depth and magnitude, which helps in identifying the seismic activity of that region. The earthquake catalogue compiled for the current

research covers instrumental as well as historical seismic events that occurred in an area of 500 km radius, with NITW as centre. The co-ordinates of NITW are 17.98 N latitude and 79.53 E longitude. Many researchers have attempted to compile an earthquake catalogue of Peninsular India. Chandra (1977) compiled for Peninsular India for the period 1594–1975, Rao and Rao (1984) for the period 1340–1983, Srivastava and Ramachandran (1985) for the time span 1839–1900. Guha and Basu (1993) collected earthquake data of magnitude greater than 3.0 for Peninsular India. Recently, Nath et al. (2017) published an earthquake catalogue for the period 1900–2014 for South Asia which includes Peninsular India. The above sources have been used in the compilation of earthquake catalogue. Along with this, internationally recognized databases of earthquakes have also been used. Among this, the India Meteorological Dept. (IMD), International Seismological Centre (ISC), and National Earthquake Info. Center (NEIC) have been accessed to complete the earthquake catalogue.

Using the available historical and instrumental data from the above sources, a comprehensive catalogue of 325 events has been compiled for the period 1800–2016. The homogeneity of the catalogue magnitude was ensured by converting all earthquake events into the moment magnitude scale (M_w). The body wave magnitude (m_b) and surface wave magnitude (M_s) are changed by using the Scordilis (2006) empirical equations. The scale of local magnitude is changed to M_w by adopting the equation given by Heaton et al. (1986). The Gutenberg and Richter (1956) equation was considered for the conversion of intensity scale (I) to moment magnitude.

There are chances of reporting the same earthquake data twice or more when the earthquake catalogue was compiled from different sources like IMD, ISC and NEIC. Such events were discarded by comparing the magnitude, location and time. In PSHA, the earthquakes are considered to comply Poisson's distribution (Gardner and Knopoff 1974). The comparatively smaller magnitude aftershocks and foreshocks depend on the higher magnitude earthquake event which follows a different probability distribution. In order to attain Poisson's distribution, declustering of earthquake catalogue was performed by adopting the modified windowing technique proposed by Uhrhammer (1986). After declustering, 288 main earthquake events were identified with $M_w \geq 3.0$ for the period 1800–2016 (217 years). The declustered earthquake events were digitized as a separate layer. The previously developed faults and lineaments layer were then combined with the earthquake event layer in ArcGIS software to obtain the comprehensive seismotectonic map that helps in understanding area-wise seismic tectonics. The considered area of study was divided into four different zones considering the distribution of earthquakes, local geology and the location of faults and lineaments. Figure 1 represents the

detailed seismotectonic map of the study area comprising the faults, lineaments and declustered earthquake events.

Completeness analysis of the earthquake catalogue

The estimation of recurrence parameters using incomplete data leads to erroneous results. Therefore, the completeness range of earthquake catalogue must be evaluated ahead of the earthquake hazard rate calculation. Historical records of high-magnitude earthquakes have larger completeness period than low-magnitude earthquakes owing to fewer instrumentation (Khan and Kumar 2018). The installation of sensitive seismograph network assisted in reporting smaller earthquakes thereby ensuring the completeness period of lower- to intermediate-magnitude earthquakes attained in the instrumental era. Several techniques have been suggested to analyse the completeness period of an earthquake catalogue (Albarello et al. 2001; Rotondi et al. 1994; Mulargia and Tinti 1985; Stepp 1972). In the present study, Cumulative Visual Inspection (CUVI) method was used to detect the completeness period of the earthquake catalogue for considered magnitude classes and seismic zones. The CUVI method is a graphical approach proposed by Mulargia and Tinti (1985). This method is simple and extensively used by several researchers (Nath et al. 2017; Desai and Choudhury 2014; Kalyan Kumar et al. 2009). In this method, the variation between the earthquakes cumulative number and time duration is plotted. The earthquake catalogue was divided into magnitude intervals starting from a magnitude of 3.0 with an increment of 0.5 magnitude. The catalogue is treated to be complete for a time period in which the occurrence rate of earthquake events is constant. This method is based on constant average slope. The completeness result obtained using the CUVI method for zone 3 is shown in Fig. 2. The completeness period for different seismic zones is tabulated in Table 1.

Evaluation of seismicity parameters

The fundamental element in the analysis of the seismic hazard of a particular area is the evaluation of the recurrence interval for earthquakes of various magnitudes. The recurrence relationship reported by Gutenberg and Richter (1944) was adopted to predict the annual earthquake occurrence rate and the relationship is given in Eq. (1):

$$\log_{10}(\lambda_M) = a - bM, \quad (1)$$

where 'a' and 'b' are the characteristic constants of the seismic zone; λ_M = the mean annual rate of exceedance of

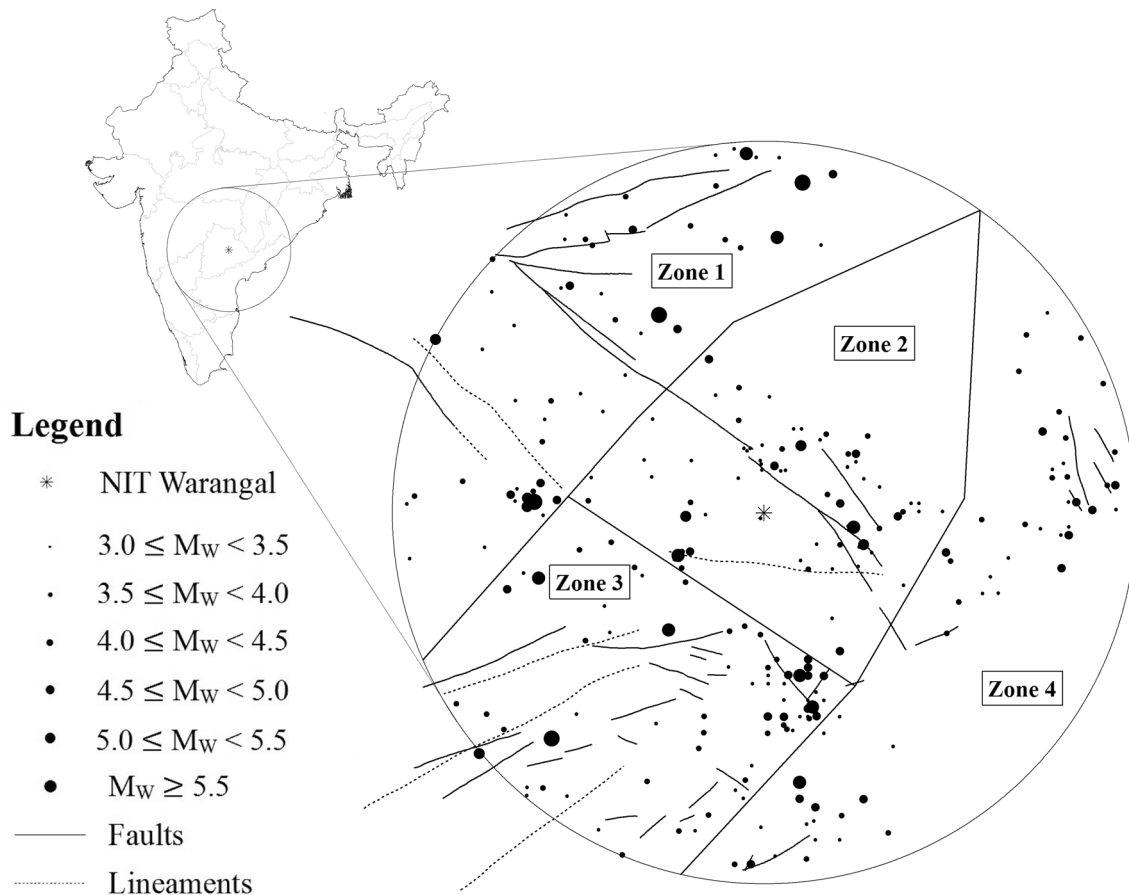


Fig. 1 Seismotectonic map of the study region

magnitude M . The constants ‘ a ’ and ‘ b ’ can be evaluated using the least square regression analysis. The ‘ b ’ value is sometimes thought of as a measure of the brittle–ductile transition of the crust (Amitrano 2003). The regression analysis estimates the ‘ a ’ and ‘ b ’ values from the cumulative annual rate of earthquake occurrence and the mean of the magnitude range. Table 1 lists the obtained G–R recurrence relationship seismicity values for all zones and Fig. 3 shows relationship for zone 1.

Maximum magnitude

The maximum magnitude (m_{\max}) is an important parameter for the disaster management agencies, insurance industry and seismologists. The m_{\max} is described as the upper limit of earthquake magnitude in the considered zone. The selection of maximum magnitude (m_{\max}) in Peninsular India is highly uncertain owing to the short time span of earthquake catalogue in contrast to the recurrence interval of high-magnitude earthquakes. The Kijko–Sellevoll–Bayes (K–S–B) approach given by Kijko (2004) considers the complete part

as well as the incomplete part of the earthquake catalogue to estimate the m_{\max} value. A MATLAB code (m_{\max}) written by Kijko was used to determine the m_{\max} value. The m_{\max} values obtained from K–S–B approach for different zones are listed in Table 1. Rout et al. (2015) used the similar method to estimate the maximum magnitude for NW central Himalayas.

Ground motion prediction equation

Ground motion prediction equation (GMPE) is the basic component in PSHA. The GMPE predicts the ground motion parameter at a particular site by relating it to the distance between the site and the source, magnitude of the earthquake, and other variables like local soil condition. Generally, Peak Ground Acceleration (PGA) and Spectral Acceleration (SA) at different structural periods are considered as the parameters to define the strong ground motion. It is preferable to choose a region-specific GMPEs in seismic hazard analysis (Muthuganeisan and Raghukanth 2016). In the absence of such GMPEs, other region GMPEs with similar seismotectonic feature can be used. The effectiveness of

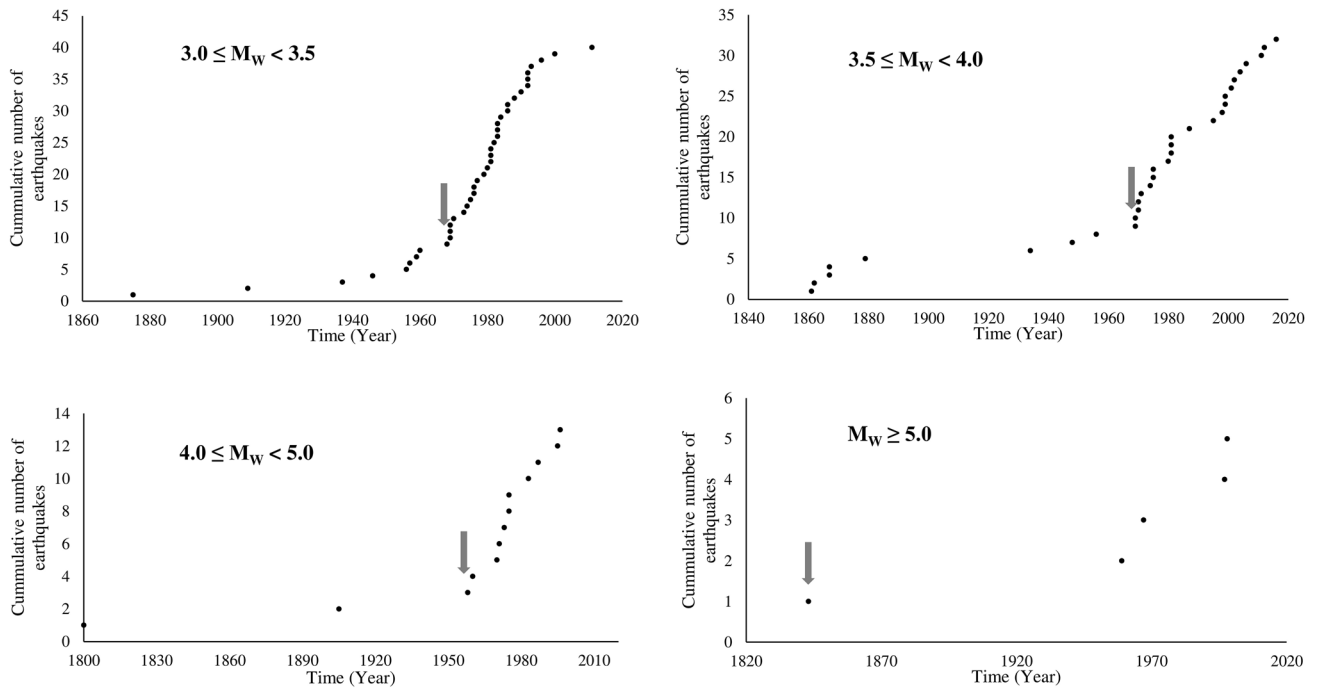
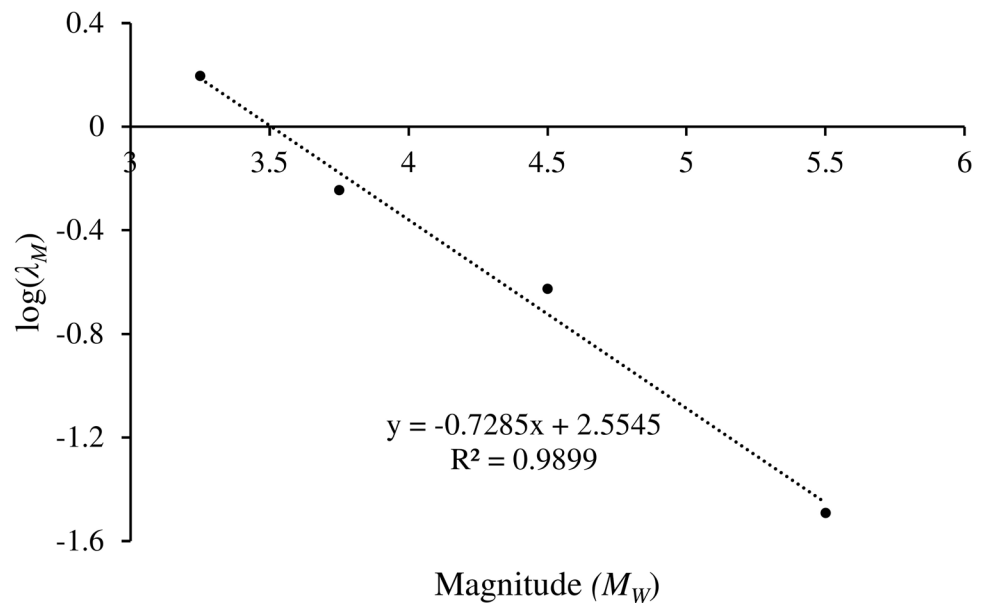


Fig. 2 Completeness analysis using the CUVI method for zone 3

Table 1 Completeness period, G–R parameters and maximum magnitude for different zones

Zones	$3.0 \leq M_w < 3.5$	$3.5 \leq M_w < 4.0$	$4.0 \leq M_w < 5.0$	$M_w \geq 5.0$	b	a	m_{max}
Z1	1995	1975	1968	1862	0.73	2.55	6.65 ± 0.46
Z2	1972	1939	1936	1876	0.82	2.68	5.50 ± 0.34
Z3	1968	1948	1946	1843	0.72	2.45	6.02 ± 0.40
Z4	1967	1959	1927	1850	0.97	3.20	5.18 ± 0.27

Fig. 3 G–R recurrence relationship for zone 1



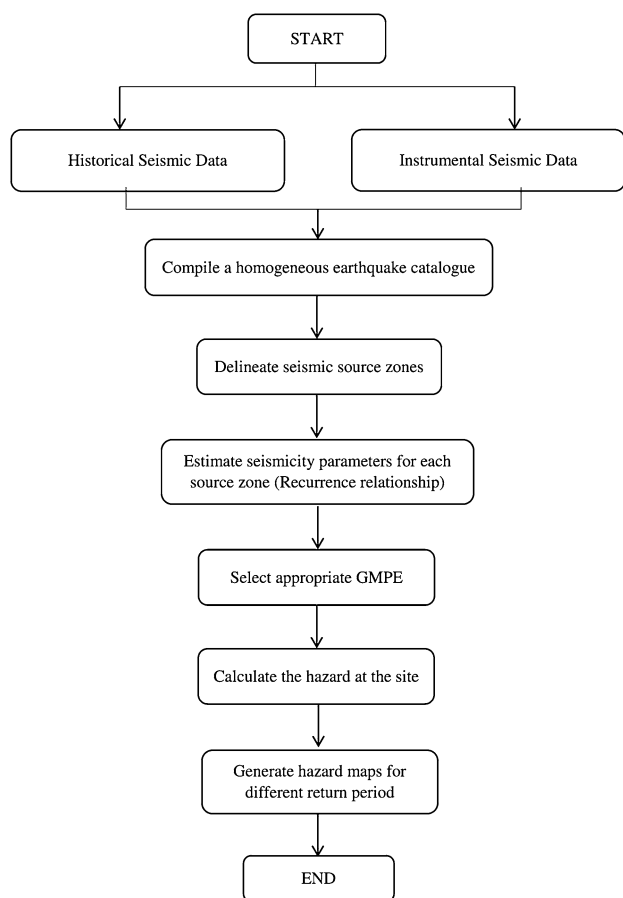


Fig. 4 Fundamental steps of the PSHA

GMPE depends on the earthquake data and the procedure adopted to develop it. Anbazhagan et al. (2017) performed the efficacy test on 27 different GMPEs and suggested that the only suitable GMPE is NDMA (2010) for hypocentral distance of more than 300 km. In this study, the GMPE suggested by NDMA (2010) was considered since the model was generated from the strong ground-motion records of Peninsular India. NDMA (2010) has developed GMPE considering the stochastic seismological model of Boore (2009) for A-type site conditions ($V_{S30} > 1500$ m/s) by dividing entire India into seven regions based on the geology and quality factor. The GMPE gives PGA and response spectra (5% damped pseudo acceleration) for the structural period ranging from 0 to 4 s, which is favourable for most of the engineering structures. The GMPE given by NDMA (2010) is of the following form:

$$\ln YF = C_1 + C_2M + C_3M^2 + C_4r + C_5 \ln(r + C_6e^{C_7M}) + C_8 \log(r/f_0) + \ln(\epsilon), \quad (2)$$

where M = the moment magnitude; Y = spectral acceleration; r = the hypocentral distance; $f_0 = \max(\ln(r/100), 0)$ and ϵ

is error associated with the regression. $C_1, C_2, C_3 \dots C_8$ are region specific coefficients that can be obtained from NDMA (2010).

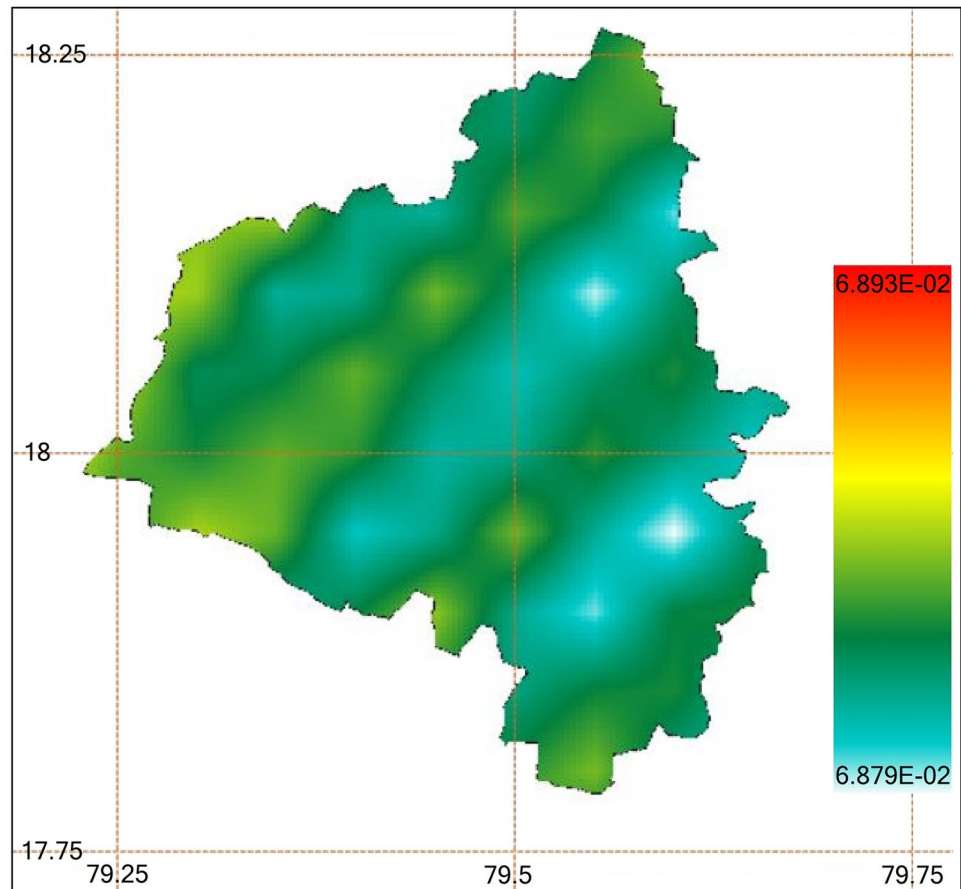
Seismic hazard computation

The seismic zones, recurrence parameters, maximum magnitude and GMPE that have been discussed previously are incorporated in the analysis of seismic hazard computation by adopting the probabilistic approach. The Probability of Exceedance (PoE) of ground acceleration in a given interval of 50 years is evaluated for Warangal province. The classical Cornell–McGuire approach which was first introduced by Cornell (1968) and later enhanced by McGuire (1976) was used in the hazard analysis. The classical approach in PSHA considers various seismic zones based on the seismicity of the site and is widely used in the evaluation of seismic hazard (Shreyasvi et al. 2019; Ramkrishnan et al. 2019; Waseem et al. 2019; Gaber et al. 2018). This method is suited for regions with medium to high seismic activity and well-defined seismic source zones. The advantages of Cornell–McGuire approach are reduction in epistemic uncertainties and the parameterisation of seismicity (Molina et al. 2001). Alternatively, a zone-less approach for seismic hazard analysis has been proposed by Frankel (1995) and Woo (1996). This technique is effective for low seismic regions where the differentiation of seismic-zone boundaries is problematic. The disadvantage of zone-less approach is that it ignores the existing seismic boundaries. The drawback of this approach is its extreme dependence on quality of the earthquake catalogue (e.g. earthquake magnitude and its location) and the smoothing parameters.

The five main steps involved PSHA are (1) to characterize the seismic zone based on seismicity, (2) to calculate the seismicity parameter for each seismic zone, (3) selection and utilizing appropriate GMPE based on regional seismicity, (4) determining the hazard values for different return periods and (5) development of PGA maps. The basic steps required for conducting PSHA are shown in Fig. 4.

The numerical calculations were performed by considering the area source model in the CRISIS2015 (Aguilar-Meléndez et al. 2017) software. NDMA (2011) defined three levels of zonations, i.e., Grade 1, Grade 2 and Grade 3 which were modified from TC4-ISSMGE4 (1999) in which Grade 1 suggest a grid size of $2 \text{ km} \times 2 \text{ km}$ to $5 \text{ km} \times 5 \text{ km}$ for Geological and Geomorphological maps. In the present study, a grid interval of 0.05° was adopted which corresponds to $5 \text{ km} \times 5 \text{ km}$ area. A similar grid size was adopted by Sitharam et al. (2012) and Desai and Choudhury (2014) for PSHA of Karnataka and Mumbai regions, respectively. The considered region was subdivided into a grid of size $0.05^\circ \times 0.05^\circ$ with 80 grid points such that all the important

Fig. 5 Spatial variation of PGA at bedrock level for 475 years' return period



and historical structures in Warangal urban district featured within the considered grid. The centre of each grid was considered for evaluating the seismic hazard. Most of the earthquakes in PI have a focal depth of 10–20 km (Ashish et al. 2016). The focal depth for the present study is considered as 15 km from the median value of focal depths for earthquakes that occurred in the study region. A total of 13 spectral ordinates were considered for the structural period varying from 0 to 2 s. The seismic hazard was calculated for a return period of 475 and 2475 years. The output generated in CRISIS2015 software was in the hazard map with exceedance rate of a particular intensity estimated at the centre of every four grid points.

Results and discussion

Seismic hazard maps

The hazard maps and hazard curves (PGA or PSA vs. λ_M) were obtained from PSHA. The seismicity parameters (a and b) calculated for considered zones were tabulated in Table 1. The seismic hazard curves and maps obtained are cumulative hazard from the four zones. The seismic hazard

map for the area of study has been generated between latitudes 17.95–18.30 and longitudes 79.50–79.95 by dividing into 80 grids of size $0.05^\circ \times 0.05^\circ$ and PGA was calculated at the centre of the grid. The spatial variation of PGA at hard stratum for 475 and 2475 years' return period for Warangal region are shown in Figs. 5 and 6, respectively. For the designing of structures, 10% probability of exceedance is considered to be ideal and appropriate. Figure 7 represents the seismic hazard curves at various time periods in the range of 0–1 s at bedrock level and the values are listed in Table 2.

Uniform hazard spectrum (UHS)

The UHS is generally employed in the response spectrum analysis of structures. The UHS is used to analyse the behaviour of structures subjected to earthquake loading. The UHS for 2% and 10% PoE in 50 years has been generated for hard stratum at NIT Warangal, bearing coordinates 17.98 N and 79.53 E, with structural period ranging from 0 to 2 s. The UHS is shown in Fig. 8 and the intensity values are listed in Table 3. The PSA and PGA values for 475 and 2475-year return period for the study region are compared with the values obtained by NDMA (2010) and IS: 1893 Part

Fig. 6 Spatial variation of PGA at bedrock level for 2475 years' return period

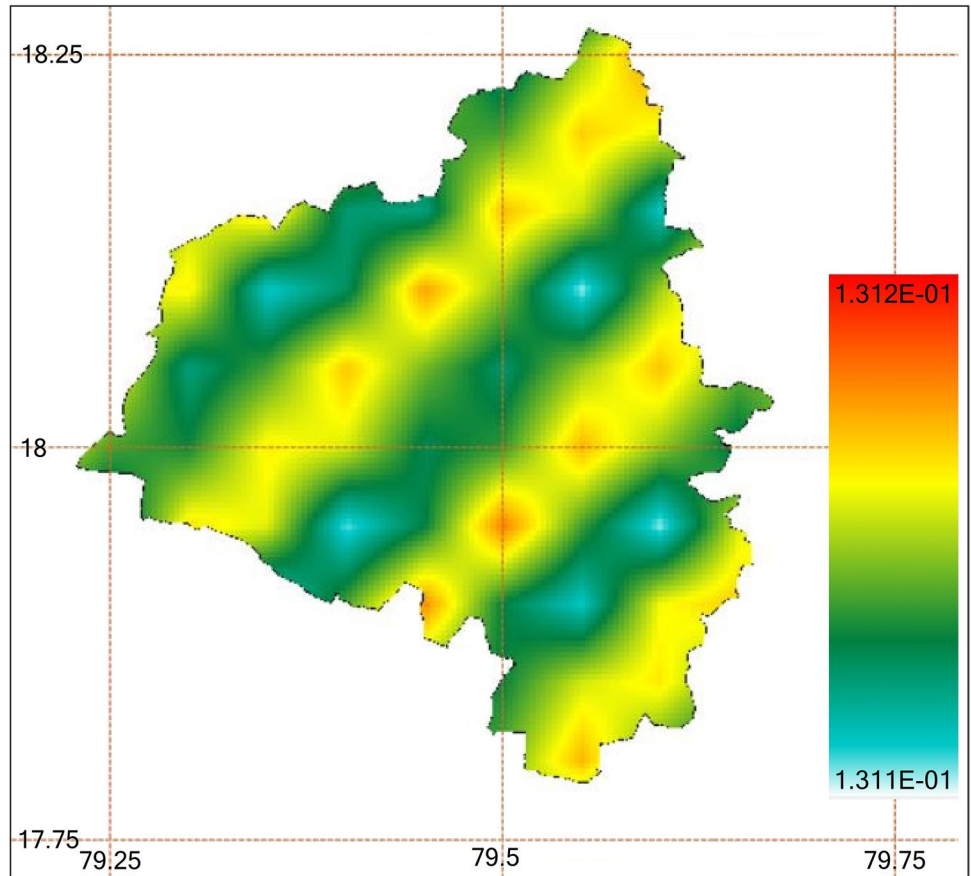


Fig. 7 Seismic hazard curve for NIT Warangal corresponding to PGA, PSA at 0.05, 0.1, 0.5 and 1 s

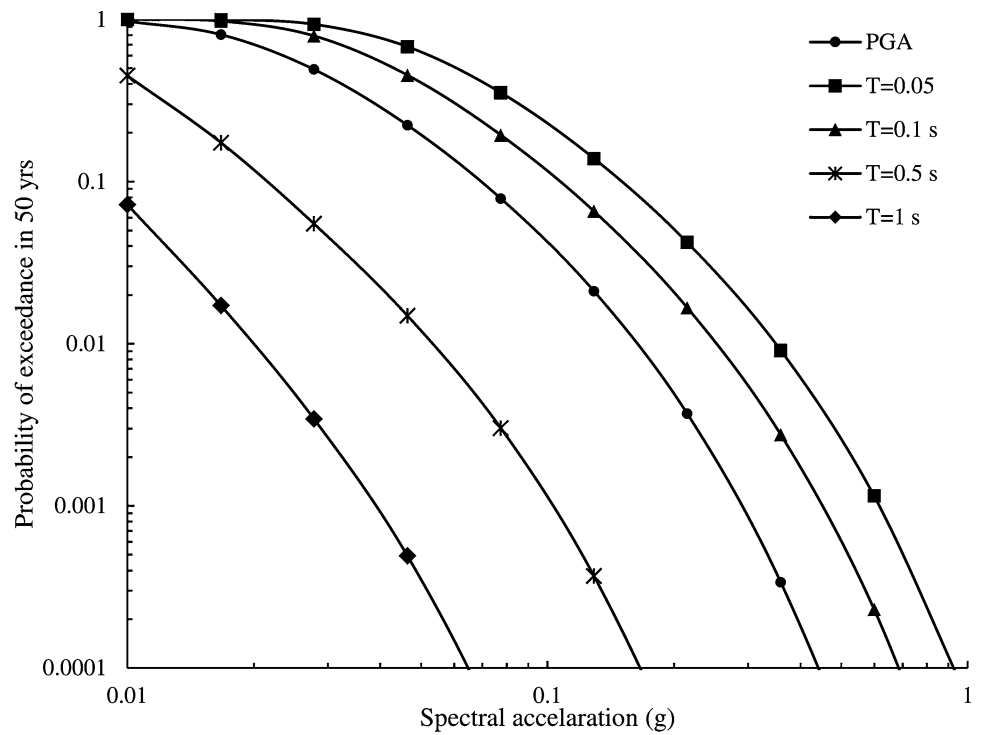


Table 2 The intensity (g) for the probability of exceedance in 50 years at different structural periods

PoE in 50 years	$T=0$ s	$T=0.05$ s	$T=0.1$ s	$T=0.5$ s	$T=1$ s
0.010	0.9760	1.0000	1.0000	0.4500	0.0721
0.017	0.8070	0.9980	0.9770	0.1740	0.0172
0.028	0.4920	0.9340	0.7930	0.0550	0.0034
0.046	0.2230	0.6800	0.4540	0.0149	0.0005
0.077	0.0787	0.3540	0.1940	0.0030	0.0000
0.129	0.0211	0.1390	0.0657	0.0004	0.0000
0.215	0.0037	0.0422	0.0167	0.0000	0.0000
0.359	0.0003	0.0091	0.0028	0.0000	0.0000
0.599	0.0000	0.0012	0.0002	0.0000	0.0000
1.000	0.0000	0.0001	0.0000	0.0000	0.0000

1 (2016) in Table 4. It is noticed that the obtained PGA and PSA values were well matched with NDMA (2010) for return periods of 475 and 2475 years. The PGA values were in accordance with the IS: 1893 Part 1 (2016), but for higher structural periods (PSA = 0.05, 0.1, 0.5 and 1 s) the code suggests higher values for both return periods. The main reason for the underestimation of PSA values compared to IS: 1893 Part 1 (2016) may be due to the probabilistic approach considered in this article. The hazard curves proposed by IS code is based on past seismicity, not on a probabilistic approach which makes it difficult to analyse the earthquake probability occurrence.

Table 3 The intensities at different structural period for 475 and 2475 years' return period

Structural period T	Return period	
	475 years	2475 years
0	0.069	0.131
0.01	0.069	0.131
0.05	0.149	0.276
0.075	0.126	0.235
0.1	0.106	0.202
0.2	0.059	0.115
0.3	0.038	0.075
0.4	0.028	0.054
0.5	0.021	0.041
0.75	0.013	0.024
1	0.009	0.016
1.5	0.005	0.008
2	0.004	0.006

Conclusions

The main focus of the work presented in the paper was to estimate the seismic hazard for Warangal province by adopting the probabilistic approach. An updated and homogeneous earthquake catalogue of magnitude 3.0 and above has been compiled from the year 1800 to 2016. A seismotectonic map was generated for the seismic study region of 500 km

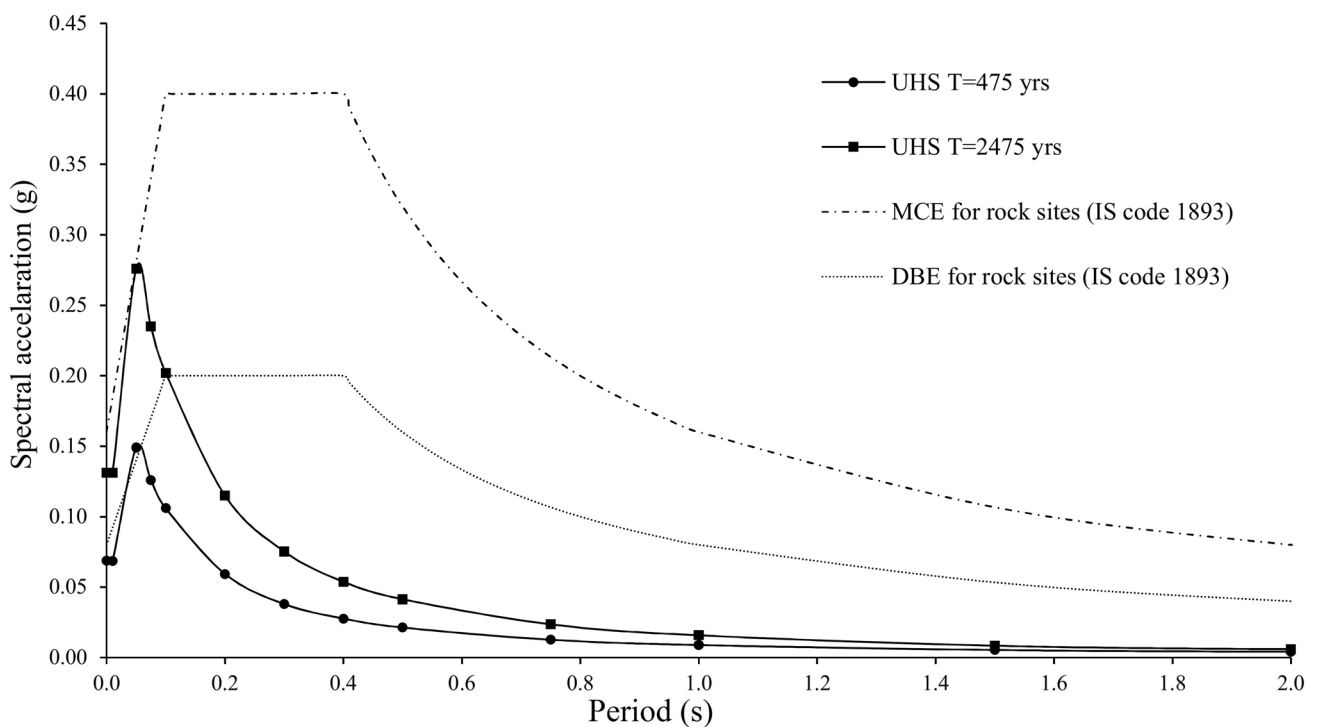


Fig. 8 Uniform hazard spectrum (UHS) for different return periods

Table 4 Comparison of PGA and PSA values with NDMA (2011) and IS 1893 code

	Present study				NDMA (2011)				IS 1893-1 (2016)			
	PGA	PSA	PSA	PSA	PGA	PSA	PSA	PSA	PGA	PSA	PSA	PSA
Return period	$T=0$	0.2	0.5	1	$T=0$	0.2	0.5	1	$T=0$	0.2	0.5	1
475	0.069	0.059	0.021	0.009	0.06	–	0.025	–	0.08	0.2	0.16	0.08
2475	0.131	0.115	0.041	0.016	0.12	0.13	0.06	0.01	0.16	0.4	0.32	0.16

that includes homogenized and declustered earthquake data in addition to faults and lineaments. The study area was subdivided into four seismic source sources by considering the geology and the earthquake distribution. The maximum magnitude was determined using Kijko's method. The attenuation relationship given by NDMA for Peninsular India region was chosen to evaluate the rock level spectral hazard curve. The seismic hazard at the considered region was evaluated by utilizing CRISIS2015 software.

The seismic hazard has been assessed and maps have been developed for the study region corresponding to 475 and 2475 years' return period, showing the PGA values across Warangal region for rock site conditions. The PGA values attained from the hazard analysis at NIT Warangal for 475 and 2475 years' return period are 0.069 g and 0.131 g, respectively. The hazard results obtained for the study region are in agreement with hazard estimated by NDMA (2010), but marginally lower compared to IS code 1893-1 (2016). A uniform hazard spectrum has also been generated for Warangal region for 475 years' and 2475 years' return period, respectively, to analyse the behaviour of structures subjected to earthquake loading. The study is region specific and detailed, which can be used in safeguarding and accessing the vulnerability of the heritage structures, and for the new constructions. The hazard values computed in the article are at bedrock site condition ($V_{S30} > 1500$ m/s). These values may vary substantially depending on site-specific soil properties. The estimated PGA values at rock condition are useful in site response analysis and liquefaction assessment of Warangal in future. The seismic hazard analysis and maps need to be updated periodically with the development of new methodology and addition of some recent seismotectonic data of a region to obtain an updated hazard map.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Appendix

Earthquake catalogue for events ≥ 4.5 magnitude

LAT	LONG	Year	Month	Day	Hours	Min-ute	Sec	Depth	M_w	Refer-ences
76.9	15.2	1843	3	31	0	0	0	0	5.67	Rao
80	18.8	1872	11	22	0	0	0	0	4.7	NDMA
78.45	17.45	1876	10	1	0	0	0	0	5	Rao
80	22	1957	8	25	21	4	50	0	5.5	ISC
80	16	1959	10	12	19	26	0	0	5.43	IMD
80	14.7	1966	4	10	0	0	0	0	5	Rao
80.16	15.62	1967	3	27	8	9	45.7	15	5.13	IMD
80.8	17.6	1968	7	27	0	0	0	0	4.5	Rao
80.67	17.81	1969	4	13	15	24	54.7	25	5.23	IMD
76	15	1975	5	12	0	0	0	0	4.6	Sacat
78.54	17.93	1983	6	30	6	59	31.1	33	4.83	IMD
79.25	22.34	1987	4	18	16	59	48	33	5.2	USGS
75.3	20	1991	4	30	0	0	0	0	4.7	Sacat
76.62	18.07	1993	9	29	22	25	47.5	12	6.23	IMD
76.52	18.11	1995	12	14	4	9	32	10	4.53	ISC
76.69	17.14	1997	1	23	2	34	50	33	5.03	ISC
78.34	16.54	1998	4	9	6	22	18.4	0	5.43	IMD
76.53	18.01	2000	6	19	8	22	5.3	15	4.53	IMD
79.67	21.32	2001	7	26	10	5	23	10	5.28	ISC
78.16	20.37	2016	2	12	10	11	14	10	5.6	ISC

Rao Rao and Rao (1984), NDMA National Disaster Management Authority (2011), Sacat <http://www.earthqaz.net/sacat/>, Nath et al. (2017), IMD India Meteorological Department, ISC International Seismological Centre, USGS United States Geological Survey

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