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Statistical Completeness Analysis of Seismic Data

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ABSTRACT

Earthquakes constitute one of the most powerful forces to which most civil engineering structures and historical constructions will ever be subjected; and thus designing and preserving structures to resist these forces is of utmost importance. The goal of earthquake-resistant design is to produce a structure or facility that can withstand a certain level of shaking without excessive damage. Seismic hazard analyses involve the quantitative estimation of ground shaking hazards at a particular site.

The main objective of this study is to develop a homogeneous earthquake catalogue for the low seismic region Warangal from 1800 to 2016 by considering a circular radius of 500 km. The catalogue is declustered using the algorithm proposed by Uhrhammer (1986) for removal of foreshocks and aftershocks. All the events have been converted to moment magnitude scale for homogenization. Completeness analysis has been carried out using the method proposed by Stepp (1972) to determine the time interval in which the data is complete over different magnitude ranges. The analysis shows that for the magnitude range of $3.0 \le M \le 3.49$, $3.5 \le M \le 3.99$, $4.0 \le M \le 4.49$, $4.5 \le M \le 4.99$, $5.0 \le M \le 5.49$ and $M > 5.49$, the data is complete for the last 50 years (1967-2016), 60 years (1957-2016), 140 years (1867-2016) and 180 years (1837-2016) respectively. This study will provide a significant under-standing in distribution of earthquakes in Warangal region as well as the assessment of seismic hazard for the region.

INTRODUCTION

Earthquakes are one of the natural hazards that are capable to cause the most extensive damage to infrastructure and human life. Every year numerous earthquakes occur all over the world. The amount of destruction caused by an earthquake depends on many factors like the magnitude of earthquake, epicentre of focus, soil profile, density of population etc. The catastrophic damage of an earthquake can be reduced significantly by accurately estimating the seismic hazard. The initial step to assess the hazard is to have a detailed knowledge of the past seismicity of the region (Ambraseys, 1971). To recognize the earthquake hazard, the first and foremost information, which gives the primary opinion is a good and homogeneous catalogue which provides the magnitude and location of the past earthquakes. Efficiency of the hazard assessment depends on the homogeneity, consistency and quality of the earthquake data. A catalogue with proper processing for identification and removal of duplicate events, eliminating foreshock and aftershock earthquakes thereby converting different magnitude scales to a homogeneous scale is required for the statistical analysis of earthquake data (Braunmiller et al., 2005). The introductory step in any data analysis is to have the information about its nature and the degree of its completeness.

The main aspect of the seismotectonic study is to have a detailed knowledge about the seismicity of the study region for hazard estimate. This can be attained from the available historical records and from the instrumental seismograph network. A complete and homogeneous earthquake catalogue provide the seismicity of the region with respect to magnitude, time and location that is used in the probabilistic seismic hazard assessment of the region (Ameer et al., 2005). Seismic hazard assessment is essential to mitigate the effect of an earthquake in a region by designing earthquake resistant structures. Seismic hazard assessment and hazard map has to be updated and revised at a regular interval with the addition of seismological data in the region. Catalogue completeness is the primary and elementary part in the analysis of the earthquake data (Singh et al., 1984). In probabilistic seismic hazard assessment (Cornell, 1968), the seismicity parameters are evaluated for the time interval of the catalogue completeness. In the pre-instrumental era, only large magnitude earthquake events are reported. Lower magnitude events were reported only from the instrumental era with the advent of seismograph network and its increasing sensitivity. In South India, the shield seismic network, Koyna seismic network and Andhra Pradesh seismic network operated by National Geophysical Research Institute, enhanced the efficiency of observing the small magnitude earthquakes (Srinagesh et al., 2015). Before the instrumental era of seismograph network, the Peninsular India was assumed to be aseismic until the 1993 Latur earthquake, the 1995 and 1987 Ongole earthquake and the 1969 Bhadrachalam earthquake which indicated that the Peninsular India is also prone to fatal earthquakes (Mohan et al., 1981).

Although Warangal is a low seismic region compared to other parts of the country but the after earthquake effect will be devastating due to many factors such as (i) very high population density in the region, (ii) presence of ancient structure like Thousand pillar temple, Warangal fort (iii) old and poor construction of buildings and (iv) the soil properties in some areas many influence seismic amplification. Thus there is a great need to conduct a seismic hazard assessment of the Warangal region to identify and classify areas based on the vulnerability. This will be the beginning for further seismic studies in the region. Thus main objective of this paper is to collect earthquake data from all the available earthquake data sources and compile a homogeneous earthquake catalogue for the Warangal region. A statistical completeness analysis has also been made to determine the time period in which the earthquake data is complete.

STUDY REGION

For the present study, the seismic events within a radius of 500 km with National Institute of Technology Warangal as centre, bearing latitude 17.981 and longitude 79.533, are considered. According to seismic zonation map of India (IS 1893 – 2002) Warangal comes under zone III whose PGA value is 0.08g. As per the seismotectonic atlas of India, the study region include major and minor faults and lineaments. Most of the epicentres of earthquake are located close to major lineaments or active faults (Raj and Nijagunappa, 2004, Dasgupta et al., 2000). Some of the important faults observed in the study region is provided in Table 1. The neotectonic Kaddam fault trending in NW-SE direction abuts the Purna fault and Tapti fault in the north near Khamgaon (Naganjaneyulu et al., 2010). The south of the Kaddam fault merges with Kinnerasani-Godavari fault which extends up to Bhadrachalam (Sangode et al., 2013).

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Table 1. List of important faults in the study region

S.No	Fault	Length (km)
1.	Kaddam fault	301
2.	Godavari Valley fault	211
3.	Parvatipuram – Bobbili fault	200
4.	Kinnerasani - Godavari fault	188
5.	Raichur - Nagarkurnool fault	181
6.	Dharma - Tungabhadra fault	144.3
7.	Karkambadi - Swarnamukhi fault	93
8.	Gundla kamma fault	76
9.	Kolleru Lake fault	72
10.	Vamsadhara fault	46
11.	Addanki - Nujivida fault	45.5
12.	Nagavali fault	43

DATA SOURCES

Earthquake catalogues constitute the first essential input for the delineation of seismic source zones and their characterization, preparation of a unified working catalogue for a region under consideration. In order to understand the seismic characteristics of the study area, internationally recognized earthquake catalogues available on the internet such as the NEIC, the International Seismological Centre (ISC, 2014) and the India Meteorological Department (IMD) have served as sources for the historical and instrumental data. Earthquake catalogue compiled by Rao and Rao (1984), Srivastava and Ramachandran (1985) and Jaiswal and Sinha (2007) for the Peninsular India were also considered. The catalogue compiled by Rao and Rao is spanning from 1800 to 1983 A.D. Catalogues of earthquakes of magnitude ≥ 3.0 in Peninsular India, are available from Chandra (1977), Guha and Basu (1993), Jaiswal and Sinha (2007), Iyengar (2010) and Nath et al. (2010). The current earthquake catalogue for Warangal region includes 325 earthquakes with $M_W \geq 3.0$ from 1800 to 2016 (Fig.1). Totally four earthquake events have been reported of magnitude greater than 5.5, with a maximum of M_W 6.2. It can be observed that earthquake catalogue is largely composed of a significant number of mild, distant events and a small number of moderate, close events from Warangal. Seismic events with magnitude greater than 3.0 are only considered in the preparation of earthquake catalogue.

MAGNITUDE CONVERSION

The earthquake events reported by various agencies in different magnitude scales such as moment magnitude (M_W), local wave magnitude (M_L), surface-wave magnitude (M_S), body-wave magnitude (m_b) and intensity scale (I). Moment magnitude is chosen as a homogeneous magnitude scale since it does not saturate at higher magnitudes (Idriss, 1985). Kolathayar et al. (2012), Bora (2016) Mahajan et al. (2010) and Thingbaijam et al. (2008) have developed regression relationship to convert different magnitude scales into moment magnitude scale for their respective study regions.

As the study area is a low seismic region, data required to develop a good regression relations is very limited (Kolathayar and Sitharam, 2012; Sawires et al., 2016). To convert the body waves and surface waves to a homogeneous moment magnitude scale, the empirical relationships developed by Scordilis (2006) were used (Khan et al., 2013; Abdelrahman et al., 2017). Scordilis (2006) has not suggested any empirical relationship to covert local magnitude scale to moment magnitude scale. Therefore, the equation given by Heaton et al. (1986) has been considered to convert local magnitude scale to moment magnitude (Anbazhagan et al., 2009; So et al., 2016). To convert Intensity scale to moment magnitude scale, Gutenberg-Richter (1956) equation, $M_W = (2/3)*I+1$, has been used. Following are the global empirical equations proposed by Scordilis (2006) to convert m_b and M_S.

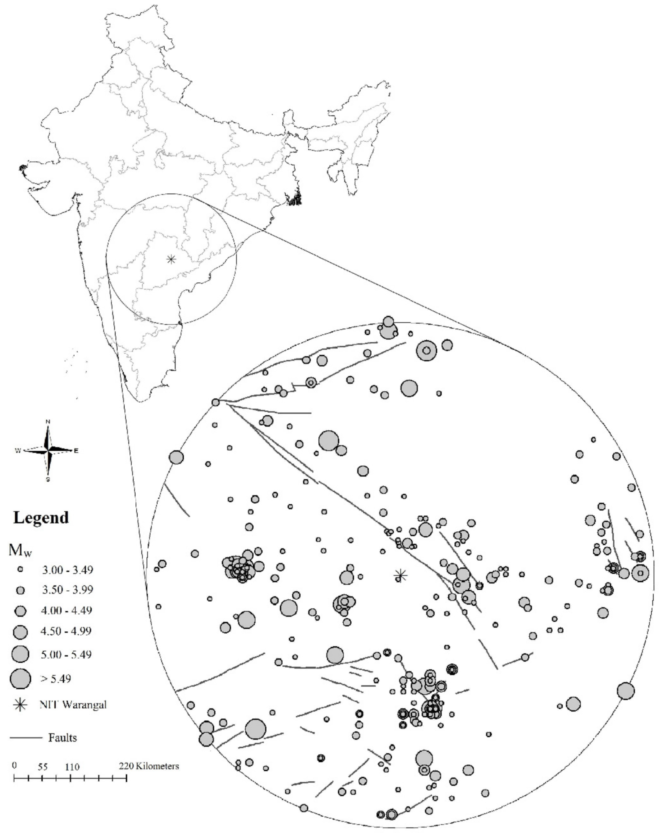

Fig.1. Epicentres of earthquakes from 1800 to 2016.

$$M_W = 0.67(\pm 0.05)\, M_S + 2.07(\pm 0.03) \quad \text{for} \quad 3 \leq M_S \leq 6.1 \tag{1}$$

$$M_W = 0.99(\pm 0.02)\, M_S + 0.08(\pm 0.13) \quad \text{for} \quad 6.2 \leq M_S \leq 8.2 \tag{2}$$

$$M_W = 0.85(\pm 0.04)\, m_b + 1.03(\pm 0.23) \quad \text{for} \quad 3.5 \leq m_b \leq 6.2 \tag{3}$$

DECLUSTERING

Aftershock and foreshock earthquake events were removed by declustering the main earthquake catalogue to have a Poisson distribution. To decluster an earthquake catalogue, Gardner and Knopoff (1974) suggested a dynamic windowing method, Reasenberg (1985) followed Second order moment method and Game theory procedure was followed by Molchan and Dmitrieva (1992). In the present study, the algorithm developed by Gardner and Knopoff (1974) modified by Uhrhammer (1986) has been used to decluster the catalogue. The algorithm considered the spatial and temporal window depends on the magnitude of the main shock. The largest event in the window will be retained, thereby removing all other smaller events (Sitharam and Sil, 2014; Sil et al., 2015; Muthuganeisan and Raghukanth, 2016).

The temporal and spatial window used to remove the aftershock and foreshock by Uhrhammer (1986) method are: time, t (days) = $e^{-2.87+1.235M}$ and distance, R (km) = $e^{-1.024+0.804M}$ respectively. After declustering, 296 events with $M_W \geq 3$ from 1800 to 2016 are recognized for the study region.

GENERAL ANALYSIS OF SEISMICITY DATA

The number of earthquakes per decade were grouped into six magnitude ranges, i.e., $3.0 \leq M \leq 3.49$, $3.5 \leq M \leq 3.99$, $4.0 \leq M \leq 4.49$, $4.5 \leq M \leq 4.99$, $5.0 \leq M \leq 5.49$ and $M > 5.49$ and are presented in Table 2. The histogram representation of the earthquake data listed in Table 2 is shown in Fig.2. From the histogram, it can be deduced that a good number of earthquakes were reported from 1967, which

Table 2. Number of earthquakes reported in each decade

Timei n Years	Number of Earthquakes within a magnitude range							
	3-3.49	3.5-3.99	4-4.49	4.5-4.99	5-5.49	5.5-5.99	6-6.49	Total
2007-2016	10	8	1	1	0	1	0	21
1997-2006	38	22	5	2	3	0	0	70
1987-1996	23	9	9	2	2	0	1	46
1977-1986	32	13	5	1	0	0	0	51
1967-1976	16	13	8	2	2	0	0	41
1957-1966	4	6	3	0	2	1	0	16
1947-1956	3	5	0	0	0	0	0	8
1937-1946	3	2	1	0	0	0	0	6
1927-1936	3	1	1	0	0	0	0	5
1917-1926	0	0	0	0	2	0	0	2
1907-1916	1	0	0	0	0	0	0	1
1897-1906	1	0	1	0	0	0	0	2
1887-1896	0	0	0	0	0	0	0	0
1877-1886	0	3	0	0	0	0	0	3
1867-1876	3	4	1	1	1	0	0	10
1857-1866	2	3	3	0	0	0	0	8
1847-1856	0	1	0	0	0	0	0	1
1837-1846	0	1	0	0	0	1	0	2
1827-1836	0	0	1	0	0	0	0	1
1817-1826	0	0	1	0	0	0	0	1
1807-1816	0	0	0	0	0	0	0	0
1797-1806	0	0	1	0	0	0	0	1

was the beginning of the instrumental era (Bolt and Brune, 1989). Prior to 1967, the earthquake reporting was poor and incomplete. Calculation of seismicity parameter with incomplete data produces inaccurate results. To overcome this problem, static windowing method suggested by Stepp (1972) was followed to check the completeness of the data.

ANALYSIS OF THE CATALOGUE COMPLETENESS

The analysis of the degree of completeness of the earthquake catalogue is the fundamental investigation in seismic hazard analysis (Mahajan and Ghosh, 2007). The completeness analysis for different magnitude interval gives the unbiased estimate of background seismicity. Completeness period of the earthquake data is mostly calculated by visual cumulative (CUVI) method suggested by Mulargia and Tinti (1985) or by Stepp's method (1972).

In the present study, the completeness analysis has been carried out using Stepp's (1972) method. To analyse the completeness of earthquake events, all the considered events are grouped in different magnitude intervals. Each magnitude range is represented as point process in time. The variance of the sample mean is inversely proportional to the number of observations in the magnitude range (Stepp, 1972). To estimate the variance, the earthquake events modelled as Poisson distribution. If x_1, x_2, x_3 …. x_n are the events in unit time interval, then the unbiased mean for each unit interval can be given as equation (4).

$$\lambda = (1/n)\ \Sigma_{i=1}^{n} x_i \qquad (4)$$

And its variance is $\sigma_\lambda^2 = (\lambda/n)$. Where 'n' is the number of unit time intervals (here n = T = 10 years). When the time interval is taken as one year, then the standard deviation for the above equation written as equation (5).

$$\sigma_\lambda = \frac{\sqrt{\lambda}}{\sqrt{T}} \qquad (5)$$

where, 'T' is the sample length (i.e., 10 years). The number of years the data is complete can be known from the standard deviation. As long as the data is complete, the standard deviation will be proportional to $1/\sqrt{T}$.

The rate of earthquake occurrence as a function of the time interval given in Table 3 for different magnitude ranges. The rate is given as N/T, where 'N' is the cumulative number of earthquakes in the time interval 'T'. Standard deviation is calculated using equation (5). The plotted points of each magnitude range follow a straight line path as

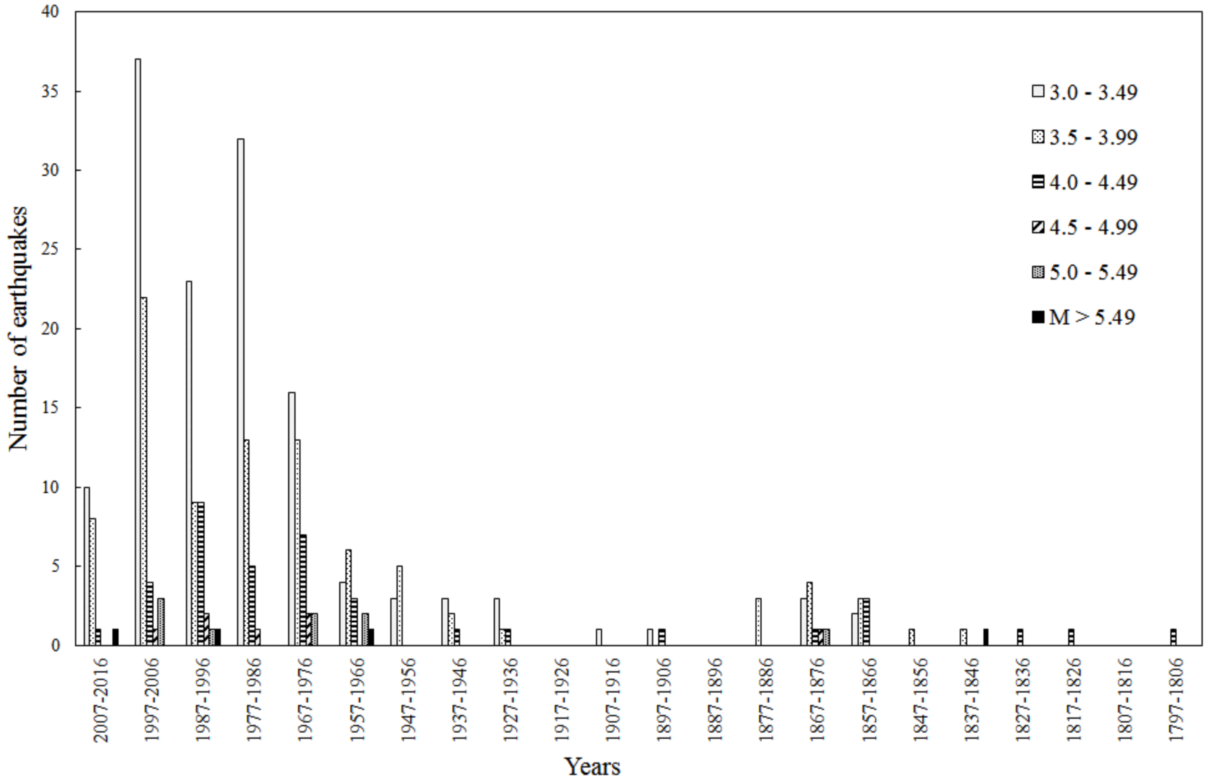

Fig.2. Histogram of the events for the study region.

Table 3. Earthquake distribution by time and magnitude

Time period	Time interval	3.0-3.49		3.5-3.99		4.0-4.49		4.5-4.99		5.0-5.49		>5.49	
		N	N/T (λ)	N	N/T (λ)	N	N/T (λ)	N	N/T (λ)	N	N/T (λ)	N	N/T (λ)
2007-2016	10	10	1.00	8	0.80	1	0.10	1	0.10	0	0	1	0.10
1997-2006	20	48	2.40	30	1.50	6	0.30	3	0.15	3	0.15	1	0.05
1987-1996	30	71	2.37	39	1.30	15	0.50	5	0.17	5	0.17	2	0.07
1977-1986	40	103	2.58	52	1.30	20	0.50	6	0.15	5	0.13	2	0.05
1967-1976	50	119	2.38	65	1.30	28	0.56	8	0.16	7	0.14	2	0.04
1957-1966	60	123	2.05	71	1.18	31	0.52	8	0.13	9	0.15	3	0.05
1947-1956	70	126	1.80	76	1.09	31	0.44	8	0.11	9	0.13	3	0.04
1937-1946	80	129	1.61	78	0.98	32	0.40	8	0.10	9	0.11	3	0.04
1927-1936	90	132	1.47	79	0.88	33	0.37	8	0.09	9	0.10	3	0.03
1917-1926	100	132	1.32	79	0.79	33	0.33	8	0.08	11	0.11	3	0.03
1907-1916	110	133	1.21	79	0.72	33	0.30	8	0.07	11	0.10	3	0.03
1897-1906	120	134	1.12	79	0.66	34	0.28	8	0.07	11	0.09	3	0.03
1887-1896	130	134	1.03	79	0.61	34	0.26	8	0.06	11	0.08	3	0.02
1877-1886	140	134	0.96	82	0.59	34	0.24	8	0.06	11	0.08	3	0.02
1867-1876	150	137	0.91	86	0.57	35	0.23	9	0.06	12	0.08	3	0.02
1857-1866	160	139	0.87	89	0.56	38	0.24	9	0.06	12	0.08	3	0.02
1847-1856	170	139	0.82	90	0.53	38	0.22	9	0.05	12	0.07	3	0.02
1837-1846	180	139	0.77	91	0.51	38	0.21	9	0.05	12	0.07	4	0.02
1827-1836	190	139	0.73	91	0.48	39	0.21	9	0.05	12	0.06	4	0.02
1817-1826	200	139	0.70	91	0.46	40	0.20	9	0.05	12	0.06	4	0.02
1807-1816	210	139	0.66	91	0.43	40	0.19	9	0.04	12	0.06	4	0.02
1797-1806	220	139	0.63	91	0.41	41	0.19	9	0.04	12	0.06	4	0.02

long as the data set is complete in that magnitude interval. For a particular region, the lines of all the magnitude ranges should have the same slope as $1/\sqrt{T}$ shown in Fig.3.

RESULTS

All the earthquake events were divided in to a magnitude range with an interval of 0.5 starting from magnitude 3.0. For the magnitude interval $3.0 \leq M \leq 3.49$ and $3.5 \leq M \leq 3.99$ the data appears to be complete for the last 50 years i.e., 1967-2016. The data in the magnitude interval $4.0 \leq M \leq 4.49$ and $4.5 \leq M < 4.99$ is complete for the last 60 years i.e., 1957-2016. The data in the magnitude range of $5.0 \leq M \leq 5.49$ and $M > 5.49$ is complete for the last 140 years (1877 – 2016) and 180 years (1837 – 2016) respectively. Higher magnitude earthquake is having greater completeness years as it can be felt by many people around the region than compared to lower magnitude earthquakes.

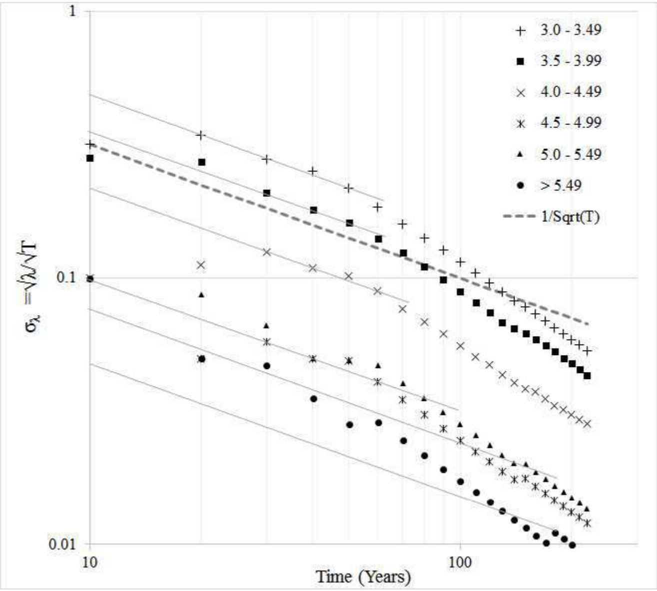

Fig.3. Completeness analysis of earthquake data.

DISCUSSION AND CONCLUSION

In this present study, an earthquake catalogue has been compiled for the Warangal region by considering a radius of 500 km with centre as NIT Warangal, bearing latitude 17.591 and longitude 79.533, from the time period 1800 to 2016. The earthquake events in different magnitude scales were converted to a homogeneous moment magnitude scale by considering the global empirical equations suggested by Scordilis (2006). A total of 325 earthquake events with magnitude, $M_w \geq 3$ were identified out of which four earthquake events have recorded a magnitude greater than 5.5, with a maximum of M_W 6.2. The events were declustred using the algorithm of Uhrhammer (1986). Completeness analysis by Stepp's (1972) method was done for the earthquake catalogue by considering the magnitude interval range of 0.5 starting from magnitude 3 which reports that for the magnitude range of $3.0 \leq M \leq 3.49$, $3.5 \leq M \leq 3.99$, $4.0 \leq M \leq 4.49$, $4.5 \leq M \leq 4.99$, $5.0 \leq M \leq 5.49$ and $M > 5.49$, the data is complete for the last 50, 50, 60, 60, 140 and 180 years respectively. The number of earthquakes reported have increased after the deployment of instrumental seismic network like Koyna seismic network and Andhra Pradesh seismic network. The earthquake catalogue prepared will be used in the seismic hazard and microzonation studies of the Warangal city. The earthquake catalogue for the Warangal region is available on request to author.

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