ORIGINAL PAPER

Estimation of Seismic Ground Motions Using Deterministic Seismic Hazard Analysis for Amaravati City, India

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Abstract Amaravati is the proposed capital city of Andhra Pradesh, India. Considering the critical structures and infrastructure systems to be built in the near future, the proposed capital city needs a seismic investigation. In the present study, an attempt was made to quantify the seismic hazard of Amaravati city (Latitude 16° 24′ 36″ N to 16° 35′ 24″ N and Longitude 80° 24′ 25″ E to 80° 36′ 18″ E), India, using a deterministic framework. The seismotectonic map is prepared by considering the seismic events of the moment magnitude $M_W \geq 3.5$ for the period 1800–2021. The seismic hazard of the Amaravati city is presented in the form of spatial variation of peak ground acceleration (PGA) at bedrock level for four scenarios. It is found that the maximum PGA values obtained for all four scenarios, i.e., 0.227 g, 0.414 g, 0.188 g, and 0.278 g, are higher than the values recommended by IS 1893-Part I (IS 1893 (Criteria for earthquake-resistant design of structures, part 1: general provisions and buildings). Bureau of Indian Standards, New Delhi, 2016). The spatial variation of 50th and 84th percentile spectral accelerations at short and long periods shows the high seismic hazard at southeastern part of Amaravati. The deterministic response spectra are developed for six important regions of Amaravati city. The study's findings will be very useful for the earthquake-resistant design of upcoming civil engineering structures in Amaravati city.

Introduction

Earthquakes are considered as one of the deadliest natural disasters. Unpredictability is the most deadly aspect of earthquakes. Although natural earthquakes cannot be prevented, their effects can be mitigated significantly by identifying hazards and building earthquake-resistant structures. Seismic hazard analysis involves quantification of expected earthquake hazard at a particular area. Seismic hazard analysis of any region can be executed deterministically or probabilistically. Deterministic seismic hazard analysis (DSHA) considers worst case scenario from the past earthquake history and estimates the hazard level of the region using suitable attenuation models. In the probabilistic method the uncertainties such as location, size and recurrence rate are explicitly considered for estimation of seismic hazard.

Amaravati is the proposed capital city of Andhra Pradesh, which is located on the banks of Krishna river in Guntur district. It is one of the important cities to the cultural heritage of India, which attracts people from different places of the world. Amaravati city is a part of peninsular India. The past earthquakes of peninsular India region such as Coimbatore earthquake (1900), Idukki earthquake (1988), Latur earthquake (1993), Jabalpur earthquake (1997), Bhuj earthquake (2001) and Koyna earthquake (1967) signify the importance of seismic hazard analysis of every region in the peninsular India. According to a zonal map of India [20], the present study area belongs to seismic zone III with a zone factor of 0.16 g (PGA). The probability of future earthquakes can be inferred by examining the locations, magnitudes, and timing

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of preceding seismic events, as suggested by Kramer [23]. The concept aligns with the principle established by Gutenberg and Richter [18], indicating that knowledge of past seismic activity enables scientific predictions of future occurrences. Significant major earthquakes of moment magnitude above (Mw) 4.5 are observed in the study region during the last decade. The recent earthquake of moment magnitude (Mw) 5.1 occurred in Bay of Bengal on 24th August 2021 is at a distance of 200 km from the Amaravati city, and the past destructive earthquakes such as Ongole earthquake of moment magnitude (Mw) 5.2 occurred in 1967 is at a distance of 117 km, and Bhadrachalam earthquake of moment magnitude (Mw) 5.7 occurred in 1969 is at a distance of 216 km from the Amaravati city respectively. Significant tectonic features like Gundlakamma fault (strike slip fault), Nallavagu fault, Krishna river fault, Kolleru lake fault (Neotectonic fault), and vasista Godavari fault were identified in the study region. In addition to this, the Srisailam dam, Prakasam Barrage and ancient undavalli caves also fall in the seismic influence zone of the Amaravati city, which enhances the importance of its seismic study. Seismic hazard analysis is very crucial for urban planning and infrastructure for upcoming capital city Amaravati. It helps in the development of critical infrastructures such as bridges, hospitals, schools and emergency response centers to ensure they are designed to withstand potential seismic events.

Previous Studies

Rapid urbanization and crucial structures and infrastructure systems of cities necessitate accurate site-specific seismic hazard analyses in order to reduce earthquake losses. As a result, the subject has attracted interest over the past 20 years in seismically active areas all over the world. This section briefs the seismic hazard studies that are conducted in the last two decades.

A deterministic approach was initially adopted by Costa et al. [13] for the Italian territory, and the author has introduced a flow chart to evaluate acceleration time series at each grid of size $0.2° \times 0.2°$ over the Italian territory. Later it was adopted by several researchers for different countries and cities of the world. Moratto et al. [27] had estimated expected ground motion in Greece by considering deterministic seismic hazard analysis procedure. A smoothing algorithm is used to the catalog of main shocks to obtain spatial smoothed distribution of magnitude. The seismic hazard maps are developed for the horizontal components such as displacement, velocity, and acceleration by considering the seismic data base of a period 420 BC to 2003. The changes in ground motion with changes in crustal velocity of seismogenic areas are investigated by sensitivity tests.

Wang and Taheri [42] presented first DSHA seismic hazard map for the Tehran region by considering one attenuation model and explained the procedure to select time histories for Tehran region. Additionally, author discussed about seismic hazard estimates to site effect, to engineering risk mitigating of earthquake designs and land uses. Mase [25] conducted seismic hazard analysis for Bengkulu city using the framework of deterministic seismic hazard analysis. The author has identified maximum magnitude of earthquake events that occurred every year, for the seismic events from 2000 to 2016. The author reported that maximum peak ground acceleration due to earthquakes in Bengkulu City ranges from 0.005 to 0.212 g.

A few works have been conducted for Indian subcontinent, to estimate seismic hazard of the important cities and regions of India. Parvez et al. [32] attempted to develop deterministic seismic hazard map of India and adjacent areas based on the computation of synthetic seismograms. A modal summation technique was adopted by the author to develop synthetic seismograms at a frequency of 1 Hz and at a grid spacing of $0.2° \times 0.2°$. Sitharam and Anbazhagan [39] conducted seismic hazard analysis for Bengaluru region by considering seismic sources within the influence zone of 350 km radius around Bengaluru city. The maximum spectral acceleration for Bengaluru city is reported as 0.332 g at a spectral period of 0.06 s.

Kolathayar et al. [22] presented seismic hazard map of India ($6°–38°$N and $68°–98°$ E) by considering deterministic approach using catalog data obtained till 2010. The author has used two different source models and twelve well-recognized attenuation models to estimate seismic hazard values at a grid size of spacing $0.1° \times 0.1°$ throughout the India. A MATLAB code was used to calculate Peak Horizontal Accelerations (PHA) and spectral acceleration at 0.1 s and 1 s. Desai and Choudhury [16] conducted deterministic seismic hazard analysis for Mumbai region (Lat. 18.875° N to 19.325° N and Long. 72.825° E to 73.125° E with grid spacing 0.05°) by using seismicity database of earthquake magnitude $M_w \geq 3.5$ since AD 1594 to 2012. The logic tree framework was adopted to overcome the epistemic uncertainty involved in the calculation of input parameters. The author has reported the results in the form of spatial variation of 50th and 84th percentile bedrock level peak horizontal acceleration and spectral acceleration at short and long periods. Naik and Choudhury [28] conducted deterministic seismic hazard analysis for Goa by considering a seismic study area with radius of 350 km from the boundary of the Goa state. The author used seven ground motion prediction equations developed for intraplate regions and shallow crustal earthquakes. For the calculation of PGA values the entire Goa state is divided into grid size of $0.1° \times 0.1°$, and the maximum PGA value of Goa state is found to be 0.15 g.

The seismic risk of three regions of Gujarat is estimated interms of probability of earthquake occurrence and earthquake return periods (Choudhry and Shukla [15]). The seismic risk in terms of earthquake occurrence in the vicinity of a newly proposed nuclear power plant was investigated by Rao and Choudhury [35]. An extreme range of risk for large (Mw≥6) and great (Mw≥7 and 8) earthquakes was estimated by varying influencing parameters, including the average recurrence interval, standard deviation, probability distributions, and time interval. The return periods of considered magnitudes were calculated using Gutenberg–Richter and bounded Gutenberg–Richter recurrence relations. Ramkrishnan et al. [34] presented seismic risk assessment of Mangalore city by accounting seismic hazard land use patterns. The author considered gridded seismicity model and linear source model for seismic hazard analysis and found that the PGA value of Mangalore city is in the range of 0.05–0.07 g. Rao and Choudhury [36] attempted to understand the earthquake forecasting in Nuclear Power Plant region of Haryana state using five stochastic models. The probability of occurrence of large earthquakes (Mw≥ 5.5) are computed on the basis of best fit model. Rao and Choudhury [37] quantified the seismic hazard for the new nuclear power plant which is going to be built in the north-western part of India. The author has considered the study area with 300 km radius from the boundary of nuclear power plant. The eight well-recognized ground motion attenuation relations were used to determine peak ground acceleration at

Fig. 1 Layout of study area, Amaravati, Andhra Pradesh, India
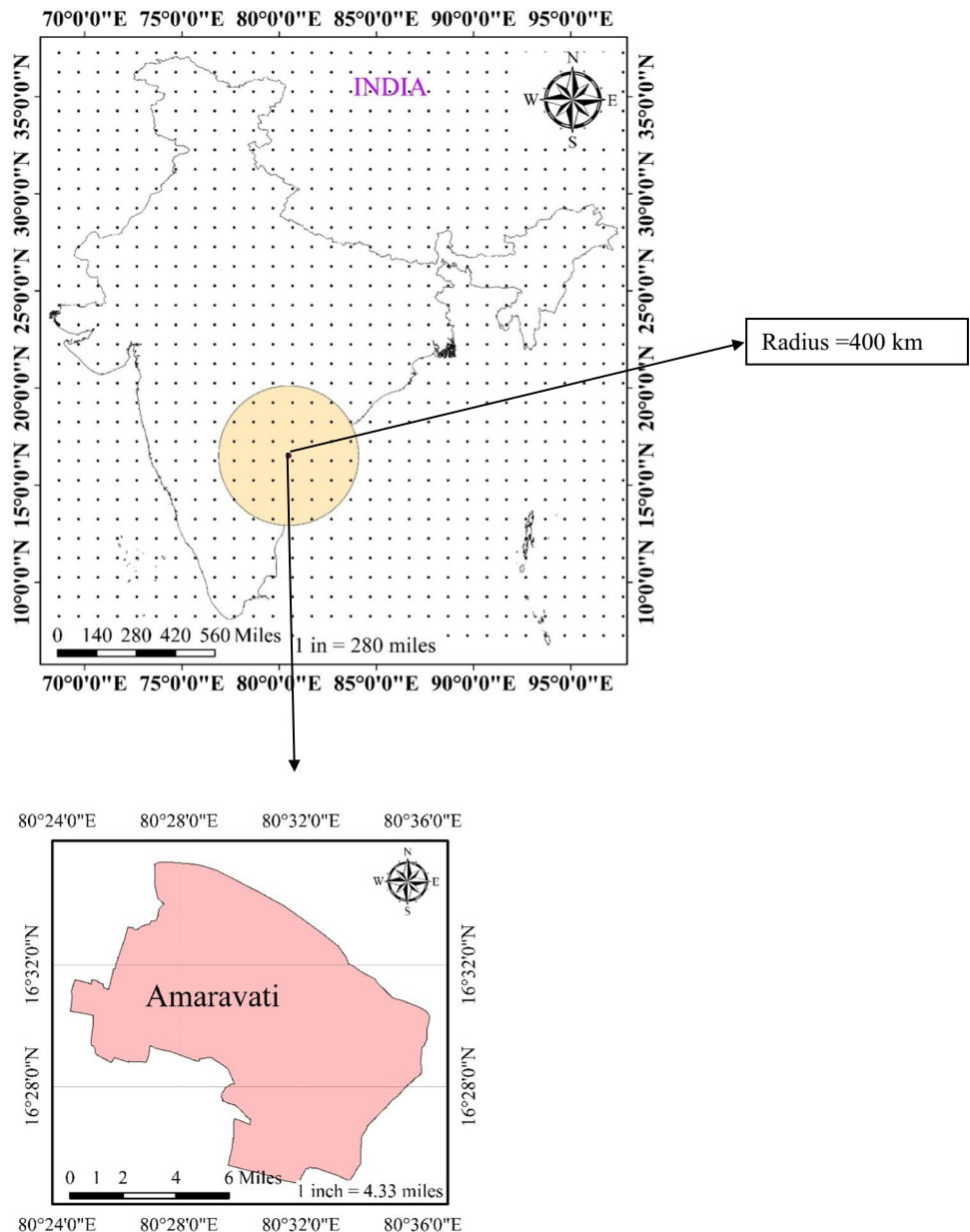
bedrock level. The results obtained are presented in the form of spatial variation of 50th and 84th percentile peak ground acceleration (PGA). The maximum PGA for the new nuclear power plant is to be found as 0.151 g.

The seismic hazard analysis using deterministic framework for the regions of India such as Chennai city [10], Andaman and Nicobar Islands [21], Patna [4], Kanpur city [3] and Vadodara region [26] are also reported in the literature. From the literature reviewed, it is found that there are no studies that address seismic hazard quantification for the Amaravati proposed capital city. Seismic hazard analyses are crucial for effective urban planning and infrastructure that reduce earthquake risk in a new proposed capital city like Amaravati. Hence in the present study an attempt was made to carry out the deterministic seismic hazard analysis for Amaravati, the proposed capital city of Andhra Pradesh.

Study Area and Seismotectonics

The present study area is a part of Peninsular India (PI), earlier which was considered as stable continental region, but the occurrence of severe earthquakes in the last few decades sent an indication that the study of seismic hazard analysis of every region in PI is mandatory. The study area is situated in the Guntur district of Andhra Pradesh state of India (Fig. 1). The proposed capital city Amaravati will be developed on the banks of the Krishna river and is situated 10 km southwest of Vijayawada, 25 km north of Guntur and 45 km South-East of Tenali, surrounding Coromandel coast of coastal region in Andhra Pradesh, India. The study area lies between the latitude (16° 24′ 36″ N–16° 35′ 24″ N) and longitude of (80° 24′ 25″ E–80° 36′ 18″ E), respectively, and having a geographically area of 217 km^2 with a population of about 0.1 million [12]. Goodess et al. [17] forecasted the population of Amaravati city on the basis of industrial growth and urbanization and stated that the population of proposed capital city is to be 3.58 million by the end of 2050.

Geologically the Amaravati city constitutes the Precambrian rocks such as Khondalites and Charnockites (3000 million years old) trending in North East and South West directions. Proterozoic Kadapa rocks (600 million years old) are found south to the Amaravati [33]. The Krishna basin mainly constitutes alluvial soils, laterite soils, red soils and black cotton soils.

In the present study, the seismic sources present in the 400 km radius from the Andhra Pradesh high court are considered for the seismic hazard analysis, and the seismotectonic map was developed as shown in Fig. 2.
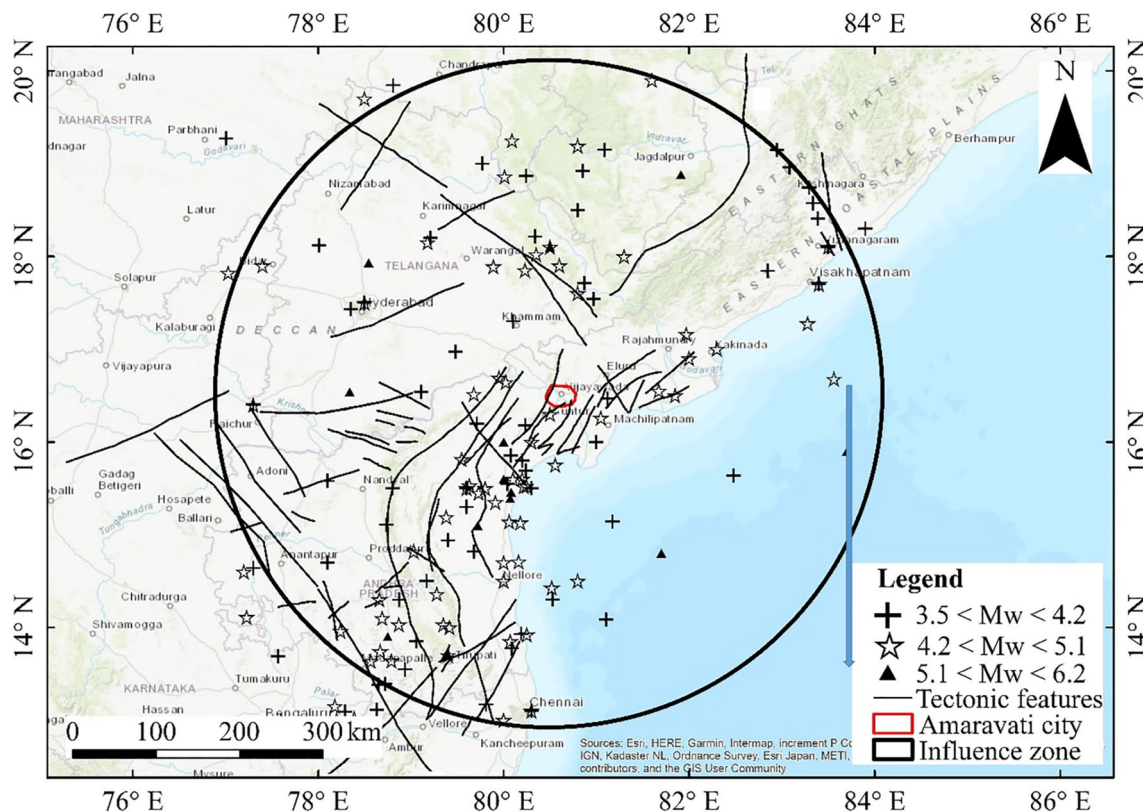

Fig. 2 Seismotectonic map of Amaravati city

Earthquake Catalog

A unified earthquake catalog data are needed for the seismic hazard analysis. Satyannarayana and Rajesh [38] presented the earthquake catalog data for the Amaravati city and conducted catalog completeness analysis by both Cumulative Visual Inspection (CUVI) method and Stepp [40] procedure. The CUVI method reveals that the catalog is completed for the last 50, 60, 60, 65, 220, and 220 years for magnitude classes (3.5–3.99), (4.0–4.49), (4.5–4.99), (5.0–5.49), (5.5–5.99) and ($M_W \geq 6.0$), respectively. Stepp [40] procedure reveals that the data are complete for the last 50, 50, 80,160 and 220 years for different classes of magnitude (3.5–3.99), (4.0–4.49), (4.5–4.99), (5.0–5.49), (5.5–5.99) and ($M_W \geq 6.0$), respectively.

Methodology

The procedure of deterministic seismic hazard analysis can be summarized into the following six steps:

1. Identification of seismic sources which are able to produce strong ground motions at the site of interest, which consists of geometry and earthquake potential of the source. In the present study all this information is considered from the seismotectonic map of Amaravati.
2. Estimation of the maximum magnitude of each and every seismic source.
3. Calculation of the shortest distance between the seismic source and each grid point in the given study area. In the present study the entire Amaravati city is divided in to a grid size of $0.03° \times 0.03°$ (about 3.33 km $\times$ 3.33 km).
4. Selection of suitable Ground Motion Prediction Equation (GMPE) for the present study area, based on their geology and tectonic characteristics. Calculation of the ground motion parameter using the magnitude-distance pair (specified in the Step-2 and Step-3) as an input for the chosen GMPE.
5. Development of seismic hazard maps for the selected areas considering the obtained ground motion parameter values.
6. Development of deterministic response spectra for the given study area by using magnitude –distance pair of controlling earthquake source.

Estimation of Hypocentral Depth and Maximum Magnitude (M_w)

Due to scarcity in the areal and volume sources, only linear seismic sources are considered for the seismic hazard analysis. In the present study, forty-seven faults and four major lineaments are considered as major sources for the seismic hazard
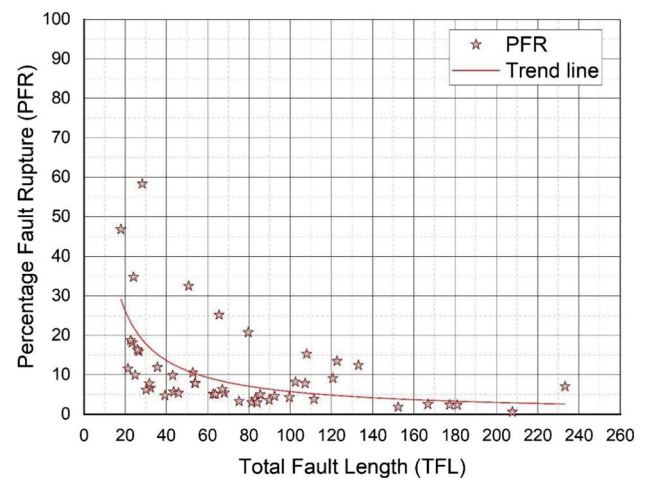
Fig. 3 Regional rupture character of Amaravati city

analysis of Amaravati. The length of the faults and lineaments is measured by using ArcGIS 10.7.1 [6] software. There are no recorded data available for the depth of focus of the all earthquake events present in the study area. An examination of earthquake catalogs in stable continental regions worldwide and specifically in peninsular India reveals that the average earthquake depth in such regions is 16 kilometers, with a range extending from a minimum depth of 3 kilometers to a maximum of 70 kilometers. In the present study, few earthquake events of focal depth as given in the earthquake catalog developed for Amaravati region varies from 7 to 120 km. For critical seismic hazard estimation, the author adopted 10 km as a hypocentral depth for the present study. Hypocentral distance and epicentral distances for every point of interest in the present study area are calculated.

In the present study, the maximum magnitude is estimated using three approaches i.e., based on regional rupture characteristics, empirical correlations and observed maximum magnitude.

The first approach is purely on the basis of fault rupture character and does not depend on the seismicity parameters [4]. The ratio of rupture length dimension (RLD) and total fault length (TFL) is defined as Percentage Fault Rupture (PFR). The PFR values for past earthquakes are calculated and plotted against total fault length (TFL). From Fig. 3, it can be noticed that the PFR value is more for the shorter faults as compared to longer faults. The maximum potential magnitude of each seismic source is calculated based on the RLD corresponding to worst case PFR and is designated as M^1_{max}.

In the second approach, empirical correlations such as Bonilla et al. [9] (represented as 'B' in Table 1), Nowroozi [30] (represented as 'N' in Table 1) and Wells and Coppersmith [43] (represented as 'W & C' in Table 1) are used to calculate the maximum magnitude. The severe earthquakes of moment magnitude (M_w) above 4.8 are identified, and

Table 1 Maximum potential earthquake moment magnitude for various faults and lineaments estimated by different empirical correlations and past seismicity

Name of the fault	Notation used	Co-ordinates				1st Approach				2nd Approach				3rd Approach
		Start latitude	Start longitude	End latitude	End longitude	TFL	PFR (%)	RLD	M^1max	B (1984)	N (1985)	W&C (1994)	M^2max	M^3max
Nizampatnam-Nagayalanka Fault	NPNLF	15.87	80.57	15.95	80.82	28.32	18.02	5.10	5.3	6.7	3.8	5.8	5.4	5.1
Kolleru Lake Fault	KLF	16.83	81.01	16.31	81.35	68.00	8.50	5.78	5.4	7.0	4.1	6.4	5.8	5.3
Vasista Godavari Fault	VGF	16.37	81.46	16.60	82.00	63.72	8.85	5.64	5.4	7.0	4.1	6.4	5.8	5.3
Tirumala Fault	TF	13.62	79.32	13.81	79.42	24.06	21.23	5.11	5.3	6.7	3.7	5.7	5.4	6.2
Karkambudi-Swarnanukhi Fault	KSMF	13.63	79.30	14.06	80.13	102.42	5.74	5.88	5.4	7.1	4.2	6.7	6.0	6.2
Badvel Fault	BF	14.60	79.36	14.86	78.96	52.78	10.55	5.57	5.4	6.9	4.0	6.2	5.7	5.9
Gani-Kalva Fault	GKF	15.44	77.63	15.70	78.44	92.35	6.50	6.00	5.5	7.1	4.2	6.7	6.0	4.7
Bhavani River Fault	BRF	15.89	78.85	16.14	78.10	85.46	6.42	5.49	5.4	7.1	4.2	6.6	5.9	4.7
Nallavagu Fault	NVF	16.34	78.63	16.25	79.02	43.03	13.02	5.60	5.4	6.9	3.9	6.1	5.6	4.4
Nekkantivagu Fault	NKVF	16.24	78.61	16.18	78.82	23.38	23.26	5.44	5.4	6.7	3.7	5.6	5.3	4.5
Krishna River Fault	KRF	15.78	75.28	16.55	77.04	207.63	3.10	6.44	5.5	7.3	4.5	7.3	6.4	4.8
Bukkapatnam Fault	BPF	14.21	77.56	14.28	77.98	45.86	12.60	5.78	5.4	6.9	3.9	6.1	5.7	5.3
Gulcheru Fault	GF	14.21	78.50	14.29	78.68	21.31	24.67	5.26	5.4	6.6	3.7	5.6	5.3	5.5
Kadiri Fault	KF	14.10	78.11	14.28	78.33	31.67	16.82	5.33	5.4	6.8	3.8	5.9	5.5	5.3
Raichur-nagarkurnool Fault	RNKF	16.31	77.37	16.53	79.02	180.97	3.42	6.19	5.5	7.3	4.4	7.2	6.3	5.7
Addanki-Nuzividu Fault	ANF	15.72	80.10	16.09	80.38	50.75	11.12	5.64	5.4	6.9	4.0	6.2	5.7	6.7
Papaghani Fault	PGF	14.37	78.62	14.70	78.98	53.78	10.09	5.43	5.4	6.9	4.0	6.3	5.7	5.5
Atmakuru Fault	AKF	15.82	78.49	15.69	78.78	35.63	15.34	5.47	5.4	6.8	3.9	6.0	5.5	4
Rudravagu Fault	RVF	16.00	78.83	16.00	79.07	25.93	20.86	5.41	5.4	6.7	3.7	5.7	5.4	4
Gundlakamma Fault	GKF	16.43	79.55	15.54	80.22	122.63	5.06	6.20	5.5	7.2	4.3	6.9	6.1	6.7
Fault 1	F1	15.87	80.73	16.38	80.99	62.68	8.93	5.60	5.4	7.0	4.1	6.4	5.8	5.1
Fault 2	F2	15.87	80.57	16.51	80.97	83.11	6.54	5.44	5.4	7.1	4.2	6.6	5.9	5.1
Fault 3	F3	15.85	80.41	16.45	80.73	107.94	5.61	6.06	5.5	7.1	4.3	6.8	6.1	4.8
Fault 4	F4	16.00	80.27	16.42	80.67	65.52	8.82	5.78	5.4	7.0	4.1	6.4	5.8	5.5
Fault 5	F5	16.36	81.10	16.75	81.71	81.35	6.94	5.65	5.4	7.1	4.2	6.6	5.9	5.1
Fault 6	F6	16.31	81.35	16.67	81.51	43.48	12.24	5.32	5.4	6.9	3.9	6.1	5.6	5.3

Table 1 (continued)

Name of the fault	Notation used	Co-ordinates				1st Approach				2nd Approach				3rd Approach
		Start latitude	Start longitude	End latitude	End longitude	TFL	PFR (%)	RLD	M^1max	B (1984)	N (1985)	W&C (1994)	M^2max	M^3max
Fault 7	F7	16.52	81.53	16.97	82.06	75.18	7.50	5.64	5.4	7.0	4.1	6.5	5.9	5.2
Fault 8	F8	16.37	81.01	16.58	81.10	24.80	21.87	5.42	5.4	6.7	3.7	5.7	5.4	5.1
Fault 9	F9	16.53	81.02	16.99	81.64	83.90	6.63	5.56	5.4	7.1	4.2	6.6	5.9	4
Fault 10	F10	18.67	79.32	17.34	81.00	233.22	2.80	6.53	5.5	7.4	4.5	7.3	6.4	6.7
Fault 11	F11	18.03	80.20	17.04	80.89	133.08	4.56	6.07	5.5	7.2	4.3	6.9	6.2	5.2
Fault 12	F12	19.65	78.01	18.75	79.39	177.31	3.34	5.92	5.4	7.3	4.4	7.1	6.3	5.4
Fault 13	F13	18.26	83.42	18.00	83.56	32.22	16.62	5.36	5.4	6.8	3.8	5.9	5.5	5.2
Fault 14	F14	19.12	83.43	18.06	83.65	120.63	4.72	5.69	5.4	7.2	4.3	6.9	6.1	5.2
Fault 15	F15	14.60	79.24	15.39	79.30	89.75	6.54	5.87	5.4	7.1	4.2	6.6	6.0	5.5
Fault 16	F16	16.65	78.65	16.36	79.20	67.06	8.46	5.67	5.4	7.0	4.1	6.4	5.8	4.7
Fault 17	F17	17.13	78.13	17.71	79.57	166.77	3.83	6.39	5.5	7.3	4.4	7.1	6.3	5.7
Fault 18	F18	18.50	78.24	19.67	78.99	152.35	3.92	5.97	5.5	7.2	4.4	7.0	6.2	5.4
Fault 19	F19	18.29	79.29	18.71	80.12	99.53	5.82	5.79	5.4	7.1	4.2	6.7	6.0	5.7
Fault 20	F20	15.03	77.05	15.13	77.40	39.28	5.33	5.94	5.4	6.8	3.9	6.0	5.6	5.1
Fault 21	F21	15.25	77.71	15.14	77.97	30.11	14.10	5.54	5.4	6.7	3.8	5.8	5.5	5.1
Fault 22	F22	13.52	79.33	13.65	79.42	17.89	29.00	5.19	5.3	6.6	3.6	5.5	5.2	6.2
Fault 23	F23	15.75	79.56	16.26	80.08	79.58	7.29	5.80	5.4	7.0	4.1	6.5	5.9	6.7
Fault 24	F24	13.00	79.70	13.85	80.17	107.16	5.62	6.02	5.5	7.1	4.3	6.8	6.1	5.5
Fault 25	F25	14.42	78.70	14.44	78.91	22.59	23.26	5.26	5.4	6.7	3.7	5.6	5.3	5.5
Fault 26	F26	16.12	78.29	15.97	78.76	54.01	10.05	5.43	5.4	6.9	4.0	6.3	5.7	4
Fault 27	F27	16.16	78.93	16.08	79.15	26.64	21.25	5.66	5.4	6.7	3.7	5.7	5.4	4
Lineament 1	L1	13.01	79.16	14.30	80.13	206.83	2.02	4.18	5.2	7.3	4.5	7.3	6.4	5.3
Lineament 2	L2	12.27	77.97	13.56	79.31	85.13	8.35	7.11	5.6	7.1	4.2	6.6	5.9	6.2
Lineament 3	L3	11.96	76.52	16.00	79.66	557.01	1.02	5.68	5.4	7.6	4.9	8.0	6.8	5.7
Lineament 4	L4	13.01	79.19	14.35	80.11	191.00	2.40	4.58	5.3	7.3	4.5	7.2	6.3	6.4
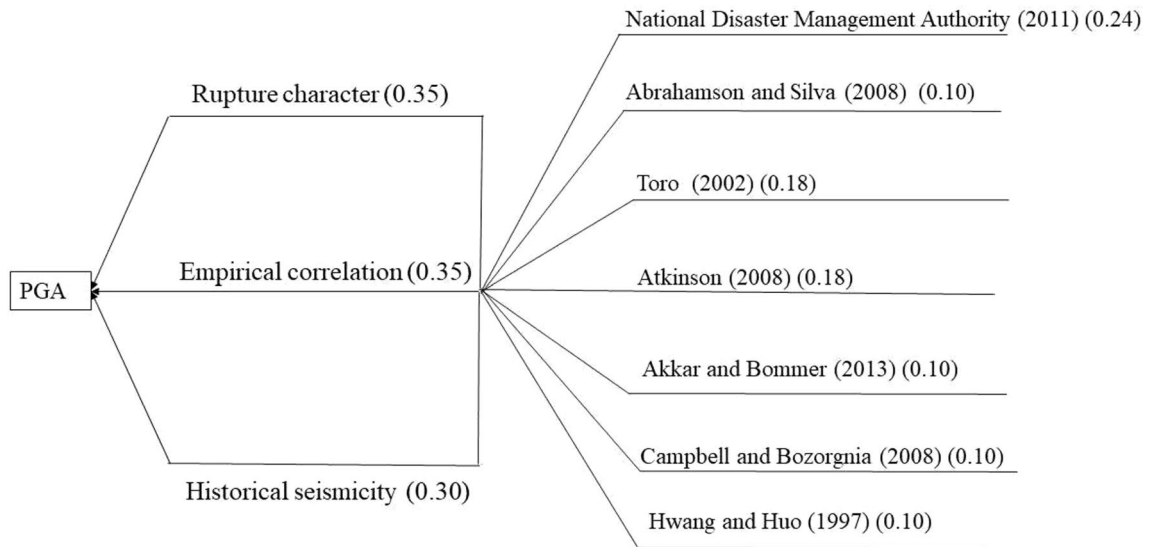
Fig. 4 Logic tree framework indicating the weights assigned for various GMPE's and scenarios

Table 2 Faultwise deterministic seismic hazard for Amaravati city

Fault name	PGA (g)		Fault name	PGA (g)	
	50th Percentile	84th Percentile		50th Percentile	84th Percentile
NPNLF	0.010	0.105	F6	0.008	0.142
KLF	0.012	0.147	F7	0.013	0.154
VGF	0.008	0.116	F8	0.009	0.101
TF	0.003	0.060	F9	0.003	0.080
KSMF	0.003	0.080	F10	0.009	0.170
BF	0.004	0.085	F11	0.002	0.012
GKF	0.007	0.102	F12	0.003	0.086
BRF	0.004	0.097	F13	0.003	0.094
NVF	0.005	0.106	F14	0.007	0.095
NKVF	0.004	0.099	F15	0.005	0.100
KRF	0.002	0.022	F16	0.002	0.013
BPF	0.004	0.094	F17	0.003	0.012
GF	0.004	0.086	F18	0.004	0.016
KF	0.003	0.069	F19	0.006	0.024
RNKF	0.003	0.094	F20	0.002	0.036
ANF	0.011	0.157	F21	0.003	0.018
PGF	0.003	0.083	F22	0.005	0.024
AKF	0.004	0.093	F23	0.004	0.020
RVF	0.005	0.105	F24	0.002	0.020
GKF	0.007	0.101	F25	0.003	0.065
F1	0.013	0.049	F26	0.001	0.010
F2	0.021	0.211	F27	0.002	0.012
F3	0.027	0.118	L1	0.001	0.012
F4	0.068	0.234	L2	0.001	0.010
F5	0.013	0.170	L3	0.002	0.013
			L4	0.003	0.012

subsurface rupture length was estimated by using well-known relation proposed by Wells and Coppersmith [43] as follows

$$\log_{10} \text{RLD} = 0.59\, M_{\text{w}} - 2.44 \tag{1}$$

The key parameter for the above correlations is rupture length. Mark [24] recommended fault rupture length as 1/3 to 1/2 of total fault length. In the present analysis, the author has taken fault rupture length as a 1/3rd of total fault length for the estimation of maximum magnitude by using this empirical correlations. The average value of the maximum magnitude obtained by the above 3 empirical correlations is assigned to the specific fault and major lineament and denoted by M^2_{max}.

In the third approach the maximum magnitude of each seismic source is estimated by increasing the 0.5 units to the maximum observed magnitude of that particular fault, which is designated as M^3_{max}. The estimated maximum magnitude for each seismic source by above three methods is listed in Table 1.

Scheme of Evaluation for Hazard Values

The seismic hazard of Amaravati city is analyzed by considering following four scenarios.

Scenario 1 (S-1): S-1 is completely based on the regional rupture characteristics of the seismic sources. The maximum potential magnitude (M^1_{max}) estimated by the regional rupture characteristics is assigned to all the sources.

Scenario 2 (S-2): In this scenario, all the seismic sources presented in the study area are accounted for and assume that they are subjected to critical stress level at everywhere in the study area. The maximum moment magnitude (M^2_{max}) estimated by second method is assigned to all the seismic sources present in study area.

Scenario 3 (S-3): In this scenario, the earthquake events occurred till the date is considered as worst earthquakes (assuming that no earthquake will occur magnitude greater than the past earthquake events). The maximum magnitude estimated (M^3_{max}) on the basis of past historical seismicity is assigned to all the seismic sources.

Scenario 4 (S-4): Scenario 4 is obtained by giving an weightage of 0.35 to the S-1 and S-2 and 0.30 to the S-3, respectively.

In the present study all the seismicity levels of sources from mild to severe seismicity are considered for the analysis.

Ground Motion prediction Equations (GMPEs) and Logic Tree Framework

Expected ground motion plays a key role in the seismic design of engineering structures. The strong ground motion of a specific study area can be estimated by an empirical relation (attenuation relation) developed from the past strong earthquake ground motion recordings of that particular area. For the present study area, no such a specific attenuation relation is available due to scarcity in the strong ground motion recordings. Hence, in the present study, seven ground motion prediction equations, which are widely used in the literature, were chosen based on the focal depth, tectonic setting and geology of the present study area. Among these seven equations NDMA [29] is specifically developed for India by a World Expert Committee (WEC) of microzonation of India. This ground motion attenuation equation can directly apply to the present study area by selecting suitable regression coefficients. Cramer and Kumar [14] concluded that the ground motion attenuations in Eastern North America are well matched with ground motion attenuation relations in peninsular India. Hence, the attenuation relations proposed by Toro [41], Hwang and Huo [19] for the crustal intraplate earthquakes in the Eastern North America are also adopted in the present study. The other ground motion prediction equations by Abrahamson and Silva [1] developed for worldwide shallow crustal earthquakes (for M_{w} varying between 5 and 8.5 and the distance up to 200 km) for a spectral period less than 10 s. As a part of PEER Next Generation Attenuation (NGA) project, Atkinson [7] updated ground motion attenuation relation for both Eastern North America and Western North America, which is function of earthquake magnitude, source to site distance, local shear wave velocity and fault type. Campbell and Bozorgnia [11] developed a new ground motion attenuation model which incorporates the effects of magnitude saturation, magnitude-dependent attenuation, style of faulting, rupture depth, hanging wall geometry, linear and nonlinear site response (valid for magnitude ranges from 4 to 8.5 and distances from 0 to 200 km). Akkar et al. [2] derived a latest ground motion attenuation model for the pan-European databases, which is very novel as compared to previous ground motion attenuation models and which includes a nonlinear site amplification function that is a function of shearwave velocity ($V_{\text{s}30}$) and reference peak ground acceleration on rock. This model is applicable for the earthquake magnitude > 4 and distance up to 200 km for a spectral period ranging from 0.01 to 4 s.

The selection of particular model for seismic hazard assessment is critical due to uncertainties associated with seismic hazard models. To consider the epistemic uncertainty, logic tree approach which permits the use of alternative models in the seismic hazard analysis is adopted. Logic tree is structure like a tree with branches and nodes, each branch representing each model. Various branches are joined at a node, and a subjective weightage was given to each model based on engineering judgement.
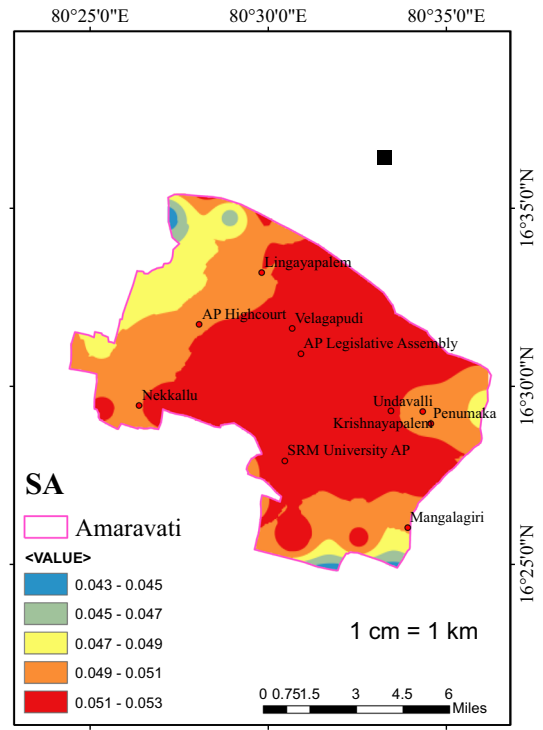
The seven ground motion attenuation models have been assigned the weightage factors such as 0.24 for NDMA
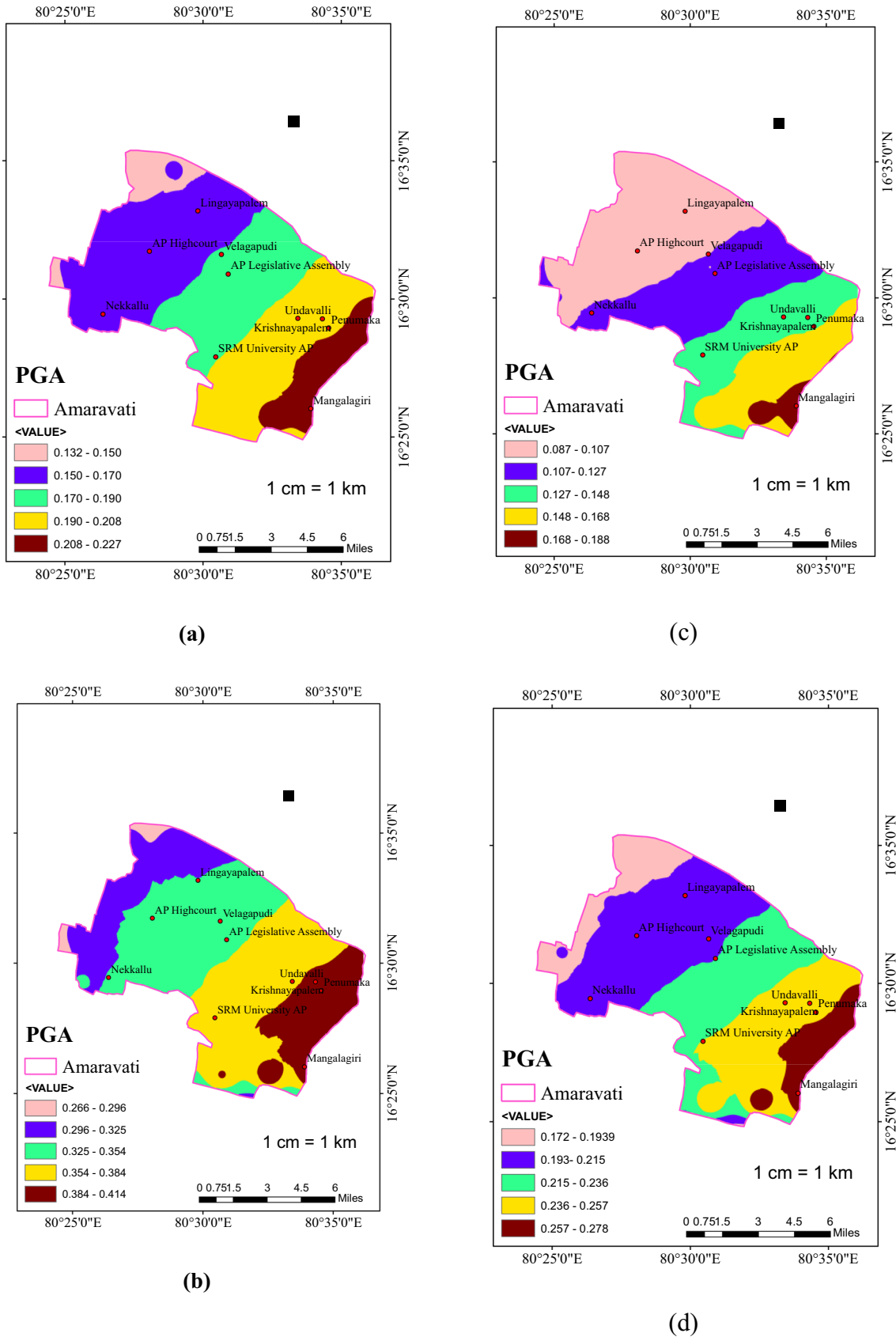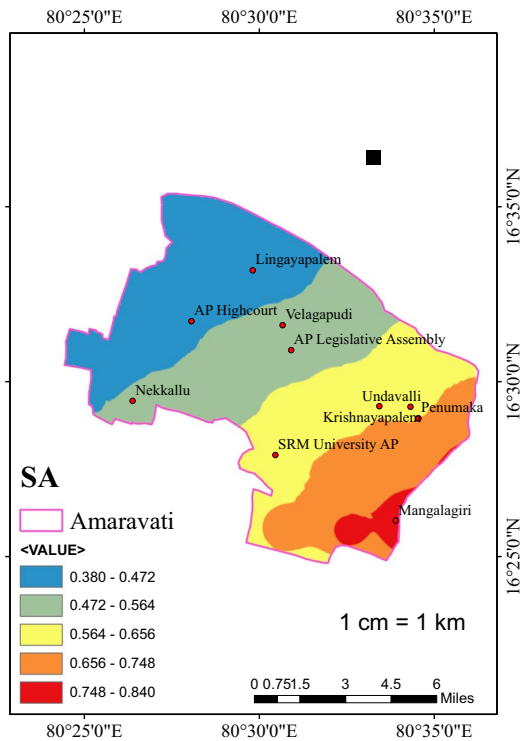
Fig. 5 DSHA map showing spatial variation of PGA values at bed rock level over Amaravati city: **a** Scenario 1, **b** Scenario 2, **c** Scenario 3, and **d** Scenario 4
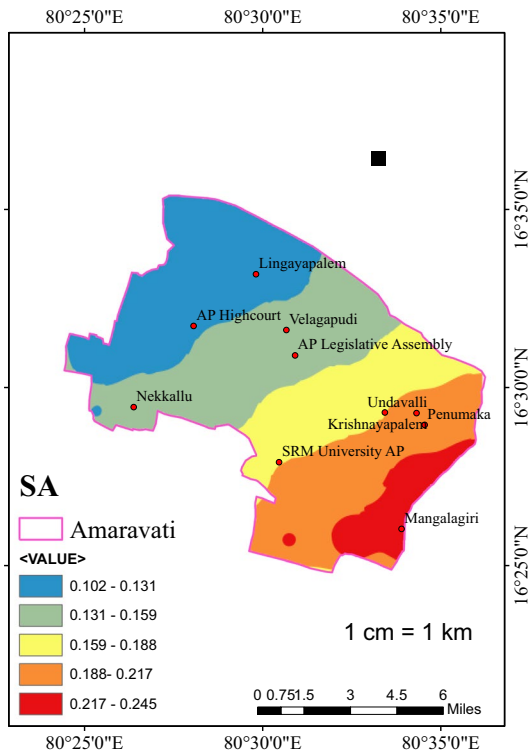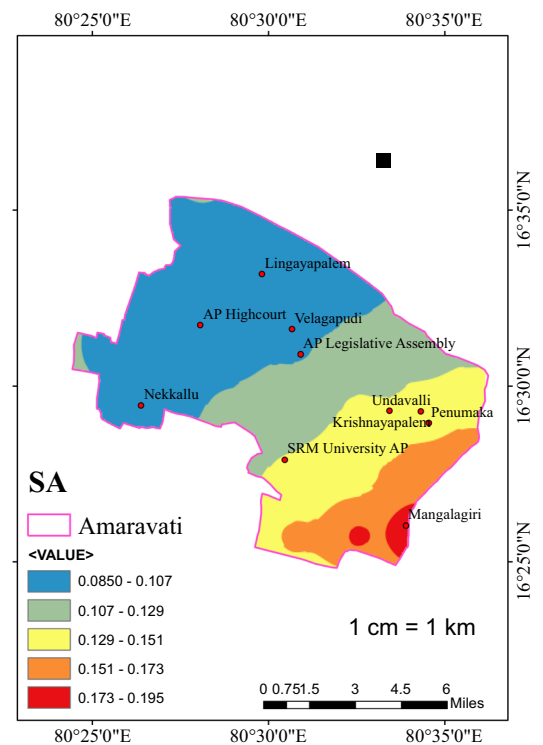
Fig. 6 Spatial variation of **a** 50th percentile, **b** 84th percentile *S*a (g) values for 0.2 s at bedrock for Amaravati city

Fig. 7 Spatial variation of **a** 50th percentile, **b** 84th percentile S_a (g) values for 1 s at bedrock for Amaravati city

Table 3 Locations of six important regions in the Amaravati city with their obtained PGA values and causative fault sources and distances

Region	Location		Scenario 1			Scenario 2			Scenario 3			Scenario 4
	Longitude (E)	Latitude (N)	PGA (g)	Fault	Distance (km)	PGA (g)	Fault	Distance (km)	PGA (g)	Fault	Distance (km)	PGA (g)
Nekkallu	80° 27′ 07.92″	16° 29′ 19.66″	0.165	F1	61.36	0.337	F3	35.44	0.109	F4	18.57	0.208
Mangalagiri	80° 34′ 19.92″	16° 25′ 43.66″	0.233	F1	41.38	0.430	F3	15.46	0.196	F4	5.77	0.291
Thullur	80° 27′ 07.92″	16° 31′ 07.66″	0.215	F1	44.69	0.320	F3	38.77	0.101	F4	21.18	0.201
Tadepalli	80° 36′ 07.92″	16° 29′ 19.68″	0.180	F1	40.71	0.406	F3	18.79	0.155	F4	10.08	0.264
Velagapudi	80° 30′ 43.92″	16° 31′ 07.66″	0.172	F1	58.03	0.346	F3	32.11	0.107	F4	18.02	0.213
Dondapadu	80° 27′ 07.92″	16° 32′ 55.66″	0.154	F1	68.02	0.321	F3	42.1	0.093	F4	24.06	0.194

[29], 0.18 for both Toro [41] and Atkinson [7], and 0.10 for remaining four attenuation relations such as Abrahamson and Silva [1], Akkar et al. [2], Campbell and Bozorgnia [11], Hwang and Huo [19], respectively, to arrive at hazard values. In the present study the highest weightage factor (0.24) was given to NDMA [29] among other ground motion attenuation relations. The reason behind this choice is that NDMA [29] is specifically developed for India, making it particular relevant to the study area. It is observed from literature that Toro [41] and Atkinson [7] give more reliable results for peninsular India than other GMPEs used in this study. Hence more weightage was given to Toro [41], and Atkinson [7] as compared to other GMPEs. Moreover Atkinson et al. [8] identified the best GMPEs. The NDMA [29] has been given a highest weightage factor as compared to other ground motion attenuation relations because it is specifically developed for the all regions India; present study area falls within this region. The logic tree approach adopted in the present study for the estimation of hazard values is shown as flow chart as given in Fig. 4.

Results and Discussion

Deterministic Seismic Hazard Maps for the Amaravati City

The Andhra Pradesh high court (16.5195° N, 80.4856° E) is considered as a center for the present seismic hazard analysis. In the present study, for Scenarios 1, 2 and 3 the estimated maximum potential magnitude, M^1_{max}, M^2_{max} and M^3_{max} is assigned to all the seismic sources, respectively. The faultwise seismic hazard is evaluated and presented in Table 2. For each grid point the highest PGA values are estimated at bedrock level through logic tree framework. At every grid point the hazard value (PGA) is calculated using seven attenuation relations and multiplying with their respective weighing factor. The severe hazard value (highest PGA) at each grid point and source causing that hazard value is identified. The identified source is called controlling source for that grid point; this procedure is repeated for all the grid points in the study area for the first three scenarios mentioned in Sect. 4.2. The subsurface faults designated as F1, F3 and F4 are identified as controlling sources for the Scenario 1, Scenario 2 and Scenario 3, respectively. For the last scenario (S-4) the hazard value is obtained by multiplying the hazard values of S-1, S-2 and S-3 with weighing factors 0.35, 0.35 and 0.30, respectively, as indicated in the logic tree (Fig. 4). The deterministic seismic hazard maps as shown in Fig. 5a–d present the spatial variation of hazard values throughout Amaravati city corresponding to S-1, S-2, S-3 and S-4, respectively. From Fig. 5a–d, it can be noticed that the estimated PGA values vary from 0.132 to 0.227 g,
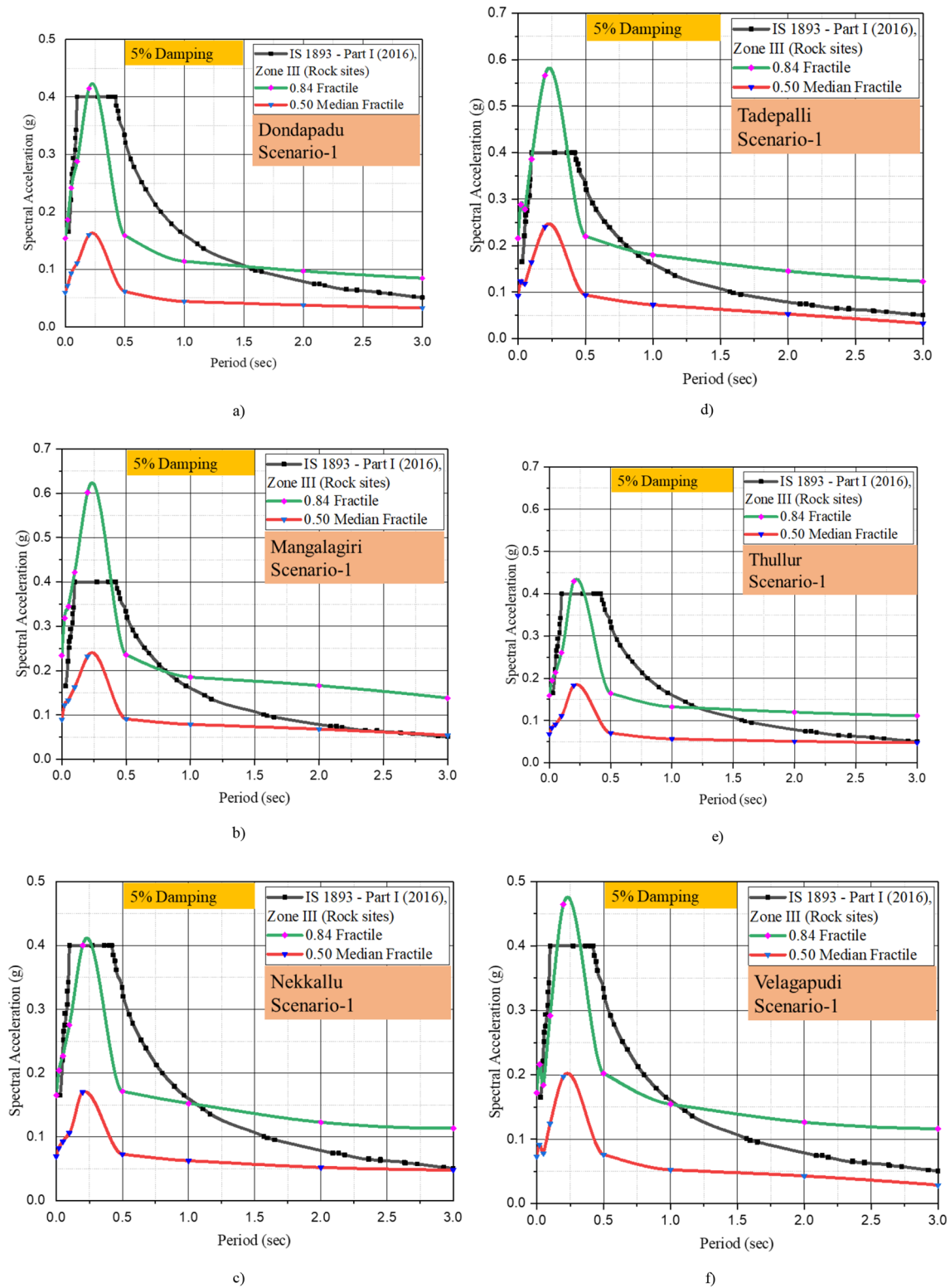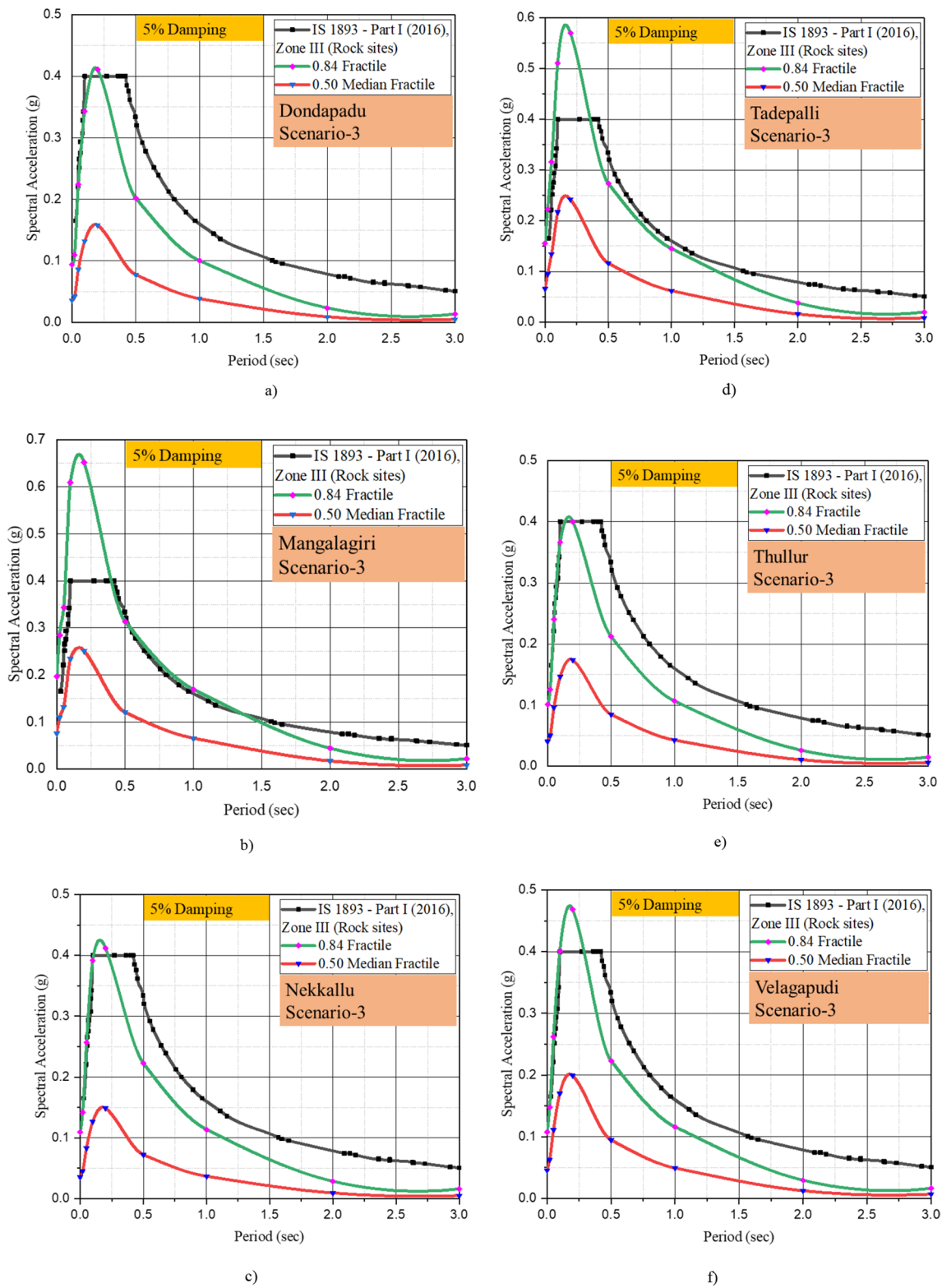
Fig. 8 Deterministic response spectra for six important regions of Amaravati city considering scenario 1
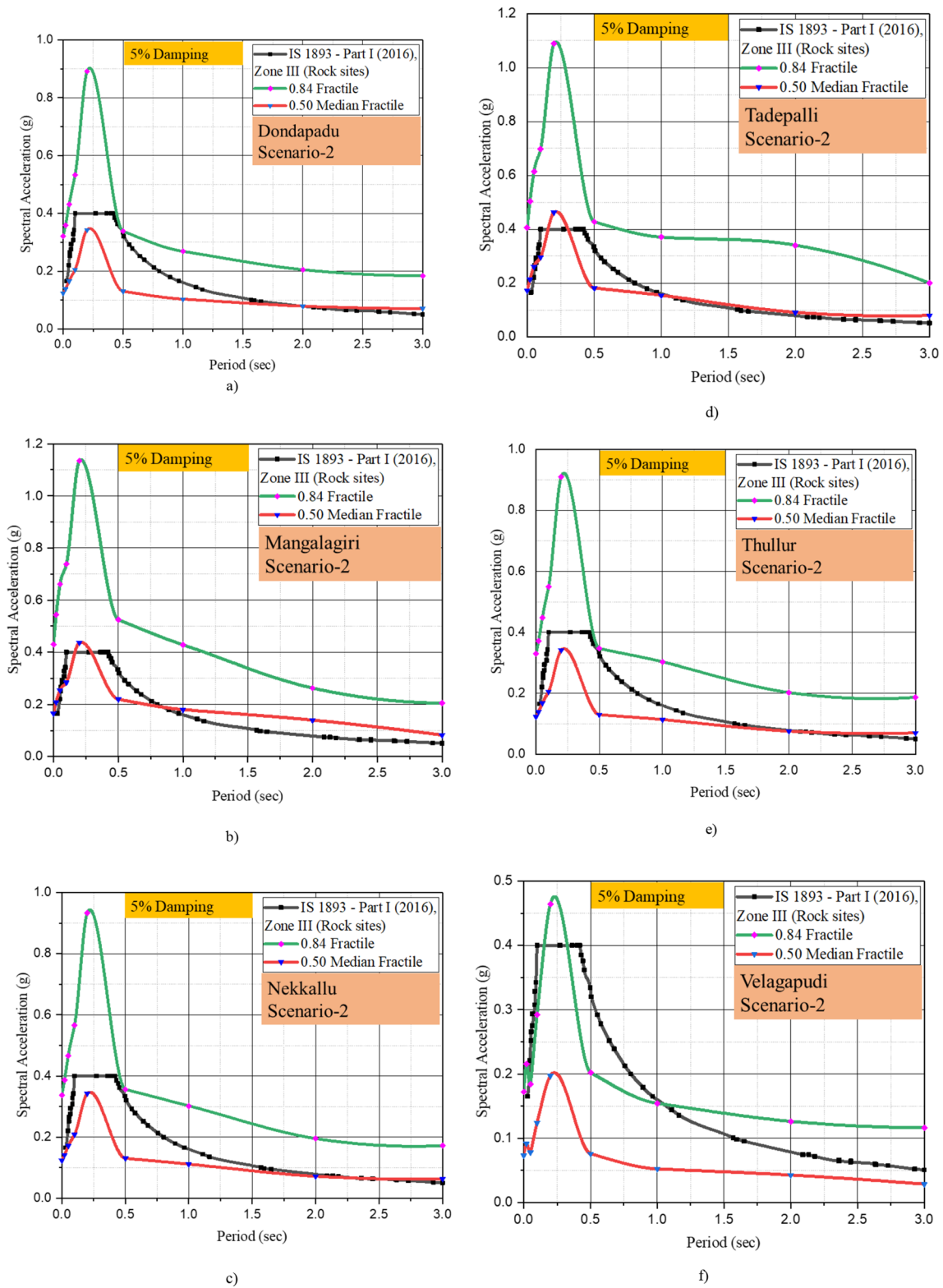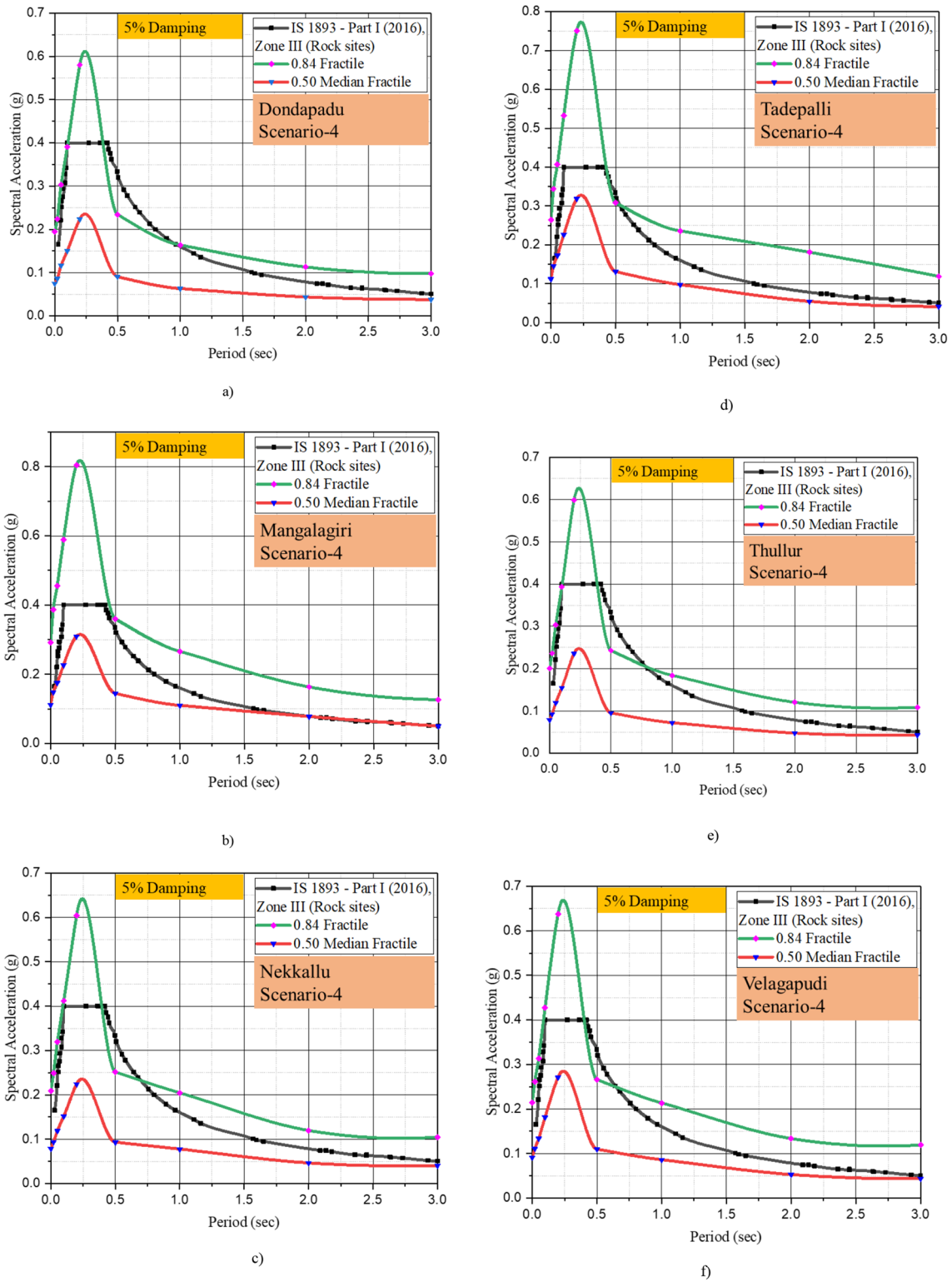
Fig. 9 Deterministic response spectra for six important regions of Amaravati city considering scenario 2

Fig. 10 Deterministic response spectra for six important regions of Amaravati city considering scenario 3

Fig. 11 Deterministic response spectra for six important regions of Amaravati city considering scenario 4

Table 4 Comparison of bedrock level PGA (g) values obtained in the present study with previous studies

Present study			Sitharam and Anabazhagan [39]	Anabazhagan et al. [5]	Naik and Choudhury [28]			Parvez et al. [31]
S-1	S-2	S-3			S-1	S-2	S-3	
0.132–0.227	0.266–0.414	0.087–0.188	0.159	0.134	0.47–1.09	0.07–0.150	0.33–0.62	0.08–0.150

0.266 g to 0.414 g, 0.087 g to 0.188 g and 0.172 g to 0.278 g for scenarios 1, 2, 3 and 4, respectively. From Figs. 5a–d it can be noticed that the Scenario 2 gives the highest hazard.

The estimated PGA value ranges from 0.266 g to 0.414g on the DSHA map for Scenario 2 (Fig. 5b). It is considerably high when compared to the PGA value of 0.16 g as per IS 1893-Part I [20]. Hence, it is always recommended to conduct site-specific seismic hazard analysis. The DSHA map in Fig. 5b for Scenario 2 indicates maximum PGA of 0.414 g near Mangalagiri taluka. From the DSHA map of Scenario 1 and Scenario 3, it is clear that the PGA values are smaller than the values based on IS 1893-Part I [20]. It can be observed from the proposed maps that the PGA values obtained for North Western region of Amaravati, i.e., places like Lingayapalem, Thulluru and Nekkallu, are within the PGA specified by IS 1893-Part I [20]. Also, the 50th percentile spectral accelerations appropriate to Maximum Credible Earthquake (MCE) and 84th percentile spectral accelerations (S_a) appropriate to Safe Shutdown Earthquake (SSE) are also developed at short (0.2s) and long (1s) period level, respectively. It is observed that the 84th percentile spectral acceleration values at short period (0.2s) and long period (1s) are steadily increasing from Northwestern to Southeastern parts of Amaravati city (Figs. 6 and 7b). From Fig. 7a, it can be noticed that the 50th percentile spectral acceleration values at long period (1s) are gradually decreased from center (AP high court) to Southern and Northern parts of Amaravati city.

Deterministic Response Spectra Developed for the Six Important Regions of Amaravati

Six important regions of Amaravati city are selected for development of response spectra in such a way that the entire Amaravati city is covered. The important regions considered are Nekkallu, Dondapadu, Mangalagiri, Tadepalli, Thulluru, and Velagapudi. The response spectra are developed for both 84th percentile (0.84 fractile) and 50th percentile (median fractile) spectral values. The PGA values of the selected regions at bedrock level are examined, and the sources causing the critical values of PGA are presented in Table 3. It is observed that the maximum PGA value is obtained for the Mangalagiri region (16° 25′ 43.66″, 80° 34′ 19.92″) in the all

scenarios. The PGA values for all the regions are higher than the PGA of 0.16 g recommended by IS 1893 Part-I [20] for both the Scenario 2 and Scenario 4, whereas for Scenario 3, the obtained PGA values of all the regions are lower than the codal value of 0.16 g except Mangalagiri, which is 0.196 g. The PGA values obtained by Scenario 2 for both the regions Thulluru (0.159 g) and Dondapadu (0.154 g) are lower than the codal value of 0.16 g, and the remaining four regions have obtained high PGA values. The causative source for Scenario 1 is F1 at a distance of 41.38 km. For Scenario 2, the causative source is F3 at a distance of 41.38 km from Mangalagiri region. The controlling source for Scenario 3 is F4 at a distance of 5.77 km.

The deterministic response spectra are developed for the six regions for all the four scenarios using controlling source magnitude distance pairs. The deterministic response spectra for Scenario 1 are shown in Fig. 8a–f. It can be observed that the codal spectra are conservative only for Dondapadu, Nekkallu, and Thulluru regions. The deterministic response spectra for Scenario 2 are shown in Fig. 9a–f. It can be observed that the response spectra given in IS 1893 Part-I [20] are nonconservative for all the selected regions. The deterministic response spectra for Scenario 3 are shown in Fig. 10a–f; it clearly indicates that the code is conservative for all the regions except Mangalagiri. The deterministic response spectra for Scenario 4 are shown in Fig. 11a–f. From the developed response spectra, it can be noticed that the maximum spectral acceleration is observed in a period ranging from 0.15 to 0.25 s. A comparison of present PGA values at bedrock level with the previous study carried out by various authors for different cities in Peninsular India region is shown in Table 4. The obtained PGA values are within the typical range of PGA values of Naik and Choudary [28] and Sitharam and Anbazhagan [39].

Conclusions

Deterministic seismic hazard analysis is carried out for the Amaravati city considering four scenarios, seven ground motion prediction equations and logic tree approach. In the first scenario, the rupture-based seismicity is considered and assumed all the faults and

lineaments are capable of producing earthquakes. In the second method the potential of maximum magnitude of seismic sources is estimated by the relevant empirical correlations. The third scenario is based on past historical seismicity data. The fourth scenario is obtained by giving the suitable weightages to the first three scenarios. The seismic hazard maps are developed for the all four scenarios. The deterministic response spectra for 0.5 fractile and 0.84 fractile are developed for all the four scenarios. The proposed results are particularly helpful for planning and designing of critical structures in the proposed capital city Amaravati. The DSHA maps show that the maximum hazard level occurs at the south-east region of Amaravati city which is found to be in the Tadepalli taluka and Mangalagiri taluka for all Scenarios. The hazard value obtained for Amaravati city is higher compared with that of 0.16 g suggested by IS 1893-Part 1 [20]. The Scenario 2 gives the highest hazard value varying from 0.266 to 0.414 g as compared to all other three Scenarios. The deterministic response spectra are developed for six important regions of Amaravati city, namely Dondapadu, Nekkallu, Thulluru, Velagapudi, Tadepalli and Mangalagiri. The response spectra are developed for both 0.84 fractile and 0.50 fractile with 5% damping for all the four scenarios. These spectra are compared with the spectra specified in IS 1893-Part 1 [20] for zone III and rock sites. It is found that the codal spectrum is conservative only for Scenario 3. For Scenarios 1, 2 and 4 the codal values are nonconservative for the Amaravati city.

Author Contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Rambha Satyannarayana and Dr. B. Giridhar Rajesh. The first draft of the manuscript was written by Rambha Satyannarayana. The first draft was improved by making considerable modifications by Dr. B. Giridhar Rajesh. Both the authors read and approved the final manuscript.

Data Availability Some or all data, models or code used during the study was provided by a third party. Direct requests for these materials may be made to the provider as indicated in the Acknowledgements.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose. The authors declare that there is no conflict of interest.

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