Natural Hazards (2007) 40: 261–278
DOI 10.1007/s11069-006-0012-z

Seismic Hazard Analysis for the Bangalore Region

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(Received: 29 November 2005; accepted: 8 February 2006)

Abstract. Indian peninsular shield, which was once considered to be seismically stable, is experiencing many earthquakes recently. As part of the national level microzonation programme, Department of Science and Technology, Govt. of India has initiated microzonation of greater Bangalore region. The seismic hazard analysis of Bangalore region is carried out as part of this project. The paper presents the determination of maximum credible earthquake (MCE) and generation of synthetic acceleration time history plot for the Bangalore region. MCE has been determined by considering the regional seismotectonic activity in about 350 km radius around Bangalore city. The seismotectonic map has been prepared by considering the faults, lineaments, shear zones in the area and historic earthquake events of more than 150 events. Shortest distance from the Bangalore to the different sources is measured and then peak ground acceleration (PGA) is calculated for the different source and moment magnitude. Maximum credible earthquake found in terms of moment magnitude is 5.1 with PGA value of 0.146 g at city centre with assuming the hypo central distance of 15.88 km from the focal point. Also, correlations for the fault length with historic earthquake in terms of moment magnitude, yields (taking the rupture fault length as 5% of the total fault length) a PGA value of 0.159 g. Acceleration time history (ground motion) and a response acceleration spectrum for the corresponding magnitude has been generated using synthetic earthquake model considering the regional seismotectonic parameters. The maximum spectral acceleration obtained is 0.332 g for predominant period of 0.06 s. The PGA value and synthetic earthquake ground motion data from the identified vulnerable source using seismotectonic map will be useful for the PGA mapping and microzonation of the area.

Key words: seismic hazard, MCE, PGA, seismotectonic, fault length

1. Introduction

Seismic hazard analyses involve the quantitative estimation of ground shaking hazards at a particular area. Seismic hazards can be analyzed deterministically as when a particular earthquake scenario is assumed, or probabilistically, in which uncertainties in earthquake size, location, and time of occurrence are explicitly considered (Kramer, 1996). Probabilistic seismic hazard analysis provides not one, two, or three choices, but infinite

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choices for the user and decision-makers (Wang, 2005). Krinitzsky (2005) comments on the problems in the application of probabilistic methods and gives an account on a deterministic alternative which highlights that ‘‘A Deterministic Seismic Hazard Analysis (DSHA) uses geology and seismic history to identify earthquake sources and to interpret the strongest earthquake each source is capable of producing regardless of time, because that earthquake might happen tomorrow. Those are the Maximum Credible Earthquakes (MCEs), the largest earthquakes that can reasonably be expected. As we cannot safely predict when an earthquake will happen, the MCEs are what a critical structure should be designed for if the structure is to avoid surprises’’.

A critical part of seismic hazard analysis is the determination of Peak Ground Acceleration (PGA) and response acceleration (spectral acceleration) for an area/site. Spectral acceleration (S_a) is preferred for the design of civil engineering structures. It is an accepted trend in engineering practice to develop the design response spectrum for the different types of foundation materials such as rock, hard soil and weak soils. Seismic hazard analysis and determination of PGA is crucial and very important for any earthquake resistant design and Microzonation. To evaluate seismic hazards for a particular site or region, all possible sources of seismic activity must be identified and their potential for generating future strong ground motion should be evaluated. Analysis of lineaments and faults helps in understanding the regional seismotectonic activity of the area. Lineaments are linear features seen on the surface of earth which represents faults, features, shear zones, joints, litho contacts, dykes, etc; and are of great relevance to geoscientists. Scientists believe that a lineament is a deep crustal, ancient, episodically reactivated a linear feature that exerts control on the make up of the crust and associated distribution of ore and hydrocarbons (O’ Leary *et al.*, 1976, Ganesha Raj and Nijagunappa, 2004).

Seismicity of an area is the basic issue to be examined in seismic hazard analysis for evaluating seismic risk for the purpose of microzonation planning of urban centres. Detailed knowledge of active faults and lineaments and associated seismicity is required to quantify seismic hazard and risk. Indian peninsular shield, which was once considered to be seismically stable, has shown that it is quite active. Large number of earthquakes with different magnitudes has occurred very often in this region (Ramalingeswara Rao and Sitapathi Rao, 1984; Bansal and Gupta, 1998). In recent years much of the seismic activity in the state of Karnataka has been in the south, in the Mysore–Bangalore region (Ganesha Raj and Nijagunappa, 2004). Seismotectonic map from Project Vasundhara (1994) also shows that there are active faults that triggered earthquake magnitude of 2–4 close to Bangalore. The morphology of Karnataka shows that the series of water falls, cascades and rabid along the Cauvery river, particularly between Sivasamudram in Karnataka and Mettur in Tamil Nadu. This is attributed due to reactivation of Precambrian faults across part of the old course here and lateral displacement of the uplifted blocks, giving rise to change in the course of the river as shown in Figure 1 (Valdiya, 1998). Figure 1 shows the active faults speculated at present by Valdiya (1998) in south of Bangalore on either side within 100 kms. Similarly, in the north, the Arkavathi River that follows a remarkably straight fault valley in the Manchenabele–Aganahalli–Ramagiri tract is shown in Figure 2. Valdiya (1998) highlighted that the recent uplift is in the order of 7–10 m on the eastern side formed gully erosion on the Manchenabele reservoir area corroborating to the recent movement of the faults. Figure 2 shows faults and lineaments identified by Valdiya (1998) close to Bangalore at a distance of about 20–50 kms; having a length varying from about 35 to 90 kms.

Valdiya (1998) indicate that in Southeast of Kanakapura (see Figure 2), the Hosdurga stream flows about 10 kms in a straight valley before entering on entrenched swing and they have pointed the evidence to the western block rising up a few meters and blocking the flow of the Hosdurga stream. As described by Radhakrishnan and Vaidyanadhan (1997), the eastern part of Karnataka (close to Bangalore) is surrounded by remobilized terrain and it is marked by a 5 km wide steep-dipping mylonite belt, which can be traced for nearly 400 km. Despite its steep dip many workers consider it as a thrust on the basis of seismic evidence. Ganesha Raj and Nijagunappa (2004) have identified an active lineament from Mandya–Channapatna–Bangalore using remote sensing data and neotectonic activity of the area. From the above discussion, it is clear that there are several active faults and lineaments in and around Bangalore.

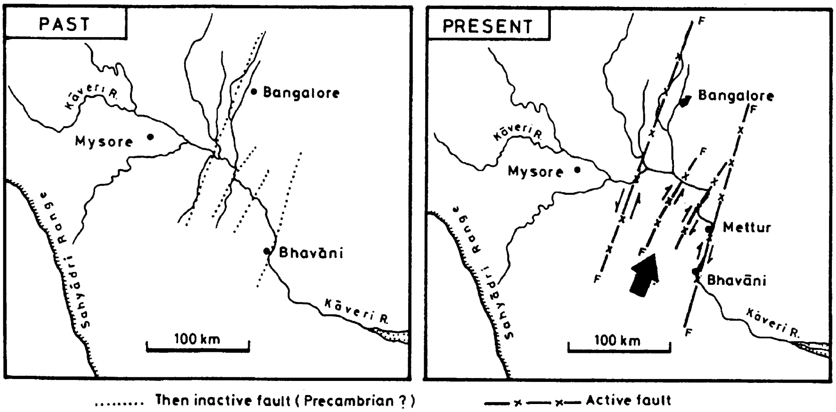

Figure 1. Active Faults present close to Bangalore (after Valdiya, 1998).

Bangalore city covers an area of over 650 square kilometres and is at an average altitude of around 910 m above mean sea level. It is situated on a latitude of 12°58″ North and longitude of 77°37″ East. The population of Bangalore city is over 6 million and Bangalore city is the fastest growing city and fifth biggest city in India. It is the political capital of the state of Karnataka. Besides political activities, Bangalore possesses many national laboratories, defence establishments, small and large-scale industries and Information Technology Companies. That is also called as Silicon Valley of India/Science city of India. These establishments have made Bangalore a

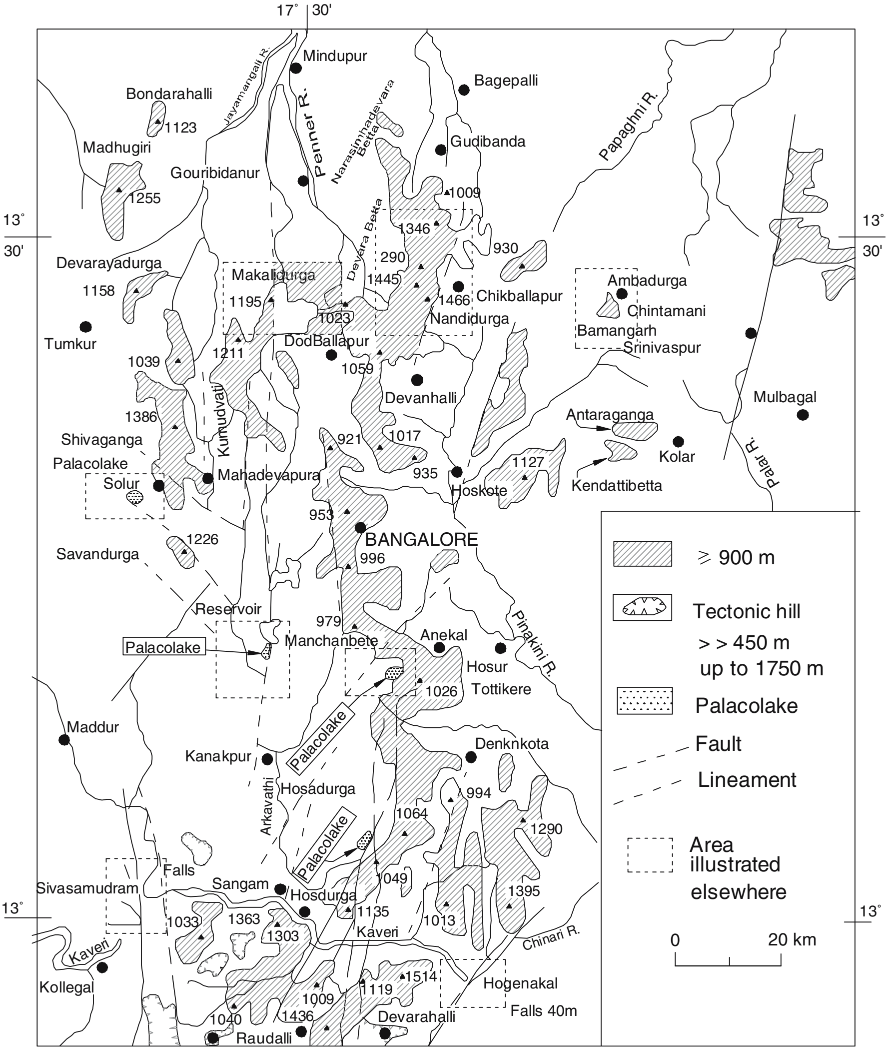

Figure 2. Active Faults present in southeast of Karnataka (after Valdiya, 1998).

very important and strategic city. Recent earthquakes in different parts of country, particularly the one at Bhuj during 2001 has influenced the importance of earthquake resistant design and construction. Because of density of population, mushrooming of buildings of all kinds from mud buildings to RCC framed structures and steel construction, improper and low quality construction practice and irregular and heavy traffic conditions; Bangalore is vulnerable even against average earthquakes. Thus there is a need to evaluate the seismic hazard of this area. As per IS 1893 (2002) Bangalore is upgraded to Zone II from Zone I in the seismic zonation map. Further, findings from geologists have shown that in the Bangalore region the reactivated reverse/normal faults have a dominant strike-strip movement resulting in repeated rupturing at close intervals. This is also evident from rejuvenation of the transcurrent faults manifested in recurrent earthquakes (Valdiya, 1998). Ganesha Raj and Nijagunappa (2004) have also highlighted the need to upgrade the seismic zonation of Karnataka; particularly the areas surrounding Bangalore, Mandya and Kolar to zone III rather than the current zone II as these areas are quite active, based on the analysis using remote sensing data and past earthquake events in the area. In this paper, as per Regulatory Guide 1.168 (1997), regional geological and seismological investigations for the Bangalore city has been carried out considering a radius of 350 km around the point of interest to identify seismic sources by using literature review, study of maps, remote sensing data and ground reconnaissance study. Study area lies between latitudes 9°50″ north to 17°12″ north and longitudes 74°24″ east to 81°42″ east covering 350 km radial distance from the city. Here, an attempt has been made to determine the maximum credible earthquake (MCE) and generation of synthetic acceleration time history plot for the Bangalore region. The seismotectonic map has been prepared by considering all the possible sources of seismic activity such as faults, lineaments, shear zones and historic earthquake events (of more than 150 events).

2. Seismotectonics

Many earthquakes have been reported in this region and the first reported seismic activity in the study area had an intensity of VI occurred on 10th December, 1807. However, earthquake recording station was not there in Bangalore city until recently. Recent tremors which are reported are from the Gauribidanur seismic recording station which is about 85 km from Bangalore and from India Meteorological Department (IMD) data. The historic earthquake shows that moderate earthquake of 4.0–5.5 in moment magnitude have occurred many times in the study area. Some of these earthquakes are listed in Table I. In recent years much of the seismic activity in the state of Karnataka has been in the south, in the Mysore–Bangalore region. Historically tremors have occurred in many other parts of the state such as Bellary, which is in the north part of Karnataka. On January 29th of 2001, earthquake magnitude of 4.3 in Richter scale hit in the Mandya area, its epicentre was about 35 km south of Bangalore. More than 50 buildings have been reported to be damaged at Kanakapura. Widespread panic in Bangalore and schools were closed. Minor damages are reported at Austin town and airport road in Bangalore. Even the Killari earthquake of 30th September 1993 was felt in Bangalore city. Sumatra earthquake of 2004 has triggered tremors of intensity IV in Bangalore city. As part of this work, in the year 2005 six strong motion accelerographs and two borehole sensors have been installed at different locations in Bangalore city.

Geologically most part of Bangalore region is comprised of Gneissic complexes, which is formed due to several tectonic-thermal events with large influx of sialic material, are believed to have occurred between 3,400 and 3,000 million years ago giving rise to an extensive group of grey gneisses designated as the "older gneiss complex". These gneisses act as the basement for a widespread belt of schist's. The younger group of gneissic rocks mostly of granodioritic and granitic composition is found in the eastern part of the state, representing remobilized parts of an older crust with abundant additions of newer granite material, for which the name "younger gneiss complex" has been given (Radhakrishnan and Vaidyanadhan, 1997). The rocks in this group range in age from 2,700 to 2,500 million years. The oldest rocks of Karnataka are the Sargur Group of rocks, which is followed by Peninsular Gneissic Complex, Dharwar Super Group, Closepet Granite, Kaladgi, Bhima's, and Deccan Traps; these are further followed by laterite and alluvium. The Peninsular Gneissic Complex occupies major part of the study area.

Seismotectonic map has been prepared using Adobe Illustrator version 9.0 package. Seismotectonic details of study area have been collected in about 350 km radius around Bangalore. A seismotectonic detail includes geology, rock type, faults orientation with length, lineaments with lengths, shear zones with length and seismic earthquake events. Earthquake data collected from different agencies [United State Geological Survey (USGS), India Meteorological Department (IMD), Geological Survey of India (GSI) and Amateur Seismic Centre (ASC)] contains different type scales measurement such as intensity, local magnitude or Richter magnitude and body wave magnitudes. These magnitudes are converted to moment magnitudes (M_W) by using magnitude relations given by Idriss (1985). Seismotectonic Atlas-2000 published by Geological Survey of India and Karnataka lineaments using remote sensing data as

Table I. List of the historic earthquakes in the study area.

Date	Latitude (°E)	Longitude (°N)	Depth Km	Data source	Moment magnitude
8.6.1988	9.8	77.2	5	NGRI	4.4
7.6.1988	9.8	77.2	5	NGRI	4.8
17.03.1856	9.9	78.1	–	OLD	4.6
17.2.1981	9.95	76.8		GBA	4.2
2001 8 25	10.48	76.12	15	IMD	3
16.2.1979	10.5	77		CVR	4.5
16.5.1972	12.4	77	–	UMC	5.1
13/02/2005	10.61	76.42		CESS	1.1
1994 12 2	10.75	76.25	15	IMD	3.7
25/08/01	10.76	76.25		CESS	2.8
01/08/02	10.76	76.24		CESS	2.8
18/04/04	10.76	76.78		CESS	1.7
22/07/04	10.76	76.30		CESS	1.5
05.01.1864	10.8	78.7	–	OLD	4.6
8.2.1900	10.8	76.8		UC	6.2
17/04/04	10.92	76.04		CESS	1.8
1.3.1978	10.98	75.37		GBA	4
24.6.1865	11	76.95		UGS	4.6
29.7.1972	11	77		IMD	5.4
0.10.1964	11.3	75.8		GUB	4.9
13.8.1858	11.4	76		OLD	5
28/12/04	11.42	76.55		CESS	2
28.2.1882	11.46	76.7		MIL	6.2
21.7.1959	11.5	75.3		IMD	4.7
27.7.1959	11.5	75.25		IMD	4.7
17.12.1859	11.6	78.1	–	OLD	4.6
26/08/2005	11.61	76.18		CESS	2.5
22.09.1985	11.67	79.06	–	GBA	4.2
17.12.1959	11.7	78.1	–	GUB	4.9
8/11/03	11.72	75.55		CESS	3.2
2001 9 25	11.79	80.31	23	IMD	5.5
18.04.1979	11.8	78.3	–	BRR	4.6
2001 9 25	11.83	80.44	33	IMD	4
12/01/03	11.83	75.65	33	CESS	2.6
20.01.1860	11.9	78.2	–	OLD	4.2
17.01.1860	11.9	78.2	–	OLD	4.6
04.03.1861	11.9	78.2	–	OLD	4.6
25/09/01	11.95	80.23	10	IRIS	5.5

identified by Ganesha Raj and Nijagunappa (2004) are used for base map creation over which earthquake moment magnitude with available latitude and longitudes are superposed. The seismotectonic map contains 65 numbers of faults with length varying from 9.73 to 323.5 km, 34 lineaments and 14 shear zones. The map differentiates the different geology with colour layers information. Faults, lineaments and shear zones are differentiated by colour layers and also earthquake magnitude variations are shown in different diameters circle with colours. The numbers of earthquake events collated are about 150 with minimum moment magnitude of 1.0 and a maximum of 6.2. Seismotectonic map developed for Bangalore region is shown in Figure 3a. Figure 3a shows clearly that large number of earthquake events have occurred close to Bangalore and also in southern part of Karnataka. The legend for Figure 3a is enclosed in Figure 3b.

3. Seismic Hazard Analysis

Seismic hazard analysis has been carried out using deterministic approach. Deterministic seismic hazard assessments seek to identify the maximum credible earthquake (MCE) that will affect a site. The MCE is the largest earthquake that appears possible along a recognized fault under the presently known or presumed tectonic activity (USCOLD, 1995). MCE assessment gives little consideration to the probability of future fault movements. For the vulnerable earthquake source identification minimum moment magnitude considered was 3.5 and above. The number of earthquake sources on which earthquake of greater than 3.5 moment magnitude have occurred are 21 faults and lineaments (which are listed in Table II). Shortest distance from source to Bangalore city centre has been measured from the seismotectonic map shown in Figure 3a and they are also listed in Table II. With these distance and moment magnitude Peak Horizontal Acceleration is calculated at bed rock level by assuming focal depth of the earthquake of about 15 km from the surface. This depth is also arrived at considering past events of earthquake. The PGA for the Bangalore has been calculated using the attenuation relation developed for south India by Iyengar and Raghukanth (2004). The attenuation relation used to calculate PGA is given below

$$\ln y = c_1 + c_2(M-6) + c_3(M-6)^2 - \ln R - c_4 R + \ln \varepsilon \tag{1}$$

where y, M and R refer to PGA (g), moment magnitude and hypo central distance respectively. Since PGA is known to be distributed nearly as a lognormal random variable ln y would be normally distributed with the

(a)

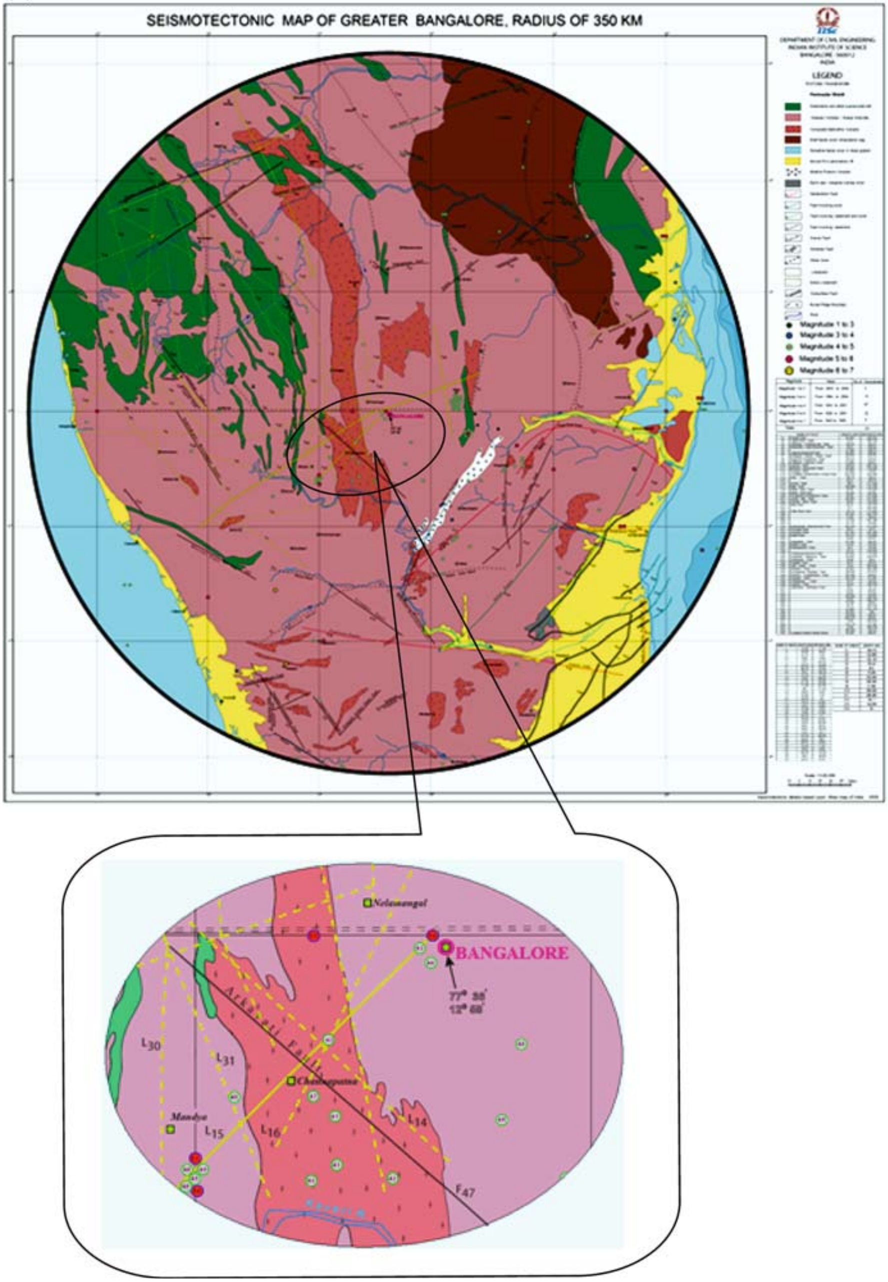

Figure 3. (a) Seismotectonic map for Bangalore region (b) Seismotectonic map legend for Figure 3a.

NAME OF FAULT		LENGTH (KM)	DISTANCE (KM)
F1	Periyar Fault	69.365	336.225
F2	Vaigai River - Fault	31.61	326.145
F3	Ottipalam - Kuttampuzah Fault	102.56	282.35
F4	Malayattur -Vada Kkanetteri Fault	36.67	299.64
F5		37.945	288.79
F6	Valparai-Anaimudi Fault	46.265	290.06
F7	Kottagudi - Kokkal - Palani Fault	60.575	273.79
F8	Ayakkudi-Virupaksha Fault	30.015	276.64
F9	Pattikkad - kollengod Fault	41.845	280.67
F10	Cauveri Fault	323.05	224.155
F11	Bhavani - Kanumodi Fault	63.365	176.455
F12	Tiruppur Fault	87.585	178.93
F13	Crystalline-Sedimentary Contact Fault	222.325	243.485
F14	Attur Fault	160.74	198.15
F15		46.21	199.76
F16	Amirdi Fault	100.3	171.545
F17	Main Fault	129.085	137.105
F18	Mettur East Fault	85.56	133.925
F19	Mettur East Fault	38.235	95.535
F20	Tirukkavilur Pondicherry Fault	66.58	219.395
F21	Javadi Hills Fault	90.495	161.895
F22	Pambar River Fault	98.52	123.945
F23	Main Fault	82.27	142.745
F24		51.7	263.985
F25	Palar River Fault	135.75	175.485
F26		22.165	227.725
F27		9.725	185.23
F28		111.52	241.185
F29		18.115	210.98
F30	Karkambadi -Swarnamukhi Fault	105.925	210.845
F31	Tirumala Fault	48.31	218.5
F32	Gulcheru Fault	22.155	181.295
F33	Kadiri Fault	47.615	133.085
F34		22.23	215.31
F35	Papaghani Fault	54.745	204.49
F36	Badvel Fault	54.78	275.94
F37	Bukkapatnam Fault	45.5	145.48
F38		20.14	140.525
F39	Chitradurga Boundry Fault	83.635	115.235
F40	Gudekota - Rampura Fault	50.625	238.575
F41	Wajrakarur Fault	38.88	246.2
F42	Pyapalli Fault	29.67	253.57
F43	Gani - Kalva Fault	143.8	283.535
F44	Atmakur Fault	35.225	347.305
F45	Kumadavati - Narihalli Fault	148.045	270.915
F46	Dharma - Tungabhadra Fault	155.485	308.83
F47	Arkavati Fault	125.125	51.245
F48	Chitradurga Fault	78.77	182.38
F49	Yagachi Fault	28.39	188.745
F50	Sakleshpur - Bettadpur Fault	80.2	181.19
F51		53.62	263.66
F52		90.29	218.84
F53		164.685	244.92
F54		23.56	294.155
F55		32.545	299.81
F56		46.15	306.545
F57		37.825	323.145
F58		28.935	334
F59		129.665	259.07
F60		226.975	299.81
F61		13.95	324.675
F62		112.115	311.08
F63		72.84	309.795
F64		160.365	323.18
F65	Cudapah Eastern Magin Shear	94.255	268.97

Magnitude	No of Eq Occuranced
Magnitude 1 to 3	16
Magnitude 3 to 4	15
Magnitude 4 to 5	93
Magnitude 5 to 6	22
Magnitude 6 to 7	3
Totale	149

NAME OF LINEAR	LENGTH (KM)	DISTANCE (KM)
L1	118.405	171.595
L2	130.265	100.25
L3	321.99	6.375
L4	94.04	114.39
L5	178.91	206.445
L6	169.415	144.895
L7	289.815	179.565
L8	98.17	182.116
L9	102.305	172.835
L10	133.66	250.645
L11	317.705	234.965
L12	111.525	214.785
L13	100.8	271.485
L14	100.59	43.65
L15	104.895	5.215
L16	108.975	18.1
L17	158.49	29.685
L18	125.37	24.065
L19	112.235	52.93
L20	110.89	57.595
L21	102.475	72.11
L22	130.425	26.355
L23	129.58	265.005
L24	248.61	265.46
L25	182.81	158.185
L26	172.47	158.11
L27	167.015	204.555
L28	222.54	294.1
L29	207.95	183.83
L30	148.425	77.245
L31	190.25	58.68
L32	224.755	114.795
L33	225.8	104.255
L34	223.35	55.415

NAME OF SHEAR	LENGTH (KM)
S1	108.015
S2	124.665
S3	120.125
S4	334.44
S5	65.5
S6	76.005
S7	332.945
S8	206.365
S9	81.565
S10	290.265
S11	469.485
S12	194.11
S13	144.935
S14	93

Figure 3. Continued.

average of (ln ε) being almost zero. Hence with ε = 1, coefficients for the southern region are: (Iyengar and Raghukanth, 2004):

$$c_1 = 1.7816;\ c_2 = 0.9205;\ c_3 = -0.0673;\ c_4 = 0.0035;$$
$$\sigma(\ln \varepsilon) = 0.3136 \text{ (taken as zero)} \tag{2}$$

Table II shows the calculated PGA values.

For the cross validation of the findings, Wells and Coppersmith (1994) relation of moment magnitude with subsurface rupture length (RLD) has been used. Mark (1977) recommends that the surface rupture length may be assumed 1/3 to 1/2 of the total fault length (TFL) based on the world wide data. However, assuming such large subsurface rupture length yields very large moment magnitude and also it does not mach with the historic earthquake data. By parametric analyses, it is found that less than 5% yields a moment magnitude closely matching with historic earthquakes (see Table III).

Table II. Calculated peak horizontal accelerations at bed rock level based on historic earthquakes.

Fault number and name	Short distance to site km	Max. magnitude occurred (Mw)	Hypocenter distance (h = 15)km	PGA in g
F3 Ottipalam–Kuttampuzah Fault	282.35	3.7	282.75	0.001
F6 Valparai–Anaimudi Fault	290.06	4.5	290.45	0.002
F9 Pattikkad–Kollengol Fault	280.67	6.2	281.07	0.009
F10 Cauveri Fault	224.16	5.4	224.66	0.007
F13 Crystalline–Sedimentary Contact Fault	243.48	5.3	243.94	0.005
F14 Attur Fault	198.15	4.5	198.72	0.003
F17 Main Fault1	137.1	4.6	137.92	0.006
F20 Tirukkavilur Pondicherry Fault	219.4	5.7	219.91	0.009
F21 Javadi Hills Fault	161.9	4.7	162.59	0.006
F22 Pambar River Fault	123.94	4.6	124.84	0.007
F23 Main Fault2	142.74	4.9	143.53	0.008
F25 Palar River Fault	175.48	5	176.12	0.007
F28	241.1	3.5	241.57	0.001
F30 Karkambadi–Swarnamukhi Fault	210.84	5	211.37	0.005
F36 Badvel Fault	275.94	4	276.35	0.001
F47 Arkavati Fault	**51.24**	**4.7**	**53.39**	**0.025**
F50 Sakleshpur–Bettadpur Fault	181.19	4	181.81	0.002
F52 Bhavani fault	216.84	6.2	217.36	0.015
L15 Mandya–Channapatna–Bangalore	**5.215**	**5.1**	**15.88**	**0.146**
L20 Chelur–Kolar–Battipalle	**57.6**	**5.2**	**59.52**	**0.037**
L24 Sorab–Narihalla	265.46	6	265.88	0.009

The least PGA values from historic earthquake records and considering RLD approach for the different sources are 0.001 and 0.002 g. The large PGA values for Bangalore city are caused from Mandya–Channapatna–Bangalore lineament from the adopted two methods are 0.146 and 0.159 g. In total, 3 sources have generated the higher PGA values close to Bangalore city. (i) the Arkavati fault (F47 in Figure 4) which is 51.24 km away from Bangalore and having the length of about 125 km with a PGA of 0.025 g (0.047 g from RLD approach) due to an earthquake a moment magnitude M_W of 4.7. (ii) Chelur–Kolar–Battipalle Lineament (L20 in

Table III. Calculated peak horizontal accelerations at bed rock level based on assumed subsurface rupture length.

Fault number and name	Hypocenter Dist (h = 15)km	Max magnitude occurred (Mw)	RLD (km)	Excepted M_W	PGA (g) Based on RLD	RLD (as %) TFL
F3 Ottipalam–Kuttampuzah Fault	282.748	3.7	3.846	5.168	0.003	<5%
F6 Valparai–Anaimudi Fault	290.448	4.5	1.735	4.667	0.002	5%
F9 Pattikkad–kollengol Fault	281.071	6.2	17.261	6.114	0.009	55%
F10 Cauveri Fault	224.661	5.4	12.114	5.891	0.011	<5%
F13 Crystalline–Sedimentary Contact Fault	243.942	5.3	8.337	5.655	0.007	<5%
F14 Attur Fault	198.717	4.5	6.253	5.474	0.009	<5%
F17 Main Fault1	137.918	4.6	4.841	5.313	0.014	<5%
F20 Tirukkavilur Pondicherry Fault	219.912	5.7	8.489	5.667	0.009	17%
F21 Javadi Hills Fault	162.593	4.7	3.394	5.089	0.008	<5%
F22 Pambar River Fault	124.844	4.6	3.695	5.143	0.013	<5%
F23 Main Fault2	143.526	4.9	3.085	5.029	0.010	<5%
F25 Palar River Fault	176.120	5	5.091	5.345	0.010	<5%
F28	241.566	3.5	4.182	5.221	0.005	<5%
F30 Karkambadi–Swarnamukhi Fault	211.373	5	3.972	5.189	0.006	<5%
F36 Badvel Fault	276.347	4	2.053	4.773	0.002	<5%
F47 Arkavati Fault	**53.390**	**4.7**	**4.692**	**5.293**	**0.047**	**<5%**
F50 Sakleshpur–Bettadpur Fault	181.810	4	3.233	5.059	0.007	<5%
F52 Bhavani fault	217.358	6.2	18.961	6.173	0.015	28%
L15 Mandya–Channapatna-Bangalore	**15.881**	**5.1**	**3.934**	**5.182**	**0.159**	**<5%**
L20 Chelur–Kolar-Battipalle	**59.521**	**5.2**	**4.158**	**5.217**	**0.038**	**<5%**
L24 Sorab–Narihalla	265.883	6	14.917	6.022	0.009	8%

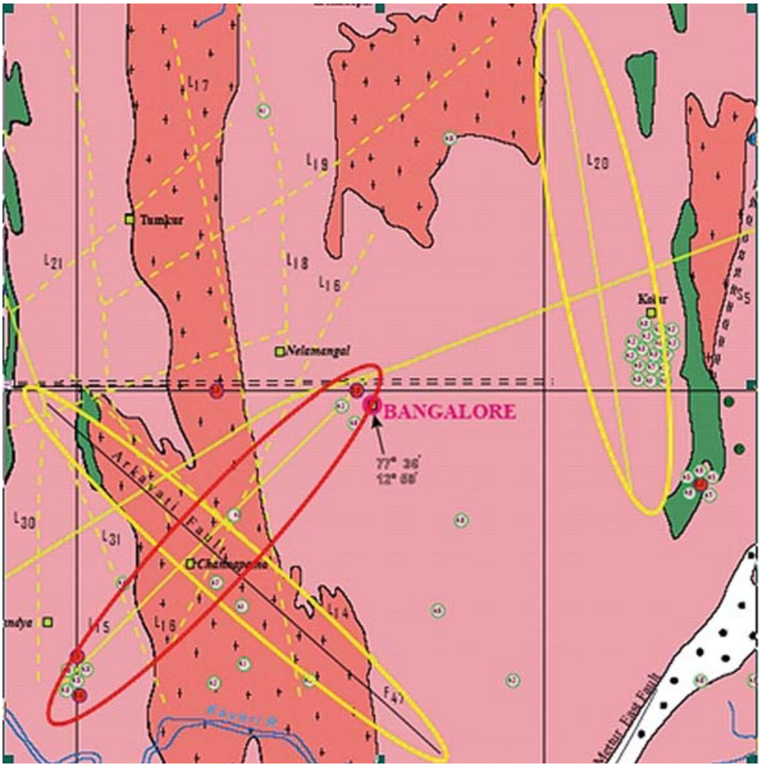

Figure 4. Vulnerable sources close to Bangalore.

Figure 4) having a length of about 111 km, which is 57.6 km away from Bangalore causing a PGA value of 0.037 g(0.038 g from RLD approach) due to an earthquake of M_W of 5.2. (iii) Mandya–Channapatna–Bangalore lineament (L15 in Figure 4) having a length of about 105 km which is 5.2 km away from the Bangalore causing a PGA value of 0.146 g due to an earthquake with an M_W of 5.1 occurred on 16th May 1972 (corresponds to a latitude of 12.4N and longitude of 77.0E) and also it matches with the predicted PGA value of 0.159 from assumed subsurface rupture length for the same active source. The source, Mandya–Channapatna–Bangalore-(L15) which triggered the highest PGA of about 0.150 is taken as vulnerable source and corresponding moment magnitude M_W 5.1 is considered as the maximum credible earthquake for the Bangalore region.

4. Synthetic Earthquake Data Generation

In regions lacking strong motion data, it is necessary to generate the synthetic earthquake data (strong motion). Seismological model by Boore

(1983) is used for generation of synthetic acceleration-time response (Atkinson and Boore 1995; Hwang and Huo 1997). Iyengar and Raghukanth (2004) attenuation equation to the Peninsular India and suggested coefficients for southern region have been used. Boore (1983, 2003) gives the details of estimating ground motion based on the Fourier amplitude spectrum of acceleration at bedrock and this is expressed as:

$$A(f) = C[S(f)]D(f)P(f) \tag{3}$$

where, $S(f)$ is the source spectral function, $D(f)$ is the diminution function characterizing the attenuation, and $P(f)$ is a filter to shape acceleration amplitudes beyond a high cut-off frequency f_m, and C is a scaling factor. In the present study, the single corner frequency model has been used (Brune, 1970) which is given as:

$$S(f) = (2\pi f)^2 M_0/[1 + (f/f_c)] \tag{4}$$

where, f_c is the corner frequency, M_0 is the seismic moment, and, $\Delta\sigma$ is the stress drop are related through:

$$fc = 4.9 \times 10^6 V_S(\Delta\sigma/M_0)^{1/3} \tag{5}$$

Here, the shear wave velocity (V_S) in the source region is taken as 4.2 km/s (Sarkar *et al.*, 2001). The diminution function $D(f)$ is defined as

$$D(f) = G\exp[-\pi fR/V_S Q(f)] \tag{6}$$

In which, G refers to the geometric attenuation and the other term to an elastic attenuation. In this equation, $Q(f)$ is the quality factor of the region.

The high-cut filter in the seismological model is:

$$P(f,f_m) = \left[1 + (f/f_m)^8\right]^{-1/2} \tag{7}$$

where f_m controls the high frequency fall of the spectrum. The scaling factor C is given by

$$C = \langle R_{\theta\varphi}\rangle\sqrt{2}/\left(4\pi\rho V_3^S\right) \tag{8}$$

where $\langle R_{\theta\ \varphi}\rangle$ is the radiation coefficient averaged over an appropriate range of azimuths and take-off angles. The coefficient √2 in the above equation arises as the product of the free surface amplification and partitioning of energy in orthogonal directions. Following the work of Singh *et al.* (1999), the geometrical attenuation term G, for the Indian shield region, is taken to be equal to $1/R$ for $R < 100$ km and equal to $1/(10\sqrt{R})$ for $R > 100$ km. For Southern Indian region, Rao *et al.* (1998) used strong motion records of small magnitude earthquakes and estimated Q value to be $460f^{0.83}$(after Iyengar and Raghukanth, 2004). The strong motion data simulated for the moment magnitude of 5.1 and hypocentre distance of 15.88 km is shown in Figure 5. The obtained PGA value 0.153 g from Boore's model matches well with the PGA value of 0.146 g estimated from deterministic approach and 0.159 g from RLD approach.

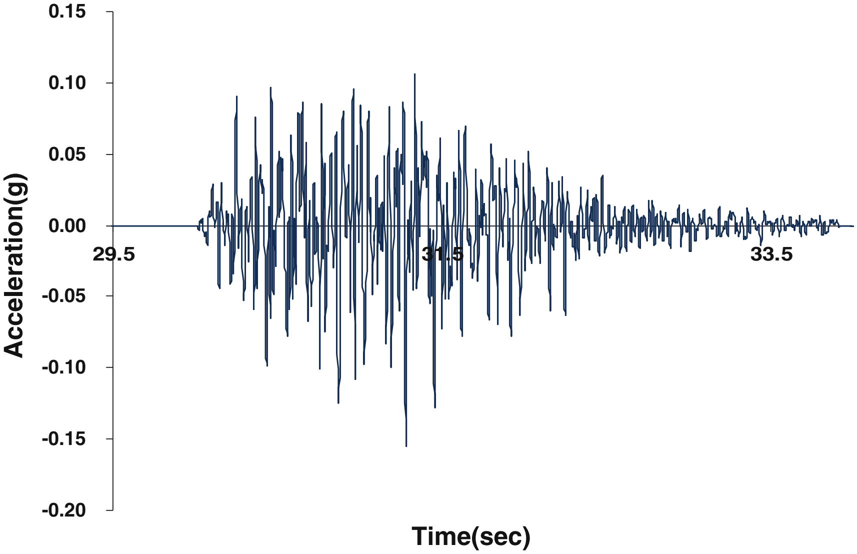

Figure 5. Simulated strong motion data for the moment magnitude of 5.1.

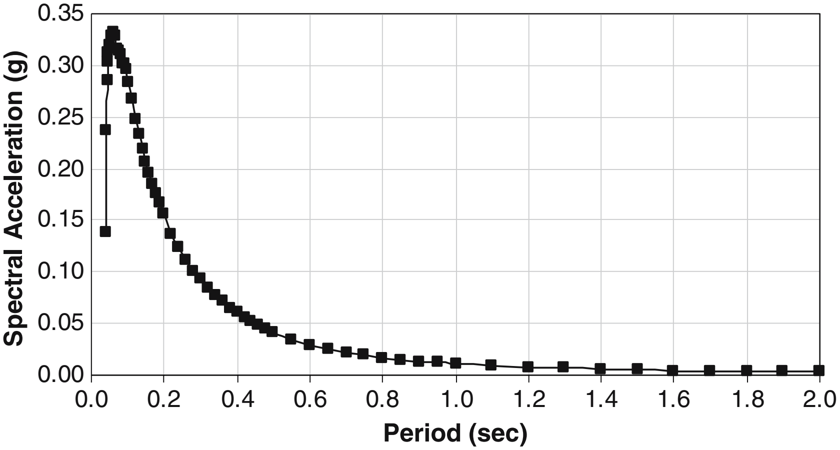

Figure 6. Response spectra for an earthquake magnitude of 5.1 at rock level.

Response acceleration spectra for the synthetic earthquake are shown in Figure 6, which clearly indicate that predominant period of the earthquake 0.06 s and peak spectral acceleration of 0.332 g. Shape of the curve also matches with the uniform hazard response spectra. The source, Mandya–Channapatna–Bangalore-(L15) which triggered the highest PGA is a vulnerable source for the Bangalore region. From available 900 borehole data and large number of shear wave velocity profile obtained using Multichannel Analysis of Surface Wave (MASW) technique in the area, it is being planned to estimate the rock depth and also characterization of overburden in the area. A 3D subsurface Geographical Information System (GIS) model is being developed for the 220 sqkm area of Bangalore city on scale of 1:20,000. Futher work is under progress to evaluate the regional rock and surface PGA values and synthetic ground motion at different locations in the city. Also, 8 strong motion accelerographs have been installed at different locations in the city as part of the national network.

5. Conclusions

Regional, geological and seismological investigations for Bangalore region is carried out by considering faults, lineaments and shear zones existing in a radius of 350 km around Bangalore and past earthquake events in the area. Seismotectonic map for the Bangalore region has been prepared along with identification of vulnerable sources after superposing locations of more than 150 past earthquake events triggered in the region. About 21 numbers of faults and lineaments are identified as a vulnerable sources as a first step. A deterministic seismic hazard analysis approach to determine PGA was adopted. The vulnerable source for Bangalore city is identified as Mandya–Channapatna–Bangalore lineament with an earthquake moment magnitude of 5.1. This combination has been estimated to develop a PGA of about 0.146 g at rock level at the city centre with assuming hypo central distance of 15.88 km from the focal point. The synthetic strong motion data was simulated using seismological model of Boore (1983) by considering regional seismological factors. The obtained high PGA value of 0.153 g from Boore's model matches closely with estimated PGA value from deterministic approach. As part of this programme, 8 strong motion accelerographs have been installed in the city and being monitored continuously. Further work is being carried out to estimate the rock depth and characterization of the overburden in the area to prepare regional rock and ground surface PGA mapping. Further it is planned to develop microzonation maps such as amplification, PGA at the ground surface and liquefaction susceptibility of the area.

Acknowledgements

Authors thank Seismology Division, Department of Science and Technology, Government of India for funding the project titled "Microzonation and geotechnical site characterization of greater Bangalore region (Ref no. DST/23(315)/SU/2002 Dated October 2003)".

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