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Use of remote sensing and seismotectonic parameters for seismic hazard analysis of Bangalore

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Abstract. Deterministic Seismic Hazard Analysis (DSHA) for the Bangalore, India has been carried out by considering the past earthquakes, assumed subsurface fault rupture lengths and point source synthetic ground motion model. The sources have been identified using satellite remote sensing images and seismotectonic atlas map of India and relevant field studies. Maximum Credible Earthquake (MCE) has been determined by considering the regional seismotectonic activity in about 350 km radius around Bangalore. The seismotectonic map has been prepared by considering the faults, lineaments, shear zones in the area and past moderate earthquakes of more than 470 events having the moment magnitude of 3.5 and above. In addition, 1300 number of earthquake tremors having moment magnitude of less than 3.5 has been considered for the study. Shortest distance from the Bangalore to the different sources is measured and then Peak Horizontal Acceleration (PHA) is calculated for the different sources and moment magnitude of events using regional attenuation relation for peninsular India. Based on Wells and Coppersmith (1994) relationship, subsurface fault rupture length of about 3.8% of total length of the fault shown to be matching with past earthquake events in the area. To simulate synthetic ground motions, Boore (1983, 2003) SMSIM programs have been used and the PHA for the different locations is evaluated. From the above approaches, the PHA of 0.15 g was established. This value was obtained for a maximum credible earthquake having a moment magnitude of 5.1 for a source Mandya-Channapatna-Bangalore lineament. This particular source has been identified as a vulnerable source for Bangalore. From this study, it is very clear that Bangalore area can be described as seismically moderately active region. It is also recommended that southern part of Karnataka in particular Bangalore, Mandya and Kolar, need to be upgraded from current Indian Seismic Zone II to Seismic Zone III. Acceleration time history (ground motion) has been generated using synthetic earthquake model by considering the revised regional seismotectonic parameters. The rock level PHA map for Bangalore has been prepared and these maps are useful for the purpose of seismic microzonation, ground response analysis and design of important structures.

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1 Introduction

Southern India once considered as a stable continent has recently experienced many earthquakes indicating that it has become moderately active region. Study of seismic hazard is mandatory for the purpose of microzonation, ground response analysis and design of important structures. Bangalore is densely populated, economically and industrially important city in India. It is one of the fastest growing cities in Asia. Even for the moderate earthquake, Bangalore is vulnerable due to mushrooming of all kinds of buildings founded on encroached areas of tank beds, which were silted up over a period of time (more than 350 lake beds in Bangalore have been converted and used for habitation in the last 50 years). It is necessary to study the seismic vulnerability, evaluating the peak ground accelerations at rock/ground levels and further microzonation of Bangalore including site response studies. The major step in the seismic hazard estimation is identifying probable seismic sources in the area. Geological Survey of India (GSI) has done extensive work in 2000 and has published these details as Seismotectonic Atlas of India in 2000 (which consists of faults, lineaments, shear zones and basement rock). Seismic activity of India is clearly evident from the recent earthquakes within the intra plate and also along the boundaries of Indo-Australian Plate and Eurasian Plate [many major earthquakes such as Bhuj (2001), Sumatra (2004) and Pakistan (2005) along the boundaries have occurred]. This paper highlights the identification of seismic

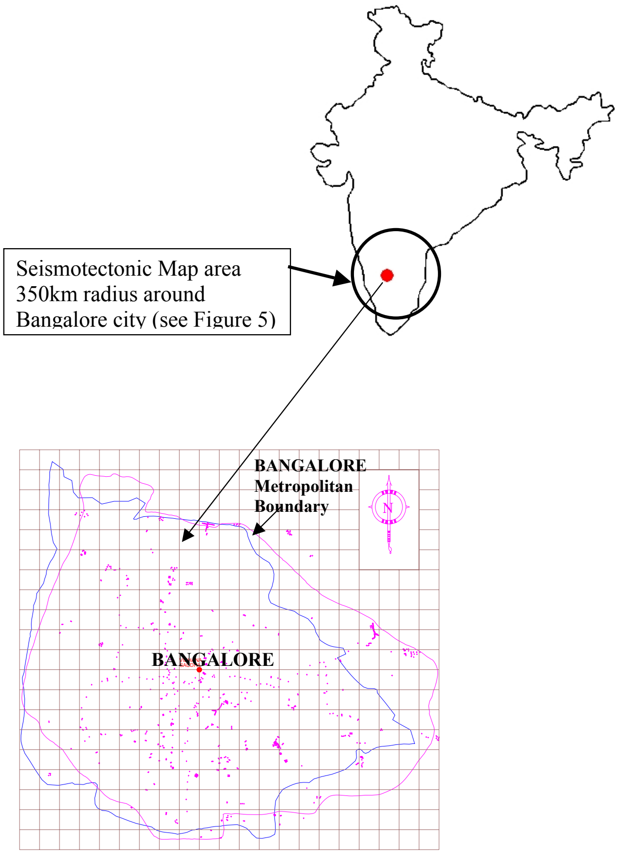

Fig. 1. Study area and Bangalore in the India map.

source by using remote sensing data in conjunction with collateral data like seismotectonic atlas of India, drainage patterns using TOPO sheets of the area and Google earth images etc. From these identified sources, Maximum Credible Earthquake has been evaluated by three methods. Further synthetic ground motion is generated for MCE using regional seismotectonic parameters to full fill the requirements of ground motion data for future study.

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, fractures, 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 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). The study has been carried out for an area of about 350 km radius around Bangalore as per the guideline available in Regulatory Guide of U.S. Nuclear Regulatory Commission (1997). The recent seismic activity of Bangalore has been studied based on the seismic sources and earthquake events in the area. A new seismotectonic map has been prepared by considering all the earthquake sources such as faults, lineaments, and shear zones. The past earthquake events (of more than 470 moderate events from 3.5 to 6.2 in moment magnitude and 1300 small tremors <3.5 moment magnitude) are superimposed on this map with available latitude and longitude details. The peak horizontal accelerations at rock level have been calculated by considering the regional attenuation relation from all the possible sources, through which vulnerable source has been identified. Maximum credible earthquake for the city has also been determined using Wells and Coppersmith (1994) relation. For the purpose of future site response studies the synthetic ground motion has been generated considering regional seismotectonic parameters using the synthetic ground motion model. A detailed seismic hazard analysis and synthetic ground motion generated for Bangalore is presented in this paper.

2 Study area and seismicity

Bangalore covers an area of over 220 square kilometres and is at an average altitude of around 910 m above mean sea level (see Fig. 1.). It is situated on a latitude of 12°58″ North and longitude of 77°36″ East. The population of Bangalore is over 6 million and it is one of the fastest growing cities and fifth biggest 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. This city is also known as Garden City of India and IT City of India. 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 southern Karnataka the faults/lineaments are reactivated. Valdiya (1998) highlighted that the seismic activity is generally confined to linear belts related to transcurrent and terrain-bounding faults and shear zones, implying that the Precambrian faults are being reactivated in the present time based on purely geological studies. 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 carried out using remote sensing data and neotectonic activity in the area. Srinivasan and

Sreenivas (1977) have used field studies of borewell yield data and discussed the reactivation of dormant or inactive lineaments inducing seismicity in relative stable terrains of the continents. Purnachandra Rao (1999) highlighted the occurrence of earthquakes in last few decades due to enhanced seismic activity in the interior of the Indian Plate which results from reactivation of pre-existing faults under the influence of the ambient stress field due to the India-Eurasia plate collision forces, oriented NS to NNE. Ramalingeswara Rao (2000) carried out strain rate and heat flow study in the southern India and characterized as medium to low seismicity region. Subrahmanya (2002 and 1996) highlights that the entire study area becoming seismically active due to the upwarping of Mulki-Pulicat Lake (MPL) axis which connects 13° N in west to 13.4° N in east. He concludes that there is lot seismic activity around this Mulki-Pulicat Lake axis and in particular he highlights that micro to meso-seimicity to the south and mega seismicity to the north of the MLP axis. Recenly, Sridevi Jade (2004) has estimated the plate velocity and crustal deformation in the Indian subcontinent using GPS measurements. The author concludes that southern peninsular India consists of large zones of complex folding, major and minor faults and granulite exposures, and this region cannot be classified as an area of low seismic activity.

The seismic history of the area shows that 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. About 1419 earthquake have been collated and their magnitudes were converted as moment magnitude scale for the study. The data set contains 394 events which are less than 3, 790 events from 3 to 3.9, 203 events from 4 to 4.9, 29 events from 5 to 5.9 and 3 events which are more then 6. Maximum earthquake magnitude out of about 1400 events reported in the study area is 6.2. On 29 January 2001, earthquake of magnitude 4.3 in Richter scale hit the Mandya area, its epicentre was about 65 km southwest of Bangalore. More than 50 buildings reported to be damaged at Harohalli/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. Sumatra earthquake of 2004 had triggered tremors of intensity IV in Bangalore. As part of this work in the year 2005, five strong motion accelerographs and two borehole sensors have been installed at different locations in Bangalore.

3 Lineament studies using remote sensing data

It is observed that seismicity is associated with major lineaments; hence analysis of lineaments is useful for understanding the seismic status of a terrain. Remote sensing data due to its synoptic nature is found to be very useful in mapping lineaments. Images taken in the Near Infra Red (NIR) region (0.7–1.1 μm) depicts clearly more lineaments than other bands. Radar data also provides information on lineaments due to its oblique look angles. Thermal Infra Red (TIR) data is found to be useful in delineating wet lineaments with moisture/water. Lineaments present in the forest areas, soil covered areas are also clearly visible on images thus enabling us to delineate better structural features. In fact one of the major applications of remote sensing is in the area of lineament mapping. Lineaments are useful in groundwater, mineral, oil explorations, seismic studies and in engineering geological applications. Lineaments, which represent faults, fractures etc. have been mapped under the National Drinking Water Mission on 1:250,000 scale for India during 1986–1990 (Department of Space, 1990). In this project an atlas of hydro-geomorphological map of India has been prepared. These maps helped in locating bore well sites for providing potable water to villages (Department of Space, 1990). Large numbers of studies have been carried out wherein lineaments were mapped using satellite images and Aerial photos (Srinivasan and Sreenivas, 1977; National Remote Sensing Agency, 1981; Drury, 1983; Department of Space, 1990; Ganesha Raj, 2001; Naganna and Lingaraju, 1990; Project Vasundhara, 1991; Nijagunappa et al., 1999). Large scale data are useful for mapping minor and micro lineaments whereas small scale data is needed to map major lineaments and to map mega lineaments normally mosaics of images are needed. Aerial photographs are extensively used for mapping of lineaments earlier to the launch of Remote Sensing Satellites. Aerial photographs with the very high spatial resolution and stereo-view are found useful in delineating lineaments. With the advent of satellite era, aerial photos are being used only whenever very detailed information is required. Mapping of minor/micro-lineaments are better done using aerial photographs/high resolution satellite/large scale data, whereas satellite data (on smaller scale) are more useful for mapping medium/major/mega lineaments. Normally, it is difficult to decide whether the mapped lineament is a fault or not from the image itself, but if there is a clear displacement/offset of associated features then the lineament can be identified as a fault. Integration of the lineament map with the available structural and geological information of the terrain, drainage pattern of the terrain and relevant fieldwork helps to decide the nature of the lineament.

In the present study an attempt has been made to map the major lineaments and assess their significance with respect to seismicity. The satellite images and other data used in the study are as follows:

- Indian Remote Sensing Satellite (IRS) – 1-D Wide Field Sensor (WiFS) data (False Colour Composite – FCC) on 1:1 000 000 scale.
- Landsat 2/3 & 4/5 Multi Spectral Sensor (MSS)/Thematic Mapper (TM) data (band products/False Colour Composites) on 1:1 000 000 scale.
- Physical map on 1:1 000 000 scale.

- Geological and Mineral Map on 1:500 000 scale.
- Earthquake data (epicenter with latitude and longitude, year of occurrence and magnitude).
- TOPO sheets of the area on 1:50 000 scale.

Lineaments with length more than 100 km, i.e., major lineaments were mapped first from individual scenes of Landsat data (MSS/TM) on 1:1 000 000 scale, these were transferred to a base map on 1:1 000 000 scale to make a single mosaic map. This map was superimposed on physical/road network map to eliminate any cultural lineament (road/railway etc). IRS – 1-D WiFS FCC on 1:1million scale was used further to map/refine the lineaments. Lineaments were numbered and their length and direction were measured. This lineament map was compared with the maps prepared earlier by Srinivasan and Sreenivas (1977), National Drinking Water Mission (NDWM) (Department of Space, 1990), Project Vasundhara (1991), and Ganesha Raj (2001). Figure 2 show the lineaments identified in Karnataka. From Fig. 2 it is observed that there is a good match between the lineaments mapped in the seismotectonic atlas (Ganesha Raj, 2001) and the present study. And also major lineaments has been cross checked with field studies (Ganesha Raj, 2001) it shows that the position in the satellite images matches with ground which is shown in Fig. 3. Figure 3 shows the Satellite image (IRS LISS-II) of part of Cauvery River (seen in the south western side), controlled by Cauvery Lineament. Very close view of the satellite image in Mandya – Bangalore region shows that number of major lineaments like Lakshamana Thirtha-KRS-Bangalore lineament, Arkavathi-Madhugiri lineament, and Mandya-Channapatna-Bangalore lineament appearing in the region, which is shown in Fig. 4.

4 Preparation of seismotectonic map of Bangalore

Seismotectonic map showing the geology, geomorphology, water features, faults, lineaments, shear zone and past earthquake events has been prepared for Bangalore which is as shown in Fig. 5. Seismotectonic details of study area have been collected in about 350 km radius around Bangalore. The sources identified from Seismotectonic Atlas (2000) and remote sensing studies are compiled and a map has been prepared using Adobe Illustrator version 9.0. The seismotectonic map contains 65 numbers of faults with length varying from 9.73 km to 323.5 km, 34 lineaments and 14 shear zones. The map identifies rock types in different colours, faults, lineaments and shear zones are also given in different colours. Earthquake data collected from various agencies [United State Geological Survey (USGS), Indian Metrological Department (IMD), Geological Survey of India (GSI) and Amateur Seismic Centre (ASC)] contain information about the earthquake size in different scales such as intensity, local magnitude or Richter magnitude and body wave magnitudes. These magnitudes are converted to moment magnitudes (Mw) by using magnitude relations given by Idriss (1985). The earthquake events collated and converted has been super imposed on base map with available latitudes and longitudes. The earthquake events collated are about 1419 with minimum moment magnitude of 1.0 and a maximum of 6.2 and earthquake magnitudes are shown as circles with different diameters and colours. Sitharam and Anbazhagan (2006) have studied these aspects based on seismotectonic atlas of India. Further to this study of the authors, new seismotectonic map which show a closer view of surroundings of Bangalore has been developed and is shown in Fig. 6. Maximum source magnitude is assigned based on the maximum size of the earthquake in each of the sources.

5 Geotechnical data

Geotechnical data was basically collated from geotechnical investigations carried out for several major projects in Bangalore. The GIS model developed currently consists of about 900 borehole locations marked on the digitized Bangalore map of 1:20 000 scale which is shown in Fig. 7. The data consists of visual soil classification, standard penetration test results, ground water level, time during which test has been carried out, other physical and engineering properties of soil. Most investigations for residential and commercial complexes were below 15m and wherever bedrock has been encountered investigation has been terminated at that depth for these projects. This rock depth information has been used to prepare rock depth map for Bangalore. Northwestern part of the Bangalore has weathered rock varying from 6 m to 17 m depths and followed by hard rock. The Southwestern part weathered rock found at 3.5 m to 8.5 m and hard rock below 8.5 m. The Southeastern part weathered rock from 5.5 m to 17.5 m and hard rock beneath. Northeastern side weathered rock from 7.5 m–18.5 m and hard rock below. The rock depth information with latitude and longitude are obtained from the 653 boreholes out of 900, which is used for rock level PHA Mapping. Further reduced level (RL) of each bore log rock depth is calculated from contour map (see the Fig. 8) developed in GIS model. Figure 8 shows the location of boreholes with the elevation contours at 10 m intervals. The ground RL varies from 845 m to 910 m, which gives information on sloping terrains or valleys and could be used for locating the RL of ground as well as rock surface.

6 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), which will

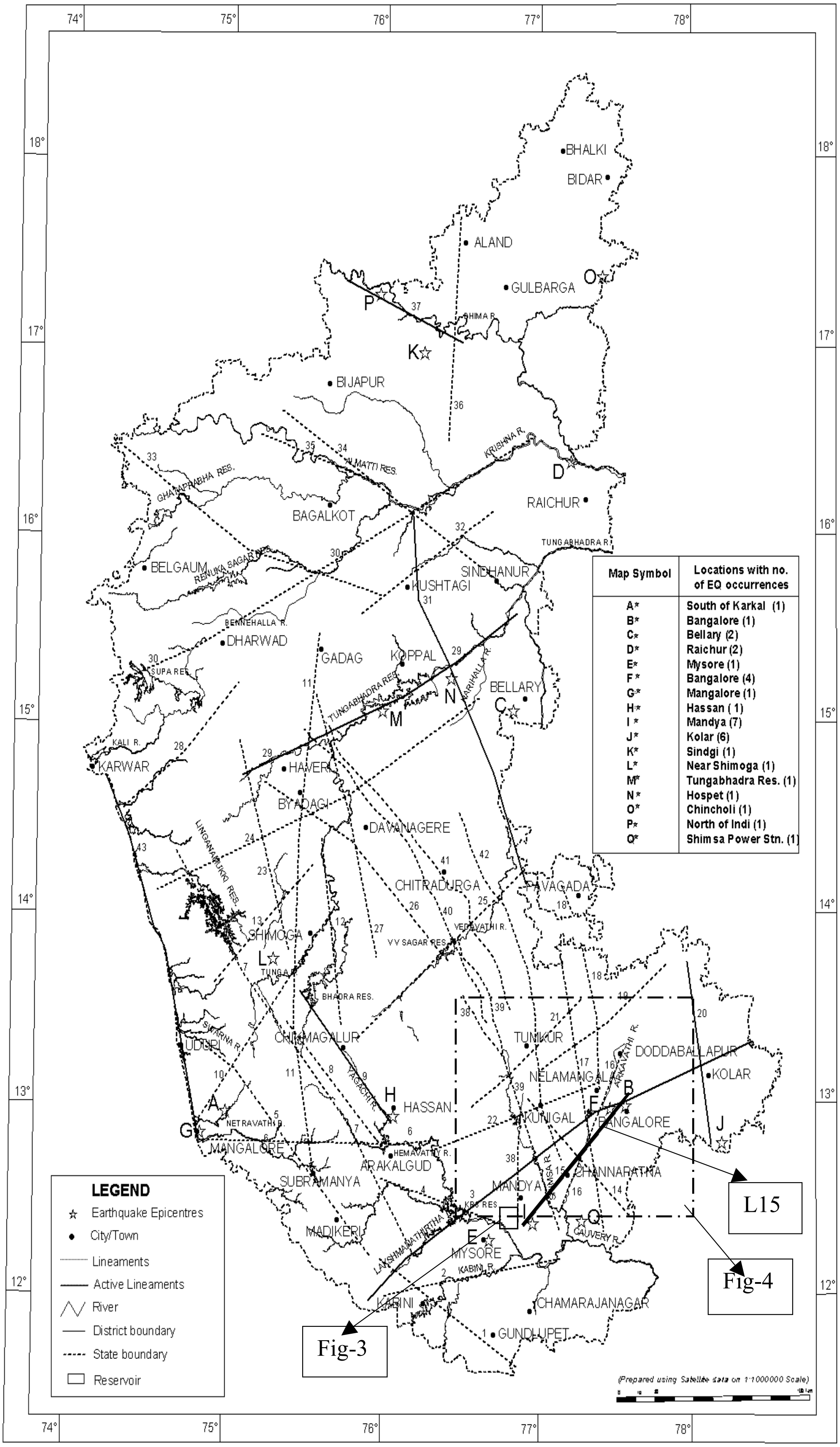

Fig. 2. Lineaments mapped using satellite images – part of the study area (after Ganesha Raj, 2001).

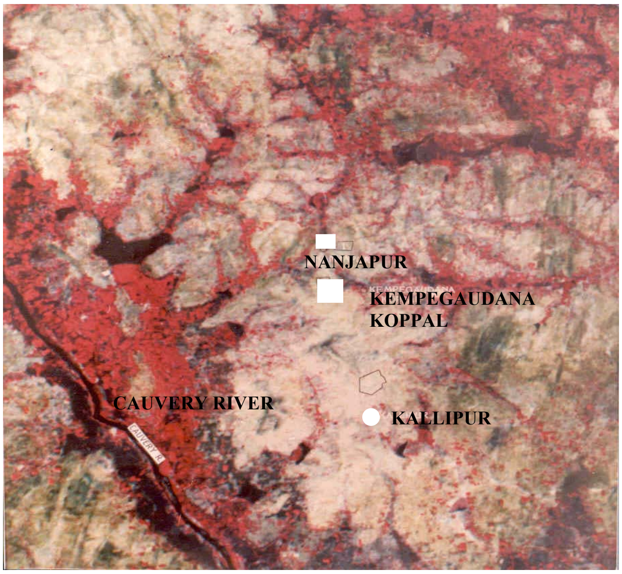

Fig. 3. Satellite image (IRS LISS-II) of part of Cauvery River (seen in the south western side), controlled by cauvery lineament.

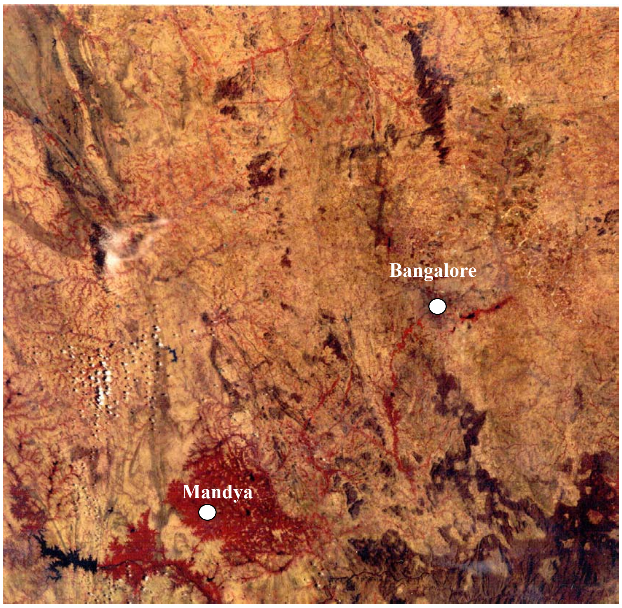

Fig. 4. Satellite image (Landsat TM) of Bangalore, Mandya and surrounding areas showing number of major lineaments.

cause the most severe consequences at the site. MCE assessment gives little consideration to the probability of future fault movements. For the vulnerable earthquake source identification the minimum moment magnitude considered was 3.5 and above. Earlier work by the authors Sitharam and Anbazhagan (2006) considered only 21 faults and lineaments and about 152 earthquakes. In the present study, 52 faults and lineaments and out of 1419 earthquake events, 470 events that are more than 3.5 moment magnitude have been considered. Shortest distances from source to Bangalore city centre have been measured from the seismotectonic map shown in Fig. 5 and they are also listed in Table 1. With these distance and moment magnitude, Peak Horizontal Acceleration (PHA) is calculated at bedrock level by considering a focal depth of the earthquake of about 15 km from the surface, which is arrived at based on the past earthquake data.

Method I: In this method the PGA for 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:

$$\ln y = c_1 + c_2 (M-6) + c_3 (M-6)^2 - \ln R - c_4 R + \ln \in \quad (1)$$

Where y, M and R refer to PGA (g), moment magnitude and hypocentral distance respectively. Since PGA known to be distributed nearly as a lognormal random variable $\ln y$ would be normally distributed with the average of $(\ln \varepsilon)$ being almost zero. Hence with ε=1, coefficients for the southern region are: (Iyengar and Raghukanth, 2004):

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

The calculation shows that the minimum PHA value is 0.001 g and maximum PHA value is 0.146 g (caused from Mandya-Channapatna-Bangalore lineament). Totally 10 sources have generated the higher PHA values close to Bangalore. Among the 10 sources, the active lineament of Mandya-Channapatna-Bangalore lineament (L15 in Fig. 6) having a length of about 105 km (which is 5.2 km away from the Bangalore) causing a PHA value of 0.146 g due to an earthquake event (Mw of 5.1 occurred on 16 May 1972 ; corresponds to a latitude of 12.4° N and longitude of 77.0° E). This is a measured earthquake event having a surface wave magnitude (Ms) of 4.6. These results confirm with the earlier analysis by the authors Sitharam and Anbazhagan (2006).

Method II: DSHA have been carried by considering subsurface fault rupture length for the revised 52 numbers of sources. Mark (1977) recommends that the surface rupture length may be assumed as 1/3 to 1/2 of the total fault length (TFL) based on the worldwide data. However, assuming such large subsurface rupture length yields very large moment magnitude and also it does not match with the past earthquake data. Wells and Coppersmith (1994) developed empirical relation between moment magnitude and subsurface fault length using past world wide earthquakes, which is as follows:

$$\log(\mathrm{RLD}) = 0.57 M_W - 2.33 \quad (3)$$

The relation between moment magnitude and subsurface rupture length (RLD) was developed using reliable source parameters and this is applicable for all types of faults, shallow earthquakes and interplate or intraplate earthquakes (Wells and Coppersmith, 1994). Using Wells and Coppersmith

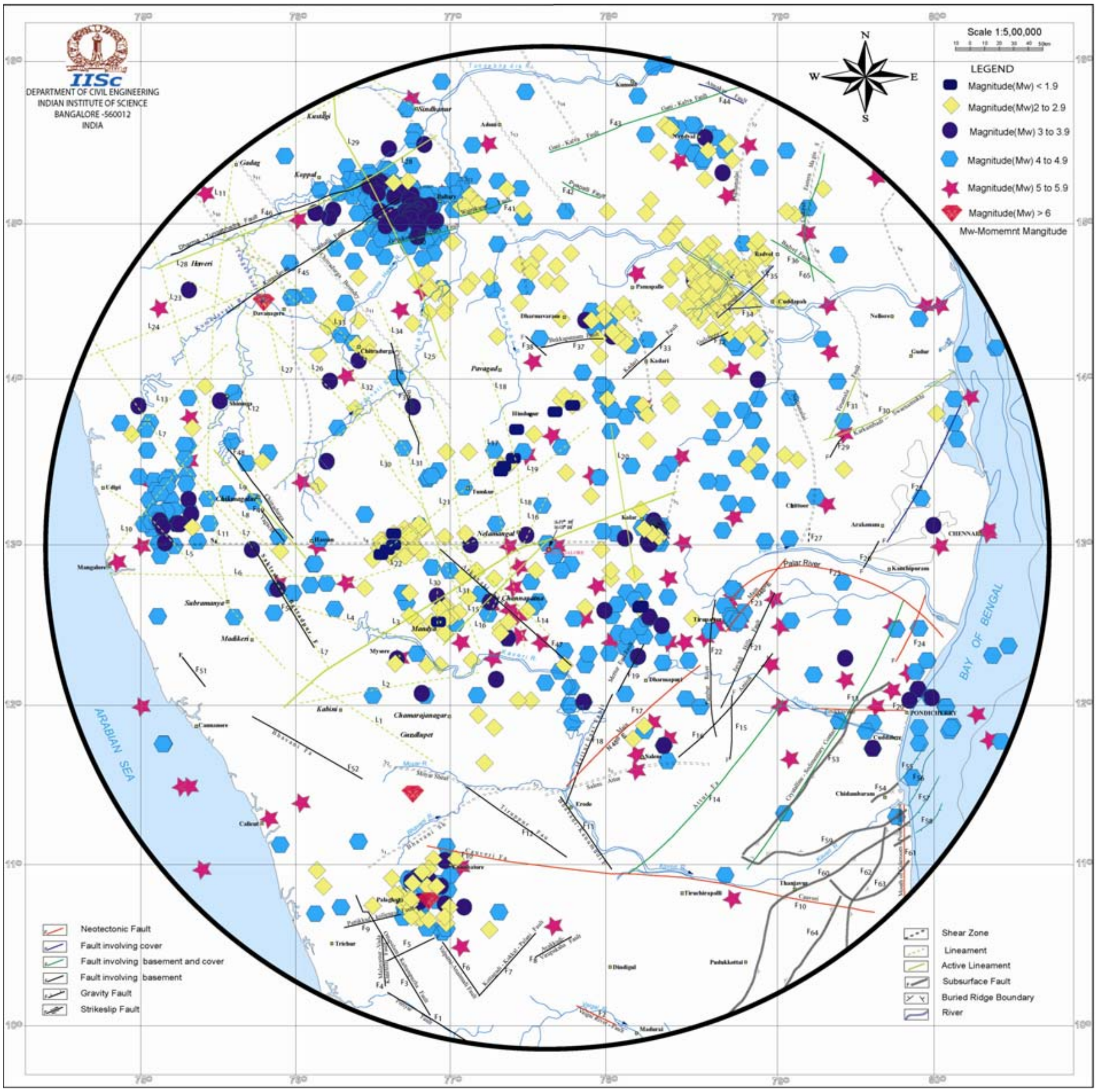

Fig. 5. Seismotectonic map of Bangalore and surroundings.

(1994) Eq. along with a parametric study, it is found that subsurface fault rupture length of about 3.8% of total fault length gives moment magnitudes closely matching with the past earthquakes. Table 2 shows the RLD calculations, expected magnitude, and corresponding PHA from all the sources. The revised PHA lies in between minimum value of 0.001 g and maximum value of 0.146 g. In total, 9 sources have generated PHA value of more then 0.045 g at rock level close to Bangalore region. Among the nine sources, the Mandya-Channapatna-Bangalore lineament (L15 in Fig. 5) has a higher PHA value of 0.146 g due to an earthquake moment magnitude of Mw of 5.1. For the earthquake event with a Mw of 5.1 (occurred on 16 May 1972 with latitude of 12.4° N and longitude of 77.0° E), the RLD works out to be 3.8% of the total fault length corresponding to a PHA of 0.146 g.

7 Synthetic earthquake model

The sources (15 numbers) causing the PHA value of 0.01 g and more, from the method I, have been used for generating the synthetic ground motion. From the above sources, using method II, 8 sources have been identified for generating the synthetic ground motion. These 8 sources considered

Table 1. Rock level PHA obtained using past earthquake events.

Number and Name of Source		Distance (km)	Hypocentral Distance (km)	Occurred Earthquake (Mw)	PHA (g)
F1	Periyar Fault	336	337	4.8	0.002
F2	Vaigai River-Fault	326	326	4.6	0.001
F3	Ottipalam-Kuttampuzah Fault	282	283	4.2	0.001
F6	Valparai-Anaimudi Fault	290	290	4.5	0.002
F9	Pattikkad-kollengol Fault	281	281	6.2	0.009
F10	Cauveri Fault	224	225	5.4	0.007
F13	Crystalline-Sedimentary Contact Fault	243	244	5.3	0.005
F14	Attur Fault	198	199	4.5	0.003
F16	Amirdi Fault	172	172	4.6	0.005
F17	Main Fault	137	138	4.9	0.009
F19	Mettur East Fault	97	98	4.6	0.010
F20	Tirukkavilur Pondicherry Fault	219	220	5.7	0.009
F21	Javadi Hills Fault	162	163	5	0.008
F22	Pambar River Fault	124	125	4.6	0.007
F23	Main Fault	143	144	4.9	0.008
F24		264	264	4.2	0.001
F25	Palar River Fault	175	176	5	0.007
F30	Karkambadi-Swarnamukhi Fault	211	211	5	0.005
F31	Tirumala Fault	216	216	5	0.005
F32	Gulcheru Fault	181	182	4.4	0.003
F35	Papaghani Fault	204	205	4	0.002
F36	Badvel Fault	276	276	4.1	0.001
F41	Wajrakarur Fault	246	247	5.7	0.008
F43	Gani-Kalva Fault	284	284	4.4	0.001
F45	Kumadavati-Narihalli Fault	271	271	6	0.008
F47	Arkavati Fault	51	53	4.7	0.025
F48	Chitradurga Fault	182	183	4.6	0.004
F50	Sakleshpur-Bettadpur Fault	181	182	4	0.002
F52	Bhavani Fault	217	217	6.2	0.015
F65	Cudapah Eastern Magin Shear	269	269	4	0.001
L2	Kabini Lineament	100	101	4.6	0.010
L6	Netravathi Hemavathy Lineament	145	146	4.6	0.006
L9	Yagachi Lineament	173	173	4.6	0.005
L10	Mangalore-Shimoga-Tunga Lineament	251	251	5	0.004
L11	Subramanya-Byadagi Gadag Lineament	235	235	6	0.011
L14	Kunigal-Arkavathi Lineament	44	46	4.1	0.015
L15	Mandya-Channapatna-Bangalore Lineament	5	16	5.1	0.146
L16	Arakavathi-Doddaballapur Lineament	18	24	4.7	0.063
L17	Arkavathi – Madhugiri Lineament	30	33	4.2	0.024
L18	Doddabelvangala-Pavagada Lineament	24	28	4.1	0.026
L20	Chelur-Kolar-Battipalle Lineament	58	60	5.2	0.037
L22	Nelamangala-Shravanabelagula Lineament	26	30	5.3	0.089
L23	Shimoga Lineament	265	265	4.5	0.002
L24	Sorab-Narihalla Lineament	265	266	6	0.009
L25	Vedavathi-Vanivilas Sagar Lineament	158	159	4.6	0.005
L26	Holalkere-Herur Lineament	158	159	6	0.021
L31	Molakalmur-Hospet-Kushtagi- Krishna Lineament	59	61	4	0.010
L34	Sindhnur-Krishna Lineament	55	57	4.2	0.013

for synthetic ground generation along with past earthquake events are shown in Table 3. Seismological model by Boore (1983, 2003) [SMSIM- program for simulating ground motions] is used for generation of synthetic acceleration-time response (Atkinson and Boore 1995, Hwang and Huo 1997). Boore (1983, 2003) gives the details of estimating ground

Table 2. PHA obtained from RLD approach.

	Number and Name of Source	Length (km)	RLD (km)	3.8 (%) TFL	Expected (3.8%) Magnitude (Mw)	Occurred Magnitude (Mw)	Distance (km)	Hypocentral Distance (km)	PHA (g)
F1	Periyar Fault	69	3	3	4.8	4.8	336	337	0.002
F2	Vaigai River-Fault	32	2	1	4.2	4.6	326	326	0.001
F3	Ottipalam-Kuttampuzah Fault	103	1	4	5.1	4.2	282	283	0.003
F6	Valparai-Anaimudi Fault	46	2	2	4.5	4.5	290	290	0.002
F9	Pattikkad-kollengol Fault	42	16	2	4.4	6.2	281	281	0.002
F10	Cauveri Fault	323	6	12	6.0	5.4	224	225	0.012
F13	Crystalline-Sedimentary Contact Fault	222	5	8	5.7	5.3	243	244	0.008
F14	Attur Fault	167	2	6	5.5	4.5	198	199	0.009
F16	Amirdi Fault	100	2	4	5.1	4.6	172	172	0.008
F17	Main Fault	129	3	5	5.3	4.9	137	138	0.013
F19	Mettur East Fault	38	2	1	4.4	4.6	97	98	0.008
F20	Tirukkavilur Pondicherry Fault	67	8	3	4.8	5.7	219	220	0.004
F21	Javadi Hills Fault	90	3	3	5.0	5	162	163	0.008
F22	Pambar River Fault	99	2	4	5.1	4.6	124	125	0.013
F23	Main Fault	82	3	3	5.0	4.9	143	144	0.009
F24		52	1	2	4.6	4.2	264	264	0.002
F25	Palar River Fault	136	3	5	5.3	5	175	176	0.009
F30	Karkambadi-Swarnamukhi Fault	106	3	4	5.1	5	211	211	0.006
F31	Tirumala Fault	48	3	2	4.6	5	216	216	0.003
F32	Gulcheru Fault	22	2	1	4.0	4.4	181	182	0.002
F35	Papaghani Fault	55	1	2	4.6	4	204	205	0.003
F36	Badvel Fault	55	1	2	4.6	4.1	276	276	0.002
F41	Wajrakarur Fault	39	8	1	4.4	5.7	246	247	0.002
F43	Gani-Kalva Fault	144	2	5	5.4	4.4	284	284	0.004
F45	Kumadavati-Narihalli Fault	148	12	6	5.4	6	271	271	0.005
F47	Arkavati Fault	125	2	5	5.3	4.7	51	53	0.047
F48	Chitradurga Fault	79	2	3	4.9	4.6	182	183	0.006
F50	Sakleshpur-Bettadpur Fault	86	1	3	5.0	4	181	182	0.006
F52	Bhavani Fault	90	16	3	5.0	6.2	217	217	0.005
F65	Cudapah Eastern Magin Shear	94	1	4	5.1	4	269	269	0.004
L2	Kabini	130	2	5	5.3	4.6	100	101	0.021
L6	Netravathi Hemavathy	169	2	6	5.5	4.6	145	146	0.015
L9	Yagachi	102	2	4	5.1	4.6	173	173	0.008
L10	Mangalore-Shimoga-Tunga	134	3	5	5.3	5	251	251	0.005
L11	Subramanya-Byadagi Gadag	318	12	12	6.0	6	235	235	0.011
L14	Kunigal-Arkavathi	101	1	4	5.1	4.1	44	46	0.045
L15	Mandya-Channapatna-Bangalore	105	4	4	5.1	5.1	5	16	0.146
L16	Arakavathi-Doddaballapur	109	2	4	5.2	4.7	18	24	0.107
L17	Arkavathi-Madhugiri	156	1	6	5.4	4.2	30	33	0.089
L18	Doddabelvangala-Pavagada	125	1	5	5.3	4.1	24	28	0.096
L20	Chelur-Kolar-Battipalle	111	4	4	5.2	5.2	58	60	0.037
L22	Nelamangala-Shravanabelagula	130	5	5	5.3	5.3	26	30	0.089
L23	Shimoga	130	2	5	5.3	4.5	265	265	0.004
L24	Sorab-Narihalla	249	12	9	5.8	6	265	266	0.007
L25	Vedavathi-Vanivilas Sagar	163	2	6	5.5	4.6	158	159	0.013
L26	Holalkere-Herur	172	12	7	5.5	6	158	159	0.013
L31	Molakalmur-Hospet-Kushtagi-Krishna	190	1	7	5.6	4	59	61	0.054
L34	Sindhnur-Krishna	223	1	8	5.7	4.2	55	57	0.064

motion based on the Fourier amplitude spectrum of acceleration at bedrock and this is expressed as:

$$A\left(f\right)=C\left[S\left(f\right)\right]D\left(f\right)P\left(f\right) \tag{4}$$

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 fm, and C is a scaling factor. In the present study, the single corner frequency model has been used (Brune, 1970) and the following regional seismotectonic parameters are considered to generate the synthetic ground motion:

– Source region Shear wave velocity = 2.7 km/s (Parvez et.al, 2003)

– $Q(f)$=488 $f^{0.88}$

– The diminution function $D(f)$ is defined as

$$D\left(f\right)=G\exp\left[-\Pi f R/V_S Q\left(f\right)\right] \tag{5}$$

In which, G refers to the geometric attenuation and the other term to an elastic attenuation. In this Eq. $Q(f)$ is the quality factor of the region. For Southern Indian region, Rao et al. (1998) used strong motion records of small magnitude

Table 3. Sources used for synthetic ground motion generation.

	Number and Name of Source	Length (km)	RLD (km)	3.8 (%) TFL	Distance (km)	Hypocentral Distance (km)	Expected (3.8%) Magnitude (Mw)	PHA (g)	Occurred Magnitude (Mw)	PHA (g)
F19	Mettur East Fault	38	2	1	97	98	4.4	0.008	4.6	0.010
F47	Arkavati Fault	125	2	5	51	53	5.3	0.047	4.7	0.025
L11	Subramanya-Byadagi Gadag	318	12	12	235	235	6.0	0.011	6	0.011
L15	Mandya-Channapatna-Bangalore	105	4	4	5	16	5.1	0.146	5.1	0.146
L16	Arakavathi-Doddaballapur	109	2	4	18	24	5.2	0.107	4.7	0.063
L20	Chelur-Kolar-Battipalle	111	4	4	58	60	5.2	0.037	5.2	0.037
L22	Nelamangala-Shravanabelagula	130	5	5	26	30	5.3	0.089	5.3	0.089
L26	Holalkere-Herur	172	12	7	158	159	5.5	0.013	6	0.021

Table 4. PHA obtained from synthetic ground motion model.

	Number and Name of Source	Length (km)	Distance (km)	Maximum (expected) Magnitude (Mw)	Hypocentral Distance (km)	PHA (g) (g)
F19	Mettur East Fault	38	97	4.6	98	0.005
F47	Arkavati Fault	125	51	4.7	53	0.014
L11	Subramanya-Byadagi Gadag	318	235	6	235	0.012
L15	Mandya-Channapatna-Bangalore	105	5	5.1	16	0.136
L16	Arakavathi-Doddaballapur	109	18	5.2	24	0.085
L20	Chelur-Kolar-Battipalle	111	58	5.2	60	0.022
L22	Nelamangala-Shravanabelagula	130	26	5.3	30	0.064
L26	Holalkere-Herur	172	158	6	159	0.020

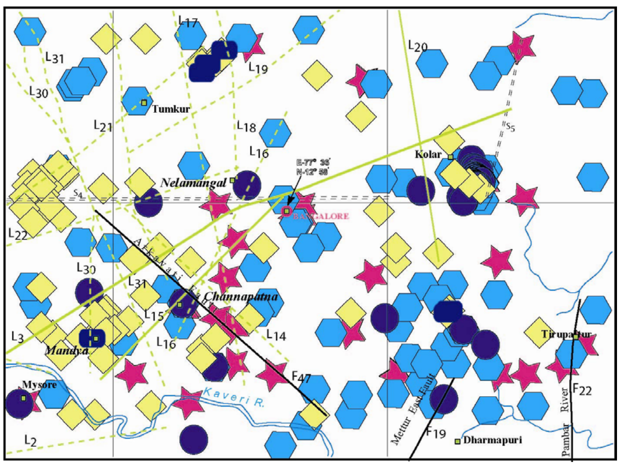

Fig. 6. Closer view of surroundings of Bangalore in seismotectonic map.

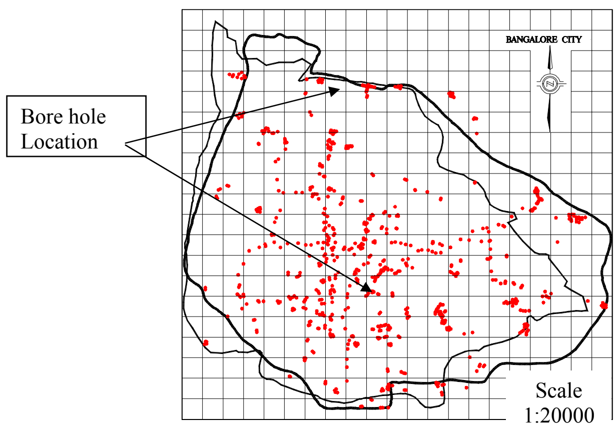

Fig. 7. Borehole locations in Bangalore.

earthquakes and estimated Q value to be $460 f$ 0.83 (after Iyengar and Raghukanth, 2004). However, for Bangalore region, Tripathi and Ugalde (2004) developed Q factor by using seismic array from the Gauribidanur seismic recording station that is about 85 km from Bangalore, They estimated and reported for the different frequency range of 1 Hz to 10 Hz. For Bangalore, the natural frequency is in the range of 3 to 6 Hz and the corresponding Q value is $488 f$ 0.88 (Tripathi and Ugalde, 2004). The strong motion data has been simulated for 8 sources. PHA obtained from the model is shown in Table 4. The PHA varies from 0.005 g to 0.136 g. The active lineament – L15 gives the highest PHA value of 0.136 g for the hypocentral distance of 15.88 km. The response spectrums for the simulated ground motions

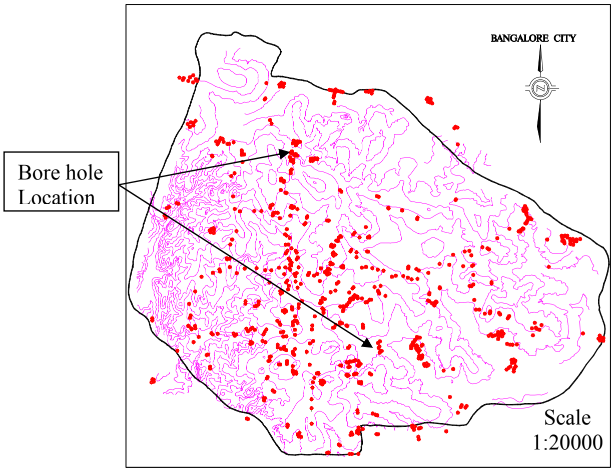

Fig. 8. Contours map of Bangalore.

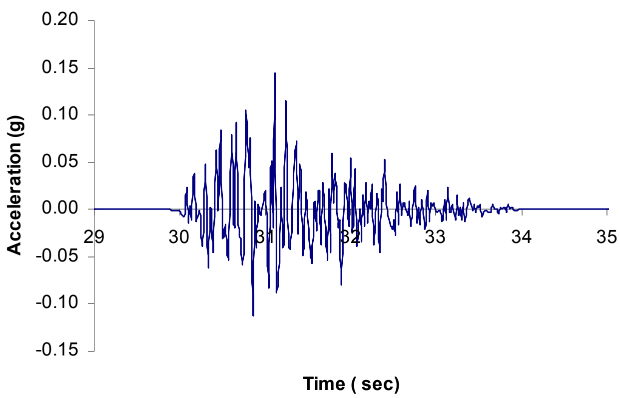

Fig. 9. Synthetic ground motion generated from Mandya-Channapatna-Bangalore lineament (L15).

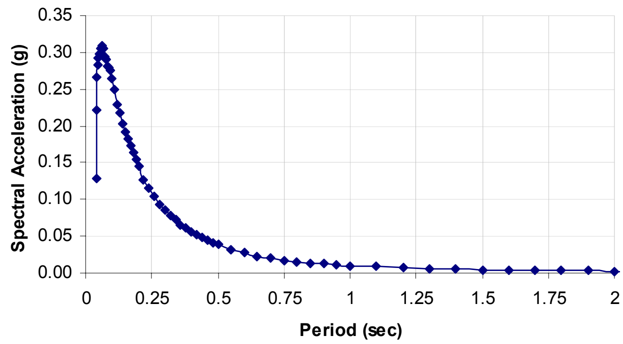

Fig. 10. Rock level spectral acceleration from synthetic ground motion.

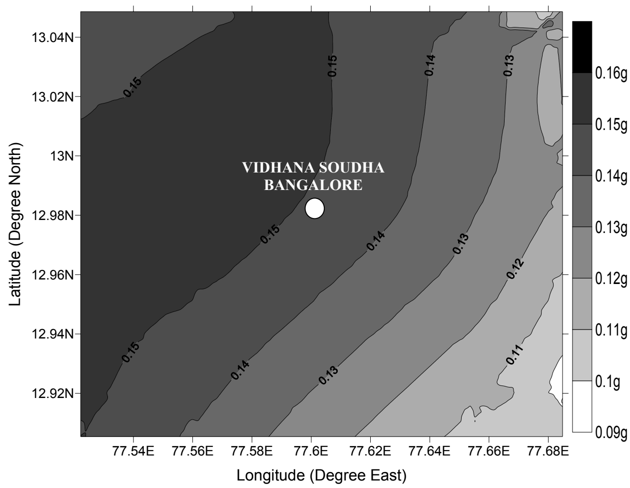

Fig. 11. Rock level PHA map of Bangalore.

are plotted; it shows that the predominant period of synthetic ground motion is 0.06 seconds irrespective of the magnitude and sources. Further, PHA obtained from the model for the L15 matches well with the PGA values from both the above approaches. The synthetic ground motion for Mandya-Channapatna-Bangalore lineament (L15) is shown in Fig. 9. Rock level spectral acceleration for Mandya-Channapatna-Bangalore lineament (L15) is shown in Fig. 10.

8 Development of rock level PHA map

From the above three approaches the highest PGA value for the Bangalore is obtained from the Mandya-Channapatna-Bangalore lineament (L15) for the past earthquake of 5.1 moment magnitude. It clearly indicates that the maximum credible earthquake for the region is 5.1 in moment magnitude and vulnerable source is active lineament of Mandya-Channapatna-Bangalore lineament (L15). Further an attempt has been made to map the rock level PHA considering the Mandya-Channapatna-Bangalore lineament (L15) as the source. The rock level PHA has been calculated using rock depth information from geotechnical data (using 653 bore holes dug for geotechnical investigations). The lineament L15 location is superimposed with borehole locations. The shortest distance between the each borehole to the lineament has been measured. Using the depth of 15 km and shortest distance, the hypocenter distance of each bore log is evaluated. The PHA due to the MCE of 5.1 from the vulnerable source of L15 has been evaluated. The rock level PHA map has been prepared and it is shown in Fig. 11. The rock level PHA map will be useful for the microzonation and site response studies of Bangalore region.

9 Conclusions

The remote sensing data has been used to identify lineaments in the area. These lineaments were integrated with the seimotectonic details of the mapped structures available in the seismotectonic atlas and past earthquake events. Deterministic seismic hazard analysis has been carried out considering all the sources in an area of 350 km around Bangalore and the past earthquake events. The PHA at base rock level has been calculated by using an appropriate attenuation relation by assigning the maximum reported earthquake to the source and also by assuming the subsurface rupture length (RLD is 3.8% of total fault length). The highest PHA value (0.146 g) is attributed to the source Mandya-Channapatna-Bangalore lineament (L15) and it is considered to be the vulnerable source for Bangalore. The earthquake event of Mw of 5.1 is considered as MCE for the Bangalore (which occurred on 16 May 1972; corresponds to a latitude of 12.4° N and longitude of 77.0° E) and this event was a measured/recorded earthquake event with surface wave magnitude (Ms) of 4.6. The synthetic ground motion has been generated using regional seismotectonic parameters for the different identified sources. The source Mandya-Channapatna-Bangalore lineament gives the highest PHA value of 0.136 g for MCE of 5.1. The synthetic ground motion and spectral acceleration has been generated and the shape of the spectral acceleration matches with the shape of uniform hazard spectrum. The rock level PHA map has been prepared and such maps will be of use for the purpose of seismic microzonation, ground response analysis and design of important structures. From this study, it is very clear that Bangalore area can be described as seismically moderately active region. This study clearly demonstrates the potential for moderate earthquakes that can affect Bangalore and its vicinity. It is also recommended that southern part of Karnataka in particular Bangalore, Mandya and Kolar, need to be upgraded from current Indian Seismic Zone II to Seismic Zone III.

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