Seismic microzonation of Bangalore, India

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In the present study, an attempt has been made to evaluate the seismic hazard considering local site effects by carrying out detailed geotechnical and geophysical site characterization in Bangalore, India to develop microzonation maps. An area of 220 km^2, encompassing Bangalore Mahanagara Palike (BMP) has been chosen as the study area. Seismic hazard analysis and microzonation of Bangalore are addressed in three parts: in the first part, estimation of seismic hazard is done using seismotectonic and geological information. Second part deals with site characterization using geotechnical and shallow geophysical techniques. In the last part, local site effects are assessed by carrying out one-dimensional (1-D) ground response analysis (using the program SHAKE2000) using both standard penetration test (SPT) data and shear wave velocity data from multichannel analysis of surface wave (MASW) survey. Further, field experiments using microtremor studies have also been carried out for evaluation of predominant frequency of the soil columns. The same has been assessed using 1-D ground response analysis and compared with microtremor results. Further, the Seed and Idriss simplified approach has been adopted to evaluate the soil liquefaction susceptibility and liquefaction resistance assessment. Microzonation maps have been prepared with a scale of 1:20,000. The detailed methodology, along with experimental details, collated data, results and maps are presented in this paper.

1. Introduction

Evaluation of seismic hazards and microzonation of cities enable us to characterize the potential seismic areas which have similar exposures to hazards of earthquakes, and these results can be used for designing new structures or retrofitting the existing ones. Study of seismic hazard and preparation of microzonation maps will provide an effective solution for city planning and earthquake resistant design of structures in an area. Seismic hazard is the study of expected earthquake ground motions at any point on the earth. Microzonation is the process of subdivision of a region into a number of zones based on the earthquake effects in a local scale. Seismic microzonation is the process of estimating response of soil layers under earthquake excitation and thus the variation of ground motion characteristics on the ground surface. Geotechnical site characterization and assessment of site response during earthquakes is one of the crucial phases of seismic microzonation, which includes ground shaking intensity, amplification and liquefaction susceptibility. Microzonation mapping of seismic hazards can be expressed in relative or absolute terms, on an urban block-by-block scale, based on local soil conditions (such as soil types) that affect ground shaking levels or vulnerability to soil liquefaction (Sitharam *et al* 2001 and Govinda Raju *et al* 2004). These maps would provide general guidelines for integrated planning of cities and design of new structures that are most suited to an area, along with information on the relative damage potential of the existing structures in a region.

Earthquake damage is commonly controlled by three interacting factors – source and path

Keywords. Seismic hazard; site characterization; SPT; MASW; ground response analysis; liquefactions; Microzonation.

characteristics, local geological and geotechnical conditions and type of structures. Obviously, all of this would require analysis and presentation of a large amount of geological, seismological and geotechnical data. History of earthquakes, faults/sources in the region, attenuation relationships, site characteristics, soil physical and engineering properties are few of the important inputs required. Microzonation has generally been recognized as the most accepted tool in seismic hazard assessment and risk evaluation and it is defined as the zonation with respect to ground motion characteristics taking into account source and site conditions (TC4-ISSMGE 1999). Microzonation of a region gives detailed information of seismic hazard of the study area in a larger scale to improve the conventional macrozonation maps and regional seismic zonation maps. Damage patterns of many recent earthquakes around the world, including the 1999 Chamoli and 2001 Bhuj earthquakes in India, have demonstrated that the soil conditions at a site can have a major effect on the level of ground shaking. For example, in the Chamoli earthquake, epicenter located at more than 250 km away from Delhi caused moderate damage to some of the buildings built on filled-up soil or on soft alluvium. The Bhuj earthquake caused severe damage not only in the epicentral region, but even in Ahmedabad, about 250 km away, which attributed to increased ground shaking of the soft alluvium. Department of Science and Technology on a mission mode has taken up 63 cities microzonation of urban centers and Bangalore is one of them (Bansal and Vandana 2007). Bangalore is also vulnerable against average earthquakes, because of the density of population, mushrooming of buildings of all kinds from mud buildings to RCC framed structures and steel construction with improper and low quality construction practice and erected structures on the filled up soil (Sitharam *et al* 2006; Sitharam and Anbazhagan 2007). Hence it is necessary to understand the effects of local site conditions on earthquake hazards and in this study it is attempted to carry out microzonation of Bangalore urban centre.

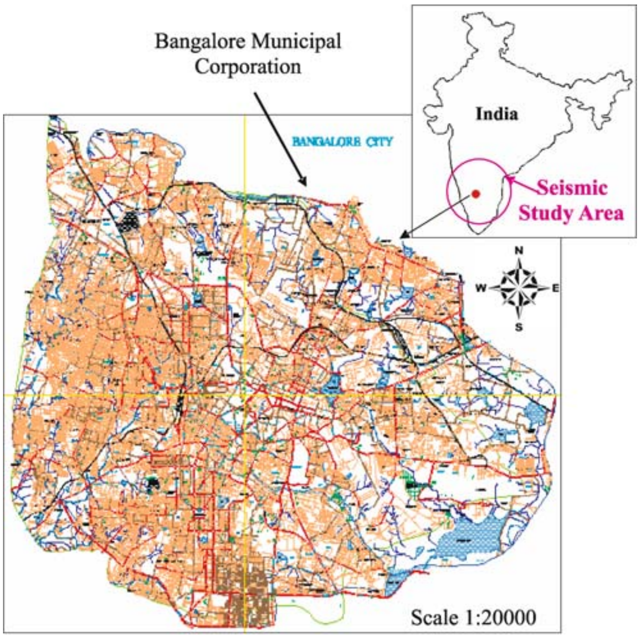

Figure 1. Study area with India map.

2. General setting of the study area

Bangalore city covers an area of approximately 696.17 km^2 (Greater Bangalore). The study area is limited to Bangalore Metropolis area (Bangalore Mahanagara Palike, BMP) covering an area of about 220 km^2. Bangalore is situated at a latitude of 12°58′ north and longitude of 77°36′ east with an average altitude of about 910 m above mean sea level (MSL). It is the principal administrative, industrial, commercial, educational and cultural capital of Karnataka state and lies in the south-western part of India (see figure 1). Bangalore city is the fastest growing city and fifth biggest city in India. Besides political activities, Bangalore possesses many national laboratories, defence establishments, small and large-scale industries and Information Technology Companies. It experiences temperate, salubrious climate and an annual rainfall of around 940 mm. There were over 150 tanks, though most of them have dried up due to silting up and encroachments leaving only 64 tanks at present in an area of 220 km^2. These tanks once distributed water throughout the city for better water supply but are presently in a dried-up condition and have been encroached for construction of residential/industrial buildings. The tank beds have silty clay and silty sand with filled-up soil above, over which buildings/structures have been built (Sitharam *et al* 2006; Sitharam and Anbazhagan 2007).

3. Geology and geomorphology

Bangalore city lies over a hard and moderately dense gneissic basement dated back to the Archean era (2500–3500 mya). A large granitic intrusion in the south central part of the city extends from the Golf Course in the north central to Vasantpur (VV Nagar) in the south of the city (almost 13 km in length) and on an average 4 km from east to west along the way. A magmatite intrusion formed within the granitic one extends for approximately 7.3 km running parallel with Krishna Rajendra

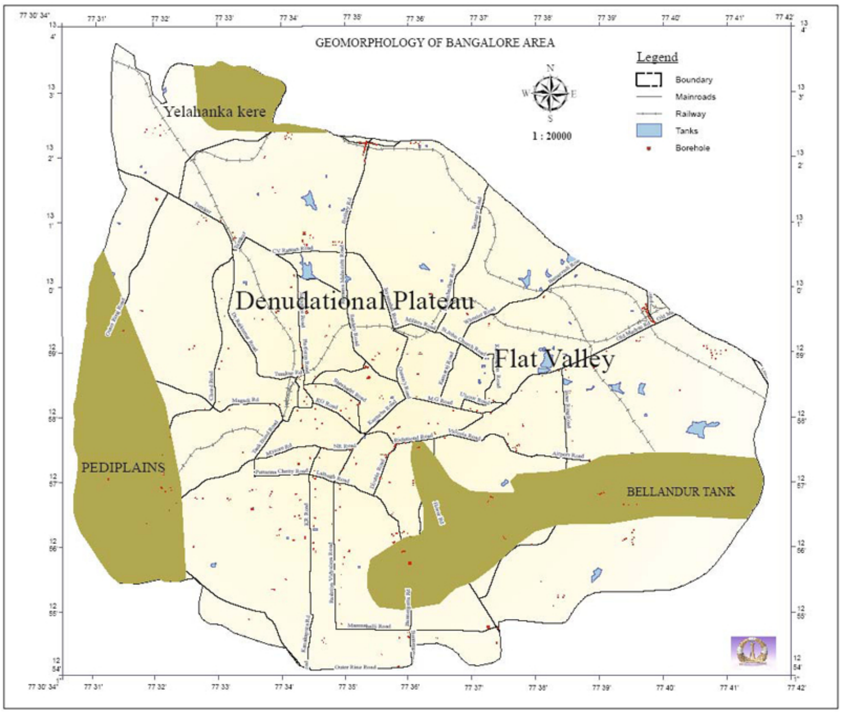

Figure 2. Geomorphology of Bangalore area.

road/Kanakpura road from Puttanna Chetty road in Chamrajpet till Bikaspura road in the south. These basic intrusions which mark the close of the Archean era (Lower Proterozoic; 1600–2500 mya) mainly constitute hard massive rocks such as Gabbro, Dolerite, Norite and Pyroxenite.

Bangalore city lies within the south pennar basin. The Vrishabhavathi, a minor tributary of the Arkavati leaves the city almost diagonally from the southwest (Kengeri). On entering, it branches off giving rise to the Nagarbhavi Thorai at the intersection of the Mysore Road and the Bangalore University Road. The river Arkavati branches north from Cauvery, most probably due to some structural control imposed by presently active faults and other north-south trending lineaments in its course. The river Ponnaiyar enters the city from the southeast and branches into two, one stream terminates in the Bellandur Lake, whereas the other continues towards northwest. The basic geomorphology of the city comprises of a central denudational plateau and pediment (towards the west) with flat valleys that are formed by the present drainage patterns (see figure 2). The central denudational plateau is almost void of any topology and the erosion and transportation of sediments carried out by the drainage network gives rise to the lateritic clayey alluvium seen throughout the central area of the city. The pediment/pediplain is a low relief area that abruptly joins the plateau. The area might have uplifted along active lineaments and may have been eroded by the river Arkavati and its subtributaries. The resulting alluvial fan deposits have been deposited or transported along the waterways.

4. Seismotectonic map of the area

A critical part of seismic hazard analysis is the determination of Peak Ground Acceleration (PGA) and response acceleration (spectral acceleration) for an area/site. Seismic hazard analysis and determination of PGA are very important steps for assessing the earthquake force to the 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. For seismic hazard assessment of the study area, seismotectonic details have been collected covering 350 km radius around the city and this is called as the seismic study area (see figure 1) as per the Regulatory Guide 1.165 (1997).

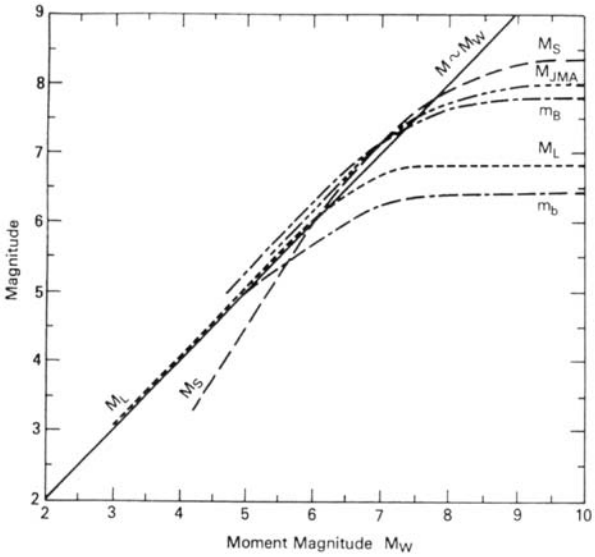

Figure 3. A comparison of moment magnitude with other magnitude scales (after Heaton *et al* 1986).

The seismic study area having the center point as Bangalore city (with latitude of 12°58″N and longitude of 77°36″E) has a radius of 350 km (which covers the latitude 9.8°N to 16.2°N and longitude of 74.5°E to 80.7°E). Study area covers major part of Karnataka, northern part of Tamil Nadu, portion of Kerala and Andhra Pradesh. A new seismotectonic map has been prepared by considering all the earthquake sources such as faults, lineaments, and shear zones. Regional, geological and seismological details have been collected by using available literature, study of maps, remote sensing data, which includes details of geology, rock type, fault orientation with length, lineaments with lengths, shear zones with length and seismic events. The seismic sources in the region have been collected by considering seismotectonic atlas map of India and lineaments identified from satellite remote sensing images. The seismic sources are mapped based on Seismotectonic atlas (SEISAT 2000) and lineaments mapped by Ganesha Raj and Nijagunappa (2004) (Sitharam *et al* 2007 and Sitharam and Anbazhagan 2007). Earthquake data collected from different agencies [United State Geological Survey (USGS), India Meteorological Department (IMD), BARC Gauribidanur station, Geological Survey of India (GSI) and Amateur Seismic Centre (ASC)] contain information about the earthquake size in different scales such as intensity, local magnitude, surface wave magnitude and body wave magnitudes. Earthquake data in different scales are converted to moment magnitude

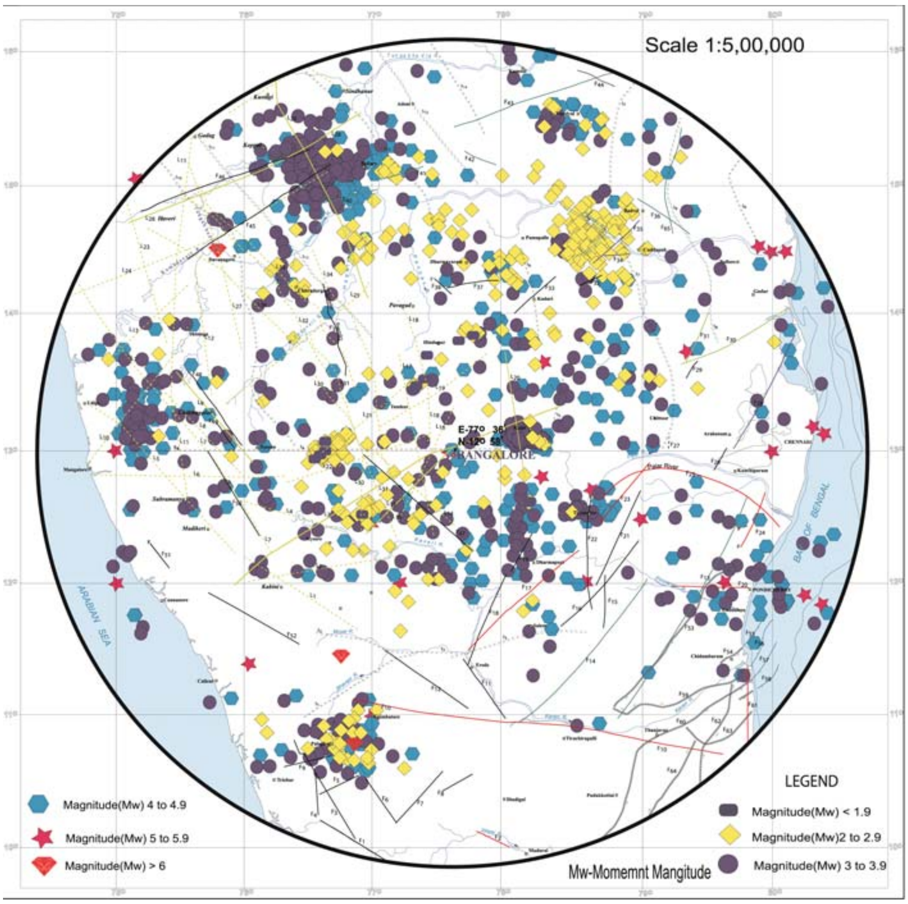

Figure 4. Seismotectonic map for Bangalore region.

(M_w) to achieve the status of the uniform magnitude by using magnitude relations given by Heaton *et al* (1986) (see figure 3). These sources and earthquake data were coupled with Adobe Illustrator version 9.0 to prepare a new seismotectonic map for Bangalore region. Seismotectonic map for Bangalore is shown in figure 4, which consists of 65 numbers of faults with length varying from 9.73 km to 323.5 km, 34 lineaments and 14 shear zones. The earthquake events mapped consist of 1421 events with minimum moment magnitude of 1.0 and a maximum of 6.2. The spatial distribution of earthquake magnitudes of the study area is shown in figure 4. The dataset contains 394 events which are less than moment magnitude 3, 790 events from 3 to 3.9, 212 events from 4 to 4.9, 22 events from 5 to 5.9 and three events which are more than moment magnitude 6. The recent seismic activity of Bangalore has been studied based on the seismic sources and earthquake events in the area.

5. Methodology

Methodology for complete seismic microzonation of the study area is formulated by considering the topology, geology, geomorphology and possible hazards during the earthquakes. The earthquake damage basically depends on three groups of factors: earthquake source and path characteristics, local geological and geotechnical site conditions, structural design and construction features. Seismic microzonation should address the assessment of the first two groups of factors. In general terms, seismic microzonation is the process of estimating the response of soil layers for earthquake excitations and thus the variation of earthquake characteristics is represented on the ground surface. For the present investigation the seismic microzonation has been subdivided into three major items:

- Evaluation of the expected input motion,
- Local site effects and ground response analysis,
- Preparation of microzonation maps.

The microzonation is graded based on the scale of the investigation and details of the study carried out. The technical committee on earthquake geotechnical engineering (TC4) of the International Society of Soil Mechanics and Foundation Engineering (TC4-ISSMGE 1999) highlighted that the first grade (Level I) map can be prepared with a scale of 1:1000,000–1:50,000 and the ground motion was assessed based on the historical earthquakes and existing information of geological and geomorphological maps. If the scale of the mapping is 1:100,000–1:10,000 and ground motion is assessed based on the microtremor and simplified geotechnical studies then it is called second grade (Level II) map. In the third grade (Level III) map ground motion has been assessed based on the complete geotechnical investigations and ground response analysis with a scale of 1:25,000–1:5000. The present investigation was carried out with a scale of 1:20,000 and ground motion is arrived based on the detailed geotechnical/geophysical investigations and ground response analysis. Hence this work can be graded as third grade (Level III) microzonation maps for Bangalore. As the study area has fairly flat ground in most of the area except in north and northwestern parts of Bangalore, possibility of a landslide is considered remote. Bangalore is situated at 910 m above mean sea level, there is no possibility of tsunami. The steps formulated for seismic hazard and microzonation of Bangalore in the present investigation is illustrated in the form of a flow chart in figure 5. These steps can also be adopted for flat terrain where possibility of landslide and tsunami are remote.

6. Seismic hazard analysis

Deterministic seismic hazard analysis (DSHA) for Bangalore has been carried out by considering past earthquakes, assumed subsurface fault rupture lengths and point source synthetic ground motion model. Maximum Credible Earthquake (MCE) has been determined by considering the regional seismotectonic activity in about 350 km radius around Bangalore. Source magnitude for each source is chosen from the maximum reported past earthquake close to that source and shortest distance from each source to Bangalore is arrived from the newly prepared seismotectonic map. Using these details and regional attenuation relation developed for southern India by Iyengar and Raghukanth (2004), the peak ground acceleration (PGA) has been estimated. To estimate the expected magnitude for seismic source, a parametric study has been carried out to find subsurface rupture length of the fault using past earthquake data and Wells and Coppersmith (1994) relation between the subsurface lengths *versus* earthquake magnitudes. About more than 60% of earthquake magnitude matches with the subsurface length corresponding to 3.8% of the total length of fault. The expected maximum magnitude for each source has been evaluated by assuming that the seismic source may rupture at subsurface level for a length of 3.8% of the total length of source. The PGA for Bangalore has been estimated using expected magnitudes and regional attenuation relation. Further seismological model developed by Boore (1983,

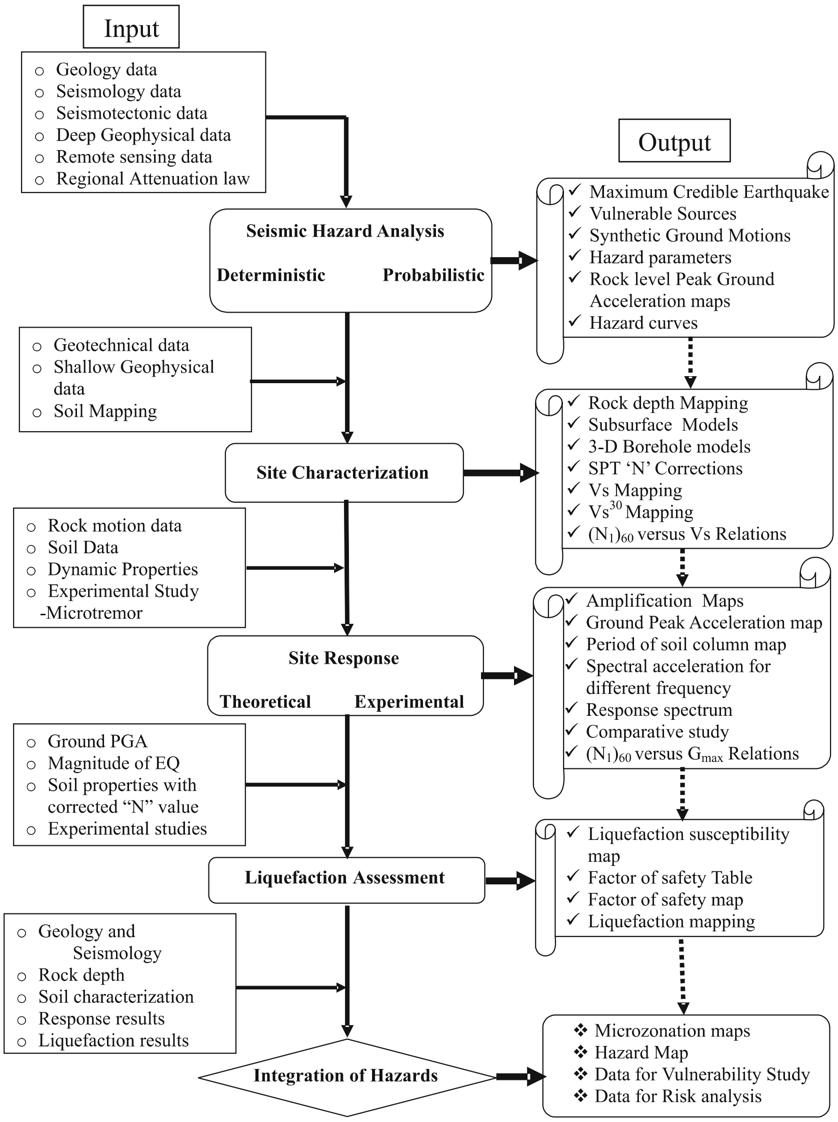

Figure 5. Steps followed for seismic hazard and microzonation.

2003), SMSIM program, has been used to generate synthetic ground motions for sources resulting in higher PGA in the above two methods:

1) using regional attenuation equation and largest earthquake close to source, and,
2) using regional attenuation equation and expected maximum magnitude arrived by assuming subsurface rupture length.

The seismic sources (8 numbers) causing considerable PGA value from the methods I and II, are further used for generating the synthetic ground motions.

6.1 *Synthetic earthquake model and peak ground acceleration map*

For microzonation, the study of local site effects needs to be carried out for a scenario earthquake estimated in the seismic hazard analysis. To study the local site effects of earthquake in the local scale level, the scenario earthquake record/ground motion in the form of time series is required. For the area having limited seismic record, synthetic ground motion models is the alternative (as the study area lacks ground motion records). Modeling of strong motion helps to estimate future hazard of the region and study the local soil effects in local scale. For south India, Iyengar and Raghukanth (2004) have developed ground motion attenuation relation based on the statistically simulated seismological model. Seismological model by Boore (1983) is used for generation of synthetic acceleration-time response (Atkinson and Boore 1995; Hwang and Huo 1997). In this study eight seismic sources are used to generate synthetic ground motions. Boore (1983, 2003) gives the details of estimating ground motion based on

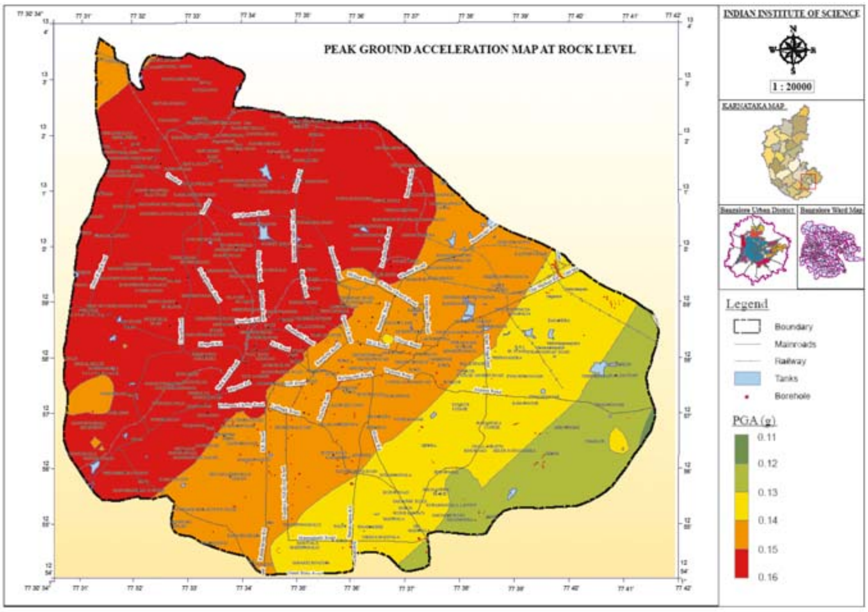

Figure 6. Rock level peak ground acceleration map.

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

$$A(f) = C[S(f)]D(f)P(f), \quad (1)$$

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. For south Indian region, Iyengar and Raghukanth (2004) used Q value of $460f^{0.83}$ based on strong motion records of small magnitude earthquakes. 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 to 10 Hz. For Bangalore, the natural frequency is in the range of 3 to 6 Hz and the corresponding Q value of $488f^{0.88}$ (Tripathi and Ugalde 2004) is considered.

The synthetic ground motion and spectral acceleration at rock level for 8 seismic sources are developed by considering expected magnitude and hypocentral distance along with the above regional seismic hazard parameters. The PGA values obtained from synthetic ground motion model using regional seismotectonic parameters varies from 0.005 g to 0.136 g. The lineament L15 gives the highest PGA value of 0.136 g by taking hypocentral distance of 15.88 km. Further, PGA obtained from the model for the L15 matches well with the PGA values from both the above approaches. The generated spectral acceleration shape matches with the shape of uniform hazard spectrum. Further rock level PGA is estimated considering the Mandya–Channapatna–Bangalore lineament (L15) as the source and maximum credible earthquake of 5.1 in moment magnitude. Using these PGA values, rock level PGA map has been prepared and is shown in figure 6. From the above three approaches maximum PGA of about 0.15 g was estimated for Bangalore. To identify PGA/hazard values at the specific location at rock level, the PGA can be used.

7. Geotechnical data

For the complete microzonation and site response study of the area, the subsurface soil characterization has to be carried out. This section presents the subsurface soil characterizations of Bangalore using geotechnical boreholes along with SPT 'N' values with depth. The geotechnical data were collected from archives of Torsteel Research Foundation, Bangalore and Indian Institute of Science, Bangalore. Bangalore city (220 km^2) base map has been generated in the scale of 1:20,000 with several layers of information (such as outer and administrative boundaries, contours, highways, major roads, minor roads, streets, rail roads, water bodies, drains, landmarks and borehole locations) using Geographical Information System (GIS). Base map with drainage and water body along with borehole information is shown in figure 7. The GIS model developed currently consists of 850 borehole locations marked on the digitized

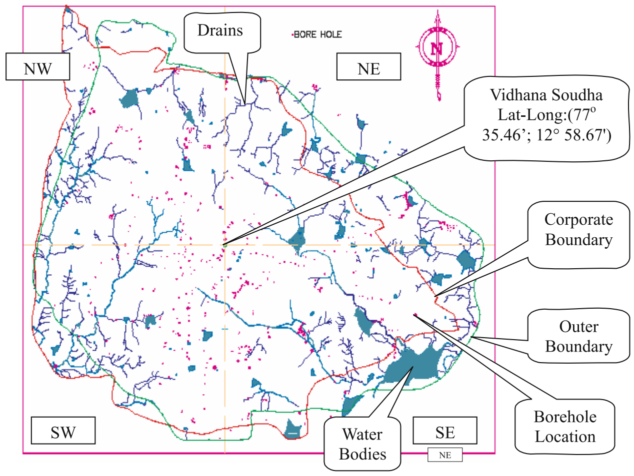

Figure 7. GIS model of borehole locations along with water body features.

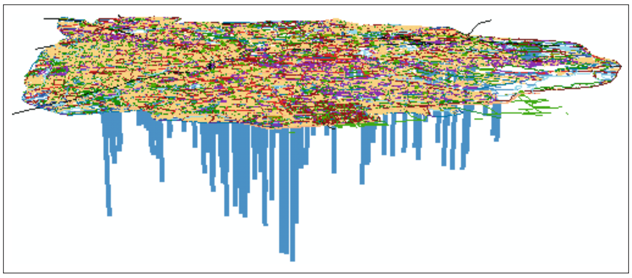

Figure 8. GIS model of borehole locations in 3-D view.

Bangalore map (see figure 7). The 3-D subsurface model with geotechnical data has been generated with base map. The boreholes are represented as 3-dimensional objects projecting below the base map layer up to the available borehole depth, geotechnical properties are represented as layers at 0.5 m intervals with density, SPT 'N' values, index properties, etc. Each borehole in this model is attached with a geotechnical data *versus* depth. Also scanned image files of borelogs and properties table are attached to the location in plan. The data consist of visual soil classification, standard penetration test results, ground water level, time during which test has been carried out, and other physical and engineering properties of soil. The model provides two options to view the data at each borehole,

- visualize the soil characteristics as colored layer with depth information along with properties in excel format and
- bore logs and properties as an image file.

From this 3-D geotechnical model, geotechnical information on any borehole at any depth can be obtained at every 0.5 m interval by clicking at that level (donut). Figure 8 shows the view of boreholes below Bangalore city map. For the purpose of general identification of soil layers in the study area, a generalized classification of soils has been done and it is presented in table 1.

7.1 *SPT 'N' corrections*

The 'N' values measured in the field using standard penetration test procedure have been corrected for various corrections, such as: (a) Overburden Pressure (C_N), (b) Hammer energy (C_E), (c) Borehole diameter (C_B), (d) presence or absence of liner (C_S), (e) Rod length (C_R) and (f) fines content (C_{fines}) (Seed *et al* 1983, 1985; Youd *et al* 2001; Cetin *et al* 2004; Pearce and Baldwin 2005). Corrected 'N' value, *i.e.*, $(N_1)_{60}$ are obtained using the following equation:

$$(N_1)_{60} = N \times (C_N \times C_E \times C_B \times C_S \times C_R). \quad (2)$$

The corrected 'N' value $(N_1)_{60}$ is further corrected for fine content based on the revised boundary

Table 1. *General soil profile distribution in Bangalore.*

	Soil description with depth and direction			
Layer	Northwest	Southwest	Northeast	Southeast
First layer	Silty sand with clay 0–3 m	Silty sand with gravel 0–1.7 m	Clayey sand 0–1.5 m	Filled up soil 0–1.5 m
Second layer	Medium to dense silty sand 3–6 m	Clayey sand 1.7–3.5 m	Clayey sand with gravel 1.5–4 m	Silty clay 1.5–4.5 m
Third layer	Weathered rock 6–17 m	Weathered rock 3.5–8.5 m	Silty sand with gravel 4–15.5 m	Sandy clay 4.5–17.5 m
Fourth layer	Hard rock below 17 m	Hard rock below 8.5 m	Weathered rock 15.5–27.5 m	Weathered rock 17.5–38.5 m
Fifth layer	Hard rock	Hard rock	Hard rock below 27.5 m	Hard rock below 38.5 m

curves presented by Idriss and Boulanger (2004) for cohesionless soils as described below:

$$(N_1)_{60cs} = (N_1)_{60} + \Delta(N_1)_{60}, \quad (3)$$

$$\Delta(N_1)_{60} = \exp\left[1.63 + \frac{9.7}{FC+0.001} - \left(\frac{15.7}{FC+0.001}\right)^2\right], \quad (4)$$

FC = per cent fine content (per cent dry weight finer than 0.074 mm).

A typical 'N' corrected table generated for a borehole data is shown in table 2.

8. Measurement of shear wave velocity using MASW

In this section the site characterization of the study area using the shallow geophysical technique is described. Multichannel analysis of surface wave (MASW) is a geophysical method, which identifies each type of seismic wave on a multichannel record using the refraction survey and produces shear-wave velocity (V_s) profiles. Test locations are selected based on three criteria:

- To sample the range of soil types and conditions,
- To have a flat ground surface free from noise, and,
- Important places.

About 58 one-dimensional (1-D) MASW surveys and 20 two-dimensional (2-D) MASW surveys have been carried out within 220 km^2 BMP area (see figure 9). MASW system consisting of 24 channels Geode seismograph with 24 geophones of 4.5 Hz capacity have been used for measuring shear wave velocity. The seismic waves are created by impulsive source of 15 pound (sledge hammer) with 300 × 300 mm size hammer plate with ten shots. The captured Rayleigh wave is further analyzed using SurfSeis software. A least-squares approach allows automation of the process (Xia *et al* 1999) which is inbuilt in SurfSeis. SurfSeis is designed to generate V_s data (either in 1-D or 2-D format) using a simple three-step procedure:

- preparation of a multichannel record (some times called a shot gather or a field file),
- dispersion-curve analysis, and,
- inversion.

The recorded seismic waves are further used to generate a dispersion curve, which is generally

Table 2. *Typical 'N' correction table for a borelog.*

Borehole											Water table = 1.4 m/19-11-2005		
						Correction factors for							
Depth (m)	Field N value	Density (kN/m^3)	TS (kN/m^2)	ES (kN/m^2)	C_N	Hammer effect	Borehole Dia	Rod length	Sample method	$(N_1)_{60}$	FC %	$\Delta(N_1)_{60}$	Corrected N value $(N_1)_{60cs}$
1.50	19	20.00	30.00	30.00	1.47	0.7	1.05	0.75	1	15.36	48	5.613	21
3.50	28	20.00	70.00	50.38	1.29	0.7	1.05	0.8	1	21.26	43	5.597	27
4.50	26	20.00	90.00	60.57	1.22	0.7	1.05	0.85	1	19.79	60	5.602	25
6.00	41	20.00	120.00	75.86	1.12	0.7	1.05	0.85	1	28.77	48	5.613	34
7.50	55	20.00	150.00	91.14	1.04	0.7	1.05	0.95	1	40.02	37	5.541	46
9.00	100	20.00	180.00	106.43	0.97	0.7	1.05	0.95	1	67.84	28	5.270	73
10.50	100	20.00	210.00	121.71	0.91	0.7	1.05	1	1	66.90	28	5.270	72
12.50	100	20.00	250.00	142.09	0.84	0.7	1.05	1	1	61.70	28	5.270	67

Note: TS – Total stress; ES – Effective stress; C_N – Correction for overburden correction; $(N_1)_{60}$ – Corrected 'N' value before correction for fines content; FC – Fines content; $\Delta(N_1)_{60}$ – Correction for fines content; and $(N_1)_{60cs}$ – Corrected 'N' value.

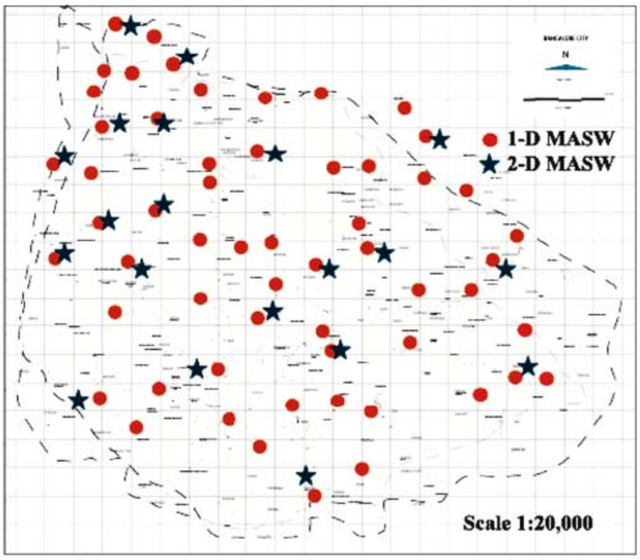

Figure 9. MASW testing locations in Bangalore.

displayed as a function of phase velocity *versus* frequency. Phase velocity can be calculated from the linear slope of each component on the swept-frequency record. Dispersion curves and shear velocity profiles in 1-D and 2-D have been evaluated using SurfSeis software.

8.1 *Site classification*

The seismic site characterization for calculating seismic hazard is usually carried out based on the near-surface shear wave velocity values. The average shear wave velocity for the depth '*d*' of soil, referred as V_H, is computed as follows:

$$V_H = \frac{\sum d_i}{\sum (d_i/v_i)}, \qquad (5)$$

where $H = \sum d_i$ = cumulative depth in m.

For 30 m average depth, shear wave velocity is written as:

$$V_s^{30} = \frac{30}{\sum_{i=1}^{N} (d_i/v_i)}, \qquad (6)$$

where d_i and v_i denote the thickness (in meters) and shear-wave velocity in m/s (at a shear strain level of 10^{-5} or less) of the ith formation or layer respectively, in a total of N layers, existing in the top 30 m. V_s^{30} is accepted for site classification as per NEHRP classification and also UBC classification (Uniform Building Code in 1997) (Dobry *et al* 2000; Kanli *et al* 2006). In order to figure out the average shear-wave velocity distribution in Bangalore, the average velocity has been calculated using the equation (5) for the each borelog location. A simple spread sheet has been generated to carry out the calculation, as shown in table 3. The V_s average has been calculated for every 5 m depth interval up to a depth of 30 m. Usually, for amplification and site response study the 30 m average V_s is considered. However, if the rock is found within a depth of about 30 m, average shear-wave velocity of soil thickness (overburden thickness) needs to be considered. Otherwise, V_s^{30} obtained will be higher due to the velocity of the hard rock mass. Site characterization using SPT data shows that, the soil overburden thickness in Bangalore varies from 1m to about 40 m. Hence, average V_s has also been calculated for overburden soil alone based on the soil thickness corresponding to that location of the borehole. Typical average V_s calculation for soil is shown in column 4 of table 3. The average shear-wave velocities calculated above are mapped for the entire BMP area of study and Arc GIS has been used for mapping average V_s in the area. Figure 10 shows the typical average velocity (for depth of 15 m) in BMP area. Most of the study area is having a velocity range of

Table 3. *Typical average shear wave velocity calculation.*

Depth (m)	V_s (m/s)	Soil thickness [d_i] (m)	Average V_s soil-7.2 m	Average V_s-5 m	Average V_s-10 m	Average V_s-15 m	Average V_s-20 m	Average V_s-25 m	Average V_s-30 m
−1.22	316	−1.2	259	265	286	310	338	362	306
−2.74	250	−1.5							
−4.64	255	−1.9							
−7.02	241	−2.4							
−10.00	388	−3.0							
−13.71	355	−3.7							
−18.36	435	−4.6							
−24.17	527	−5.8							
−31.43	424	−7.3							
−39.29	687	−7.9							

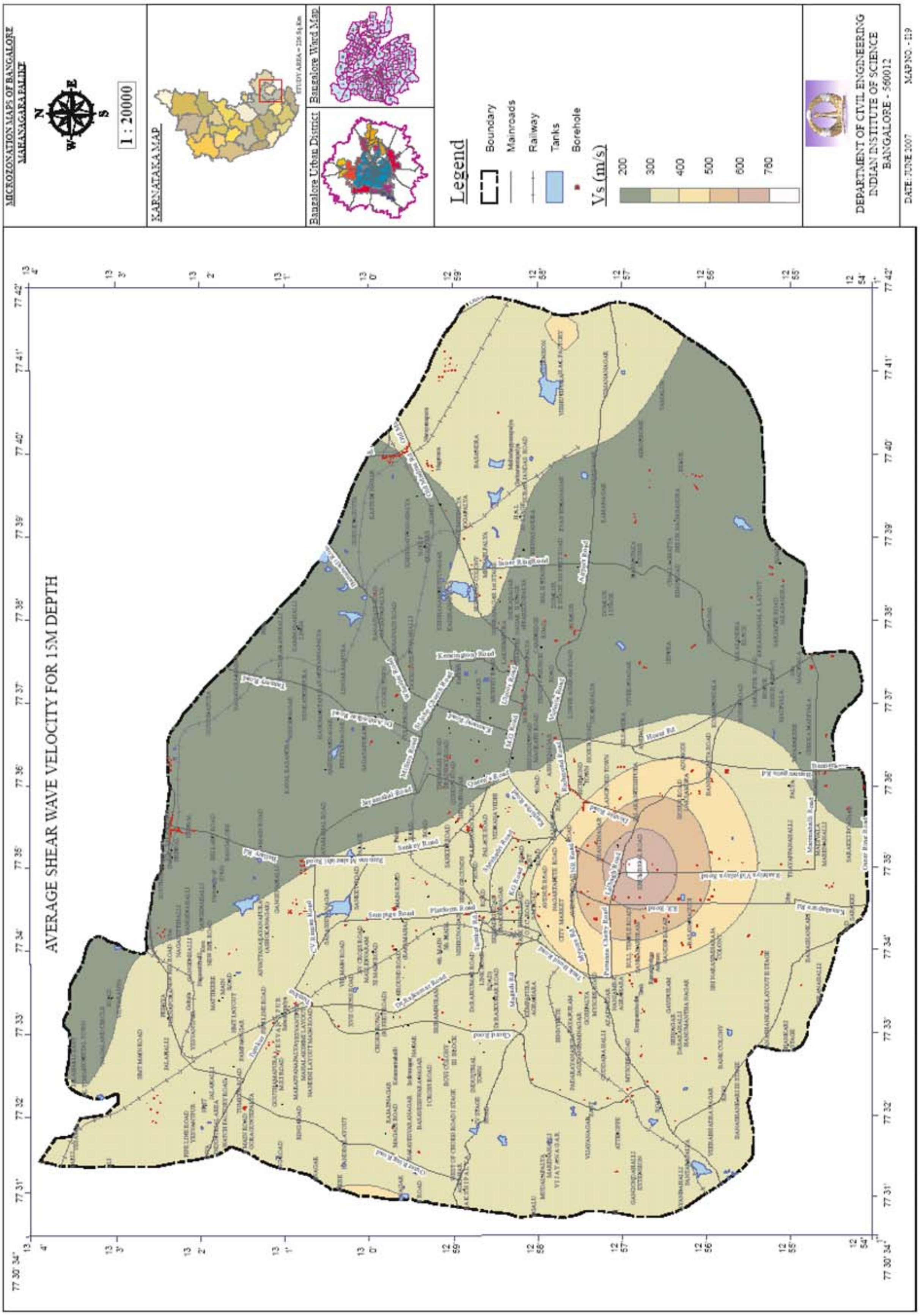

Figure 10. 15 m average shear wave velocity distribution in BMP area.

180 to 360 m/s. The study shows that whole study area has medium to dense soil with a velocity range of 180 to 360 m/s falling in to 'site class D' as per NEHRP classification.

9. Site response studies

In 1960s in the study area there were over 150 lakes, though most of them are dried up due to erosion and encroachments leaving only 64 at present in an area of 220 km^2. Bangalore city, a fast growing urban center, with low to moderate earthquake history and highly altered soil structure (due to large reclamation of land) needs a detailed study to assess the local site effects for an earthquake. In the present study, an attempt has been made to assess the site response using geotechnical, geophysical data and field experiments. The subsurface profiles of the study area within 220 km^2 area was represented by 170 geotechnical bore logs and 58 shear wave velocity profiles obtained by MASW survey. These soil properties and synthetic ground motions for each borehole location are further used to study the local site effects by conducting one-dimensional ground response analysis using the program SHAKE2000. A typical synthetic ground motion used for the ground response study having a PGA of 0.153 is given in figure 11. The response and amplification spectrum have been evaluated for each location. The natural period of the soil column, peak spectral acceleration, spectral acceleration at different frequencies and frequency at peak spectral acceleration of each location (using borehole data as well as MASW data) has been evaluated and presented as maps. Predominant frequency obtained using SPT data and MASW data are compared. Predominant frequency obtained from ground response studies and microtremor measurement is also compared.

9.1 *1-D ground response analysis using equivalent linear approach*

A ground response analysis consists of studying the behaviour of a soil deposit subjected to an acceleration time history applied to a layer of the soil profile. Ground response analysis is used to predict the ground surface motions for evaluating the amplification potential and for developing the design response spectrum. In the present study, one-dimensional ground response analysis using equivalent linear model has been carried out using SHAKE2000 software in which motion of the object can be given in any one layer in the system and motions can be computed in any other layer.

In equivalent linear approach, the non-linearity of the shear modulus and damping is accounted for the use of equivalent linear soil properties using an iterative procedure to obtain values for modulus and damping compatible with the effective strains in each layer (Idriss and Sun 1992). In this approach, first, a known time history of bedrock motion is represented as a Fourier series, usually using the Fast Fourier Transform (FFT) (Schnabel *et al* 1972; Schnabel 1973). Second, the transfer functions for the different layers are determined using the current properties of the soil profile. The transfer functions give the amplification factor in terms of frequency for a given profile. In the third step, the Fourier spectrum is multiplied by the soil profile transfer function to obtain an amplification spectrum transferred to the specified layer. Then, the acceleration time history is determined for that layer by the Inverse Fourier transformation in step four. With the peak acceleration from the acceleration time history obtained and with the properties of the soil layer, the shear stress and strain time histories are determined in step five. In step six, new values of soil damping and shear modulus are obtained from the damping ratio and shear modulus degradation curves corresponding to the effective strain from the strain time history. With these new soil properties, new transfer functions are obtained and the process is repeated until the difference between the old and new properties fit in a specified range. The basic approach of one dimensional site response study is the vertical propagation of shear waves through soil layers lying on an elastic layer of the rock which extends to infinite depth. The degradation curves used for sand and rock used for the present work are those proposed by Seed and Idriss (1970) and Schnabel (1973) respectively.

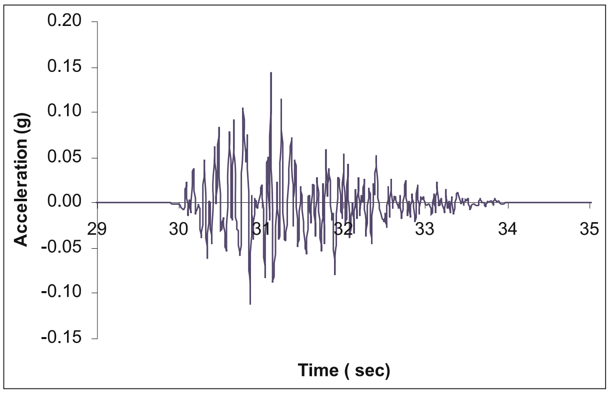

Figure 11. Synthetic ground motion generated from Mandya–Channapatna–Bangalore lineament (L15).

9.2 *Site response analysis based on SPT data*

In this study the input rock motions at bed rock were generated for each borehole location based on

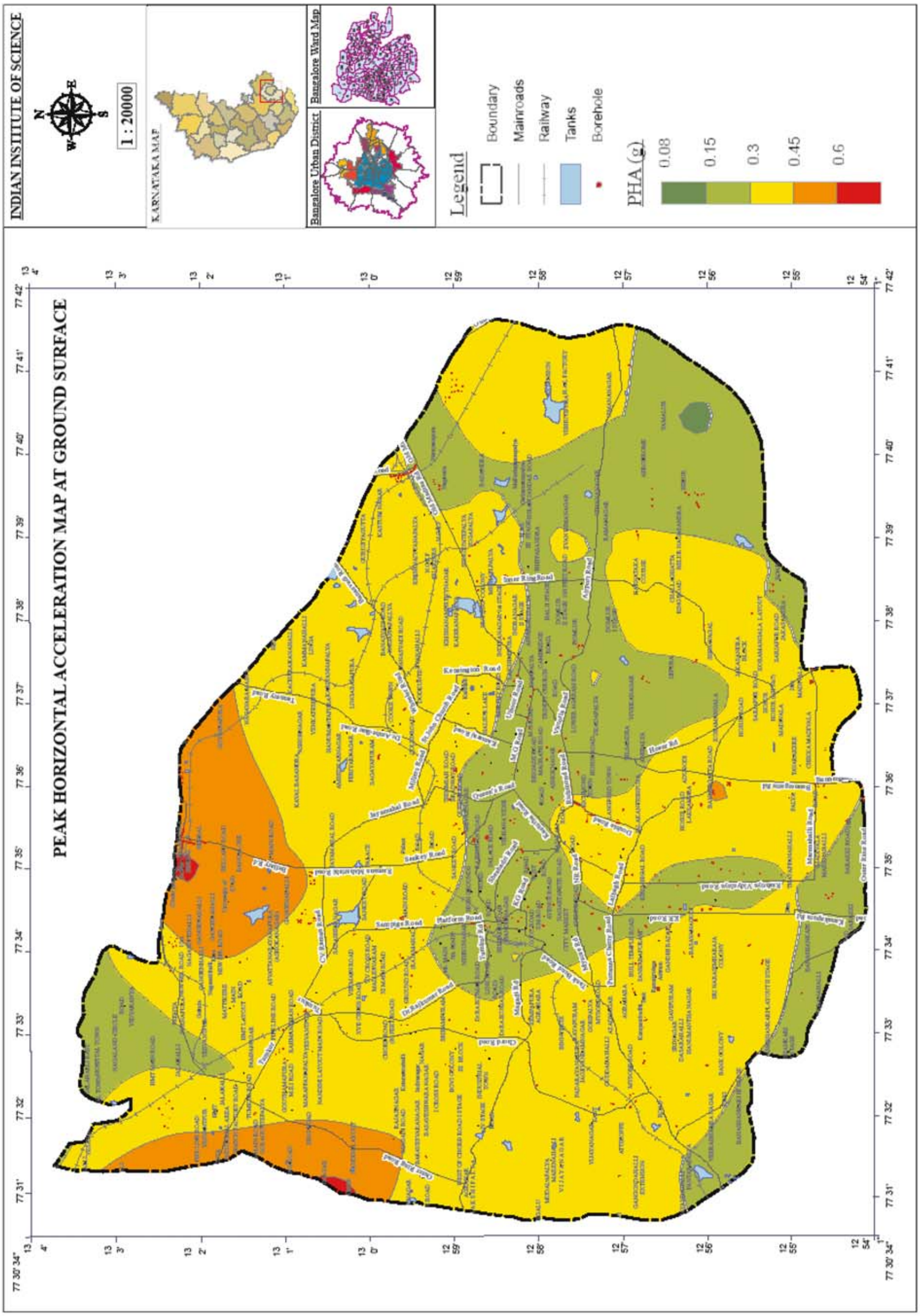

Figure 12. Distribution of peak horizontal acceleration at ground surface.

Table 4. *Zones and amplification factor range.*

Zone	Amplification factor	Approximate average 30 m shear wave velocity (m/s)
1 (I)	1.00–1.99	400–900
2 (II)	2.00–2.99	200–400
3 (III)	3.00–3.99	300–500
4 (IV)	> 4.00	300–400

the hypocentral distance calculated for each borehole to the Mandya–Channapatna–Bangalore lineament and used as input for the corresponding borehole to study the site response. Out of 850 borelogs 170 borelogs were carefully evaluated, for the engineering bed rock depth in each borelog from the rock characterization tests, and selected for the site response study. Engineering bed rock is the bed rock having the shear wave velocity of around 700 m/s. The shear modulus is evaluated based on the equation developed by Imai and Tonouchi (1982) using corrected SPT '*N*' values. The rock motion obtained from synthetic ground motion model is assigned at the bedrock level as input in SHAKE and evaluated peak acceleration values and acceleration time histories at the top of each sublayer. Response spectra at the top of the bedrock and at ground surface and amplification spectrum between the first and last layers at a frequency step of 0.125 are obtained. Similarly, stress-strain time history and Fourier amplitude spectrum have been obtained for all the borehole locations. These are compiled and presented in the form of maps depicting variation of different parameters. The peak horizontal acceleration (PGA) values at bedrock level are amplified based on the soil profile at various locations. The peak acceleration value at the ground surface obtained from SHAKE2000 is used to prepare the PGA map of Bangalore, which is shown in figure 12. The PGA value ranges from 0.088 to 0.66 g. They are not distributed uniformly due to variation in the soil profile at various locations.

9.3 *Amplification factor map*

The term **Amplification Factor** is used here to refer to the ratio of the peak horizontal acceleration at the ground surface to the peak horizontal acceleration at the bedrock. This factor is evaluated for all the boreholes using the PGA at bedrock obtained from the synthetic acceleration time history for each borehole and the peak ground surface acceleration obtained as a result of ground response analysis using SHAKE2000. The amplification factor thus calculated ranged from 1 to 4.8. The amplification factors obtained are used to prepare the amplification map of Bangalore. Bangalore city can be divided into four zones based on the range of amplification factors assigned to each zone as shown in table 4. Table 4 also lists the range of 30 m average shear wave velocity from MASW test. The amplification factor map for Bangalore city is shown in figure 13. Lower amplification values indicate lesser amplification potential and hence lesser seismic hazard. It can be observed that the amplification factor for most of Bangalore city is in the range of 2–3. A very small part of the city comes under high amplification potential with the amplification factor ranging from 3 to 5. Comparison of the variation of overburden thickness map and the amplification factor map shows that the regions having higher amplification zone has an overburden thickness in the range of 5 to 18 m. The high amplification potential in these regions can be attributed to factors other than the overburden thickness. Boreholes located in the north-eastern side of the city fall in the zone IV. The amplification factor for these soil profiles is very high due to presence of clay layer and has thickness of the clay from 2 m to about 8 m. This may be attributed to the fact that this region has a filled up soil of about 4 m depth and a shallow water table depth of 0.3 m, which considerably increases the amplification potential.

9.4 *Site response analysis using shear wave velocity*

From the wave propagation theory, it is clear that the ground motion amplitude depends on the density and shear wave velocity of subsurface material (Bullen 1965; Aki and Richards 1980). Usually *in situ* density has relatively smaller variation with depth and thus the shear wave velocity is the logical choice for representing site conditions. An attempt has been made to study the site response of study area using measured shear wave velocity obtained from MASW test.

The peak horizontal acceleration at ground surface obtained using shear wave velocity ranges from 0.188 to 0.475 g. This is comparable to peak horizontal acceleration values obtained using SPT data. The ground acceleration is considerably large in the areas of tank beds, resulting from the thick layers of silty sand with clay mixture. The shape of variation of peak acceleration with depth is similar to the SPT data. Typical PGA *versus* depth curve is shown in figure 14. Peak acceleration using SPT data is higher when compared to the MASW data and also these variations are large for shallow overburden (within 12 m) thickness. The amplification factor thus calculated using MASW data ranges from 1 to 3.5 which are comparable with the values calculated using SPT data. The dense sand soil, where average shear wave velocity is more than

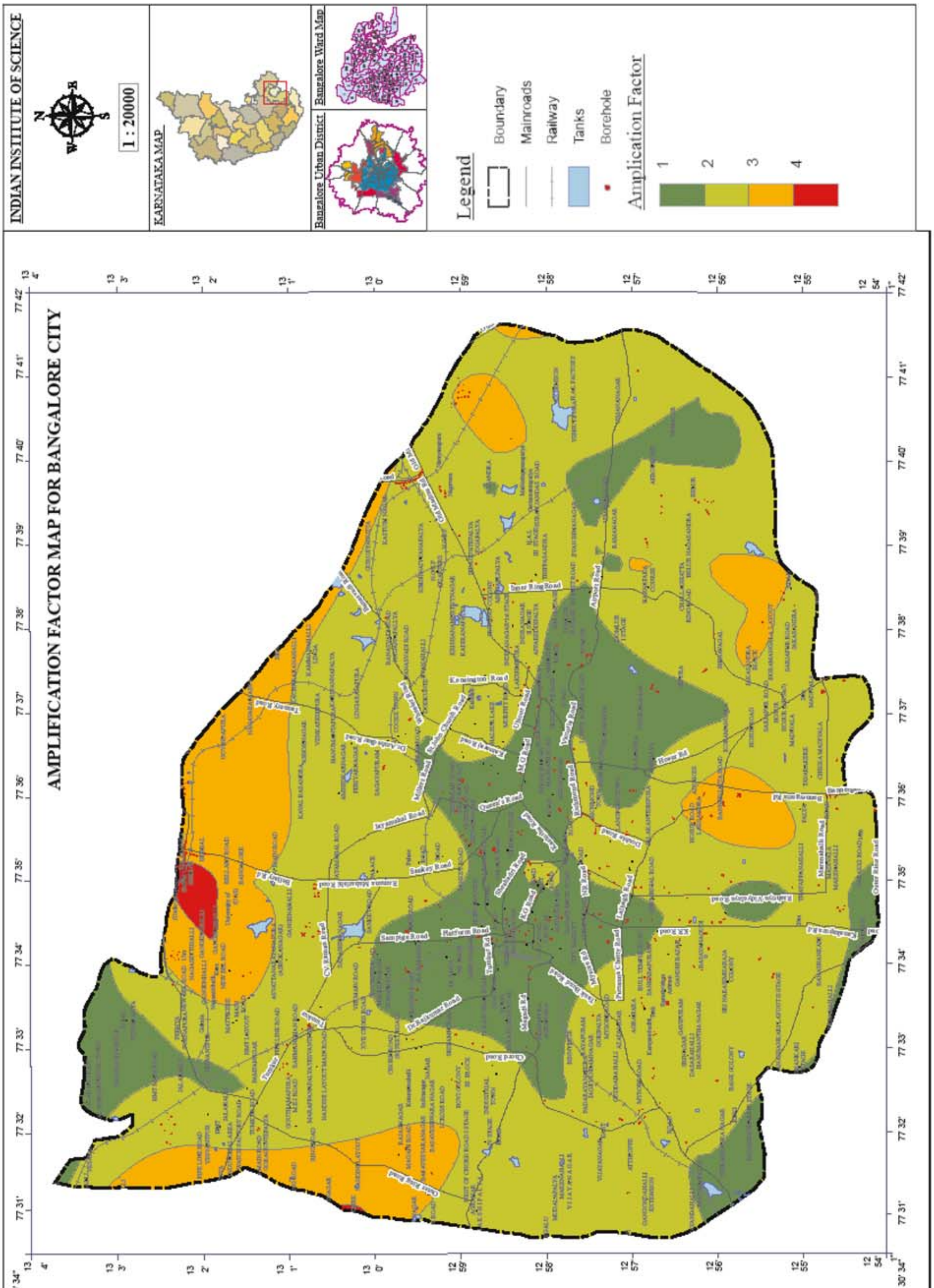

Figure 13. Amplification map of Bangalore.

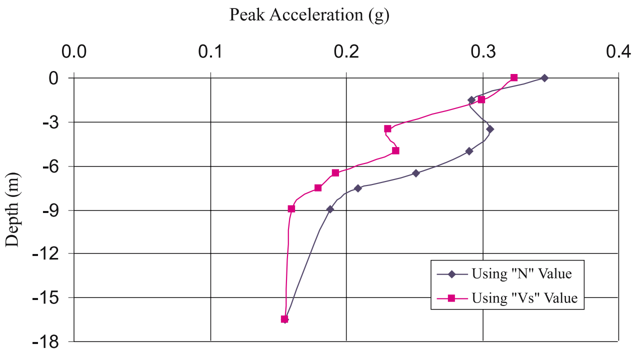

Figure 14. Typical peak ground acceleration with soil column thickness.

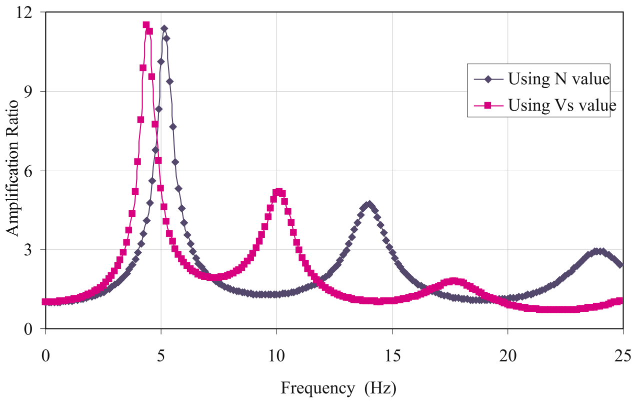

Figure 15. Typical amplification ratio using MASW and SPT.

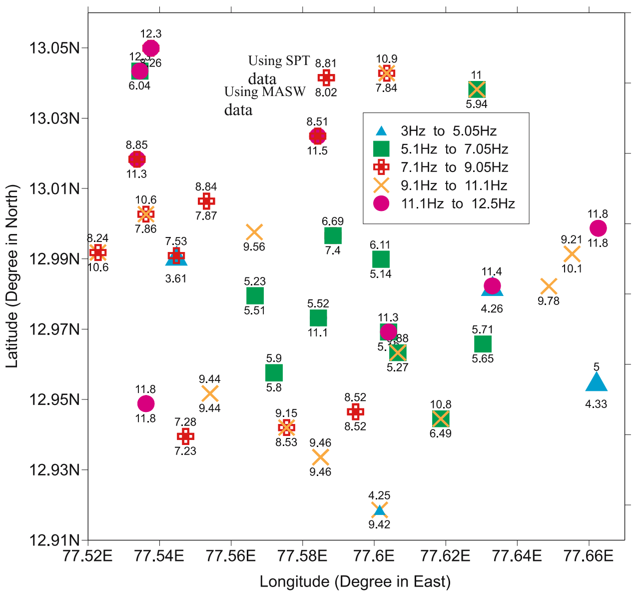

Figure 16. Predominant frequencies using SPT and MASW data.

350 m/s, has less amplification. Spectral values at different frequency using MASW data do not vary much from the values obtained using SPT data. The shape of the amplification spectrum obtained using both data matches well, however values of amplification ratio from MASW data is lower than the SPT data. Typical plot amplification ratio *versus* frequency is shown in figure 15. Figure 15 clearly shows that both data give same amplification ratio with different frequency. SPT data give 5.5 Hz and MASW data give 4 Hz corresponding to peak amplification ratio. Also amplification spectrum from both data shows the double peak but at different frequency.

9.5 *Comparison of predominant frequency obtained using SPT and MASW data*

Predominant frequency of soil is widely used to categorize the soil for a ground motion and it is mainly dependent upon the dynamic properties of soil. The predominant frequency is defined as the frequency of vibration corresponding to the maximum value of Fourier amplitude. In this study predominant frequency of soil column is obtained from Fourier spectrum estimated using SHAKE2000. Predominant frequencies are estimated using both SPT data and MASW data. Results show that predominant frequencies obtained are similar from both methods. Predominant frequency varies from 4 to 12 Hz based on SPT data and 3.45 to 12 Hz based on V_s from MASW survey. To compare predominant frequencies from both the methods, the site response study results at 38 locations (where both borehole data and MASW survey area available) are used. Predominant frequencies corresponding to these locations are presented in figure 16. Figure 16 shows that the predominant frequencies obtained from both data are comparable. Table 5 shows that most of the study area has higher predominant frequency (5 to 12.5 Hz) from both these methods. The predominant frequency of the soil layers has been better estimated using shear wave velocity data when compared to SPT data.

9.6 *Comparison of predominant frequency from site response study using V_s and microtremor*

The microtremor survey is carried out at 60 locations jointly by National Geophysical Research Institute (NGRI) Hyderabad and ourself for this project to compare predominant periods of the soil columns. The instruments used in this experiment are L4-3D short period sensors equipped with digital acquisition system. The duration of recording was for a minimum of 3 h and a maximum of 26 h. In estimating the site response, Nakamura technique has been widely used and the resonance frequency is obtained by evaluating the horizontal to vertical spectral ratios (Nakamura 1989).

Table 5. *Predominant frequency ranges.*

Predominant frequency range (Hz)	Symbols	Numbers	
		Using SPT	Using MASW
3.0 to 5.0	▲	3	3
5.1 to 7.0	■	6	9
7.1 to 9.0	✙	8	9
9.1 to 11.0	×	9	7
11.1 to 12.5	●	8	5

Table 6. *Predominant frequency using site response study and microtremor.*

Predominant frequency range (Hz)	Symbols	Numbers	
		Using MASW	Using microtremor
3.0 to 5.0	▲	7	16
5.1 to 7.0	■	15	10
7.1 to 9.0	✙	11	5
9.1 to 11.0	×	6	2
11.1 to 12.5	●	4	3
1.5 to 2.9	✶	–	7

The spectra and the H/V ratios have been computed using the JSESAME program. Site response studies using SPT and MASW data shows that the predominate frequency of Bangalore soil varies from 5 to 12 Hz. But microtremor studies show that the predominant frequency of Bangalore soil varies from 1.5 to 12 Hz. Hence a comparative study has been carried out using microtremor results and theoretical studies based on SPT and MASW data. At about 43 locations both microtremor and MASW tests are comparatively closer to each other, and these results are used to compare. The predominant frequency estimated from microtremor and estimated form site response using MASW are shown in figure 17. In figure 17, the values reported on the left side of the symbol are obtained using MASW based site response study and values reported on the right side of the symbols are obtained using microtremor experiments. Figure 17 clearly shows that at most of the locations predominant frequency from both the method matches very well. Most of the study area, predominant frequency is ranging from 3 to 12 Hz except at seven locations based on microtremor studies (see table 6). The lower predominant frequency may be attributed due to the topographical effects, which is not accounted in theoretical one-dimensional ground response analysis.

10. Factor of safety against liquefaction

To study the liquefaction hazard in Bangalore, the liquefaction hazard assessment has been carried out using standard penetration test (SPT) data and soil properties. Factor of safety against liquefaction of soil layers have been evaluated based on the simplified procedure of Seed and Idriss (1971) and subsequent revisions of Seed *et al* (1983); Youd *et al* (2001) and Cetin *et al* (2004). Cyclic Stress Ratio (CSR) resulting from earthquake loading is calculated by considering moment magnitude of 5.1

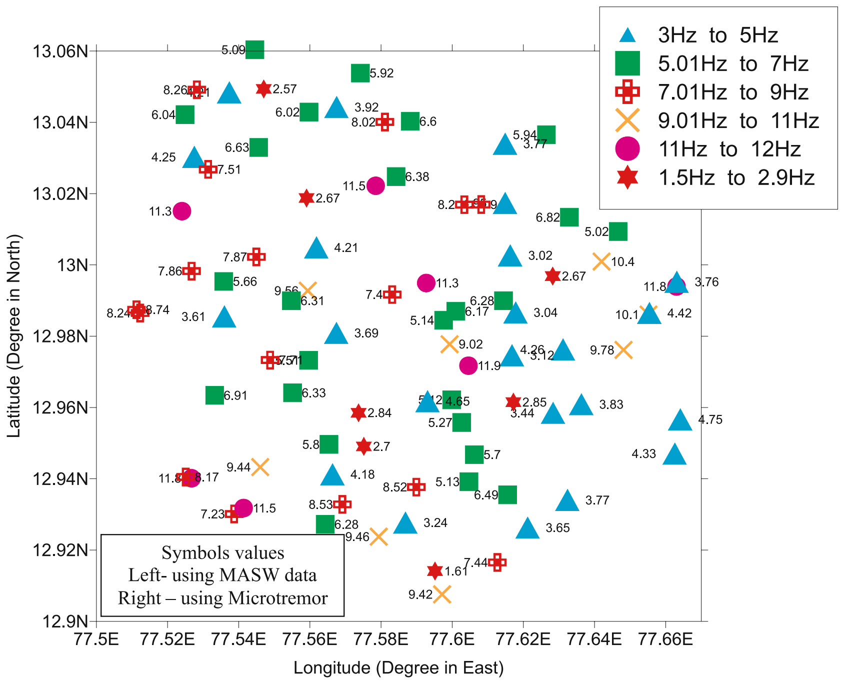

Figure 17. Predominant frequency from microtremor and site response using shear wave velocity.

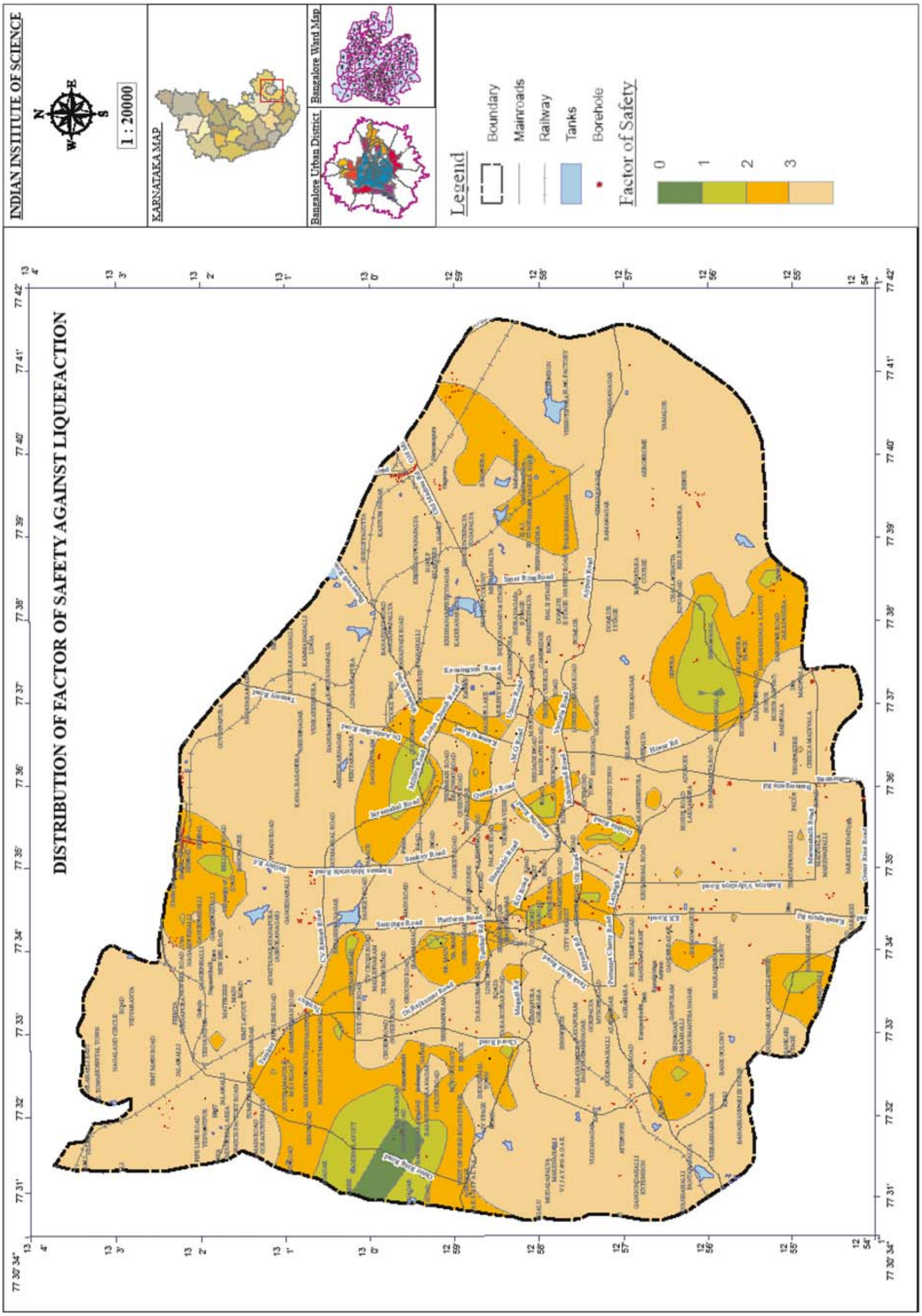

Figure 18. Distribution of factor safety against liquefaction.

and amplified peak ground acceleration at ground surface. Cyclic Resistant Ratio (CRR) is arrived using the corrected SPT '*N*' values and soil properties. Detailed procedures and analysis are available in Sitharam *et al* (2007). Figure 18 shows the map of factor of safety against liquefaction (FS) for Bangalore city to the earthquake of 5.1 in moment magnitude. Out of 620 locations, liquefaction analyses indicate that the factor of safety is less than one in 4.2% of total locations. Factor of safety of 1 to 2 and 2 to 3 is in about 14.7% and 12.5% of the total locations respectively. Factor of safety of more than 3 is in about 68% of the total locations. Typical borelogs obtained from locations where factor of safety of less than one clearly shows very loose silty sand with clay and sand up to a depth of about 6 m. Soil in these locations is classified as loose to medium sand having very low field '*N*' values (less than 8). Also in these locations water table has been met at 1.2 m from the ground level. Hence, above factors may be attributed to a low factor of safety in these locations. The study shows that the areas in Bangalore is safe against liquefaction except at few locations where the overburden is sandy silt with presence of shallow water table.

11. Conclusions

This study shows that, expected peak ground acceleration (PGA) at rock level using DSHA for Bangalore is about 0.15 g. Based on large amount of borehole data with SPT '*N*' values, 3-D geotechnical borehole model has been generated using GIS. Field '*N*' values were corrected for various corrections. The site characterization of Bangalore is attempted using measured shear wave velocity from Multichannel Analysis of Surface Wave. Average shear wave velocity at each 5 m interval up to a depth of 30 m was evaluated and presented. Based on soil average shear wave velocity and 30 m average shear wave velocity, as per NEHRP and IBC, Bangalore is classified as "Site class D". Theoretical 1-D site response study shows that the amplification factor is in the range of 1 to 4.7 and predominant frequency varies from 3 to 12 Hz. The results of site response studies using SPT data and MASW data are comparable. Ground response parameters evaluated using MASW data are slightly lower when compared to the parameters obtained using SPT data. Field study of microtremor also shows similar values of predominant frequencies for the selected sites. Predominant frequency obtained from these three methods matches very well. Liquefaction hazard map has been generated using factor of safety against liquefaction. Liquefaction study shows that Bangalore is safe against liquefaction except at few locations where the overburden is sandy silt with presence of shallow water table.

Acknowledgements

Authors thank the Department of Science and Technology (DST), Seismology Division, Govt. of India for funding the project "Seismic Microzonation of Bangalore" (Ref. no. DST/23(315)/SU/2002 dated October 2003). ISRO–IISc Space Technology Cell, Indian Institute of Science, Bangalore, India for funding the project titled "Use of remote sensing and GIS for Seismic Hazard Analyses of southern India" (Ref. no. ISTC/CCE/TGS/195/2007 dated 7 March 2007).

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MS received 28 September 2007; revised 1 April 2008; accepted 2 April 2008