Seismic Microzonation of Bangalore

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Abstract

In the present study an attempt has been made to study the seismic hazard analysis considering the local site effects and to develop microzonation maps for Bangalore. Seismic hazard analysis and microzonation of Bangalore is addressed in this study in three parts: In the first part, estimation of seismic hazard using seismotectonic and geological information. All the earthquake sources and seismicity has been considered within a radius of 350 km from the Bangalore city for the study. Second part deals about site characterization using geotechnical and shallow geophysical techniques. An area of about 220 sq.km encompassing Bangalore Municipal Corporation has been chosen as 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 BMP (Bangalore Mahanagara Palika) area. emphasizing the need to study site effects. In the last part, local site effects are assessed by carrying out one-dimensional (1-D) ground response analysis (using the program SHAKE 2000) using both borehole SPT data and shear wave velocity survey data within an area of BMP. Further, field experiments using microtremor studies have also been carried out (jointly with NGRI) 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, Seed and Idriss's simplified approach has been adopted to evaluate the liquefaction susceptibility and liquefaction resistance assessment. Microzonation maps have been prepared for Bangalore city covering 220 sq. km area on a scale of 1:20000.

Key words: *Seismic hazard, Microzonation, site characterization, shear wave velocity, site response and liquefaction*

Introduction

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 (ISSMGE/TC4, 1999). Making improvements on the conventional macrozonation maps and regional hazard maps, microzonation of a region generates detailed maps that predict the hazard at much larger scales. 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 filledup 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. Mapping the seismic hazard at local scales to incorporate the effects of local ground conditions is the essence of microzonation.

Earthquake damage is commonly controlled by three interacting factors- source and path characteristics, local geological and geotechnical conditions and type of the 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 and ground amplification, liquefaction susceptibility are few of the important inputs required. Effect of site amplification due to soil conditions and associated damage to built environment was amply demonstrated by many earthquakes during the last century. The wide spread destruction caused by Guerrero earthquake (1985) in Mexico city, Spitak earthquake (1988) in Leninakan, Loma Prieta earthquake (1989) in San Francisco Bay area, Kobe earthquake (1995), Kocaeli earthquake (1999) in Adapazari are important examples of site specific amplification of ground motion even at location as far away as 100-300km from the epicenter (Ansal, 2004). These failures resulted from the effect of soil condition on the ground motion that translates to higher amplitude; it also modifies the spectral content and duration of ground motion. Site specific ground response analysis aims at determining this effect of local soil conditions on the amplification of seismic waves and hence estimating the ground response spectra for future design purposes. The response of a soil deposit is dependent upon the frequency of the base motion and the geometry and material properties of the soil layer above the bedrock. Seismic microzonation is the process of assessment of the source & path characteristics and local geological & geotechnical characteristics to provide a basis for estimating and mapping a potential damage to buildings, in other words it is the quantification of hazard. Presenting all of this information accordingly to develop hazard maps, for the use of planners, developers, insurance companies and common public is another important aspect of microzonation.

Scale and Methodology Adopted

Rapidly growing cities with increasing population are most vulnerable to natural hazards due to agglomeration of the population at one place. Preparation of the geotechnical microzonation maps provides an effective solution to overcome to some extent from seismic hazards. Seismic microzonation has been carried out to understand the effects of earthquake generated ground motions on soil or/and man-made structures. The main objective of a microzonation study is to use the obtained variation of the selected parameters for land use and city planning. Therefore it is very important that the selected microzonation parameters should be meaningful for city planners as well as for public officials. Ansal (2004) recommend that the national seismic zoning maps are mostly at small scale level (1:1,000,000 or less) and are mostly based on seismic source zones defined at similar scales. The seismic microzonation for a town requires 1:5,000 or even 1:1,000 scale studies and needs to be based on seismic hazard studies at similar scales. The general trend in conventional microzonation studies in India was to simplify the applied methodology by adopting the macrozonation seismic hazard maps as the primary source to estimate the earthquake hazard. In addition, due to the lack of sufficient geological and geotechnical data, a site simplification is used to define the site conditions with respect to local geological units.

Seismic Microzonation falls into the category of "applied research". That is why there is a need to upgrade and revise based on the latest information, Seismic microzonation was defined world wide based on region or country. However in Indian context, "Microzonation is a subdivision of a region into zones that have relatively similar exposure to various earthquake related effects. This exercise is similar to the macro level hazard evaluation but requires more rigorous input about the site specific geotechnical conditions, ground responses to earthquake motions and their effects on the safety of the constructions taking into consideration the design aspects of the buildings, ground conditions which would enhance the earthquake effects like the liquefaction of soil, the ground water conditions and the static and dynamic characteristics of foundations or of stability of slopes in the hilly terrain" –DST Expert Group on Microzonation of Delhi Chaired by Arya (1998) and the definition was endorsed by the DST subcommittee on Microzonation, Chaired by Narula (2001).

The microzonation level is graded based on the scale of the investigation and method of ground motion assessment. The technical committee on earthquake geotechnical engineering, TC4 of the

International society of soil mechanics and foundation engineering (1993) states that the first grade (Level I) map can be prepared with scale of 1:1,000,000 – 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 1:25,000-1:5,000.

The steps in seismic microzonation has been subdivided into three major items:

1) Evaluation of the expected input motion
2) Local Site effects and ground Response analysis
3) Preparation of microzonation maps.

Even though the seismic hazard analysis and microzonation has been grouped in to three major steps as above, there is a need to adopt step by step procedure to arrive at the final map for microzonation. Based on the grade and level of the microzonation map, a detailed methodology can be formulated with the above three basic steps. The steps followed for the seismic hazard assessment and microzonation of Bangalore in the present investigation is illustrated as a flow chart in Figure 1.

Seismic Study Area and Seismotectonic map

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 Figure 2. A seismotectonic detail of the study area has been collected in a circular area having a radius of about 350 km 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 323.5km, 34 lineaments and 14 shear zones. The map shows different rock groups with different colours. Faults, lineaments and shear zones are given different colours. Earthquake data collected from different agencies [United State Geological Survey (USGS), Indian Metrological 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. These magnitudes are converted to moment magnitudes (Mw) by using magnitude relations given by Heaton et al (1986).

The earthquake events collated and converted has been super imposed on the base map with available latitudes and longitudes. The earthquake events collated are about 1420 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 (2007) have presented these aspects and new seismotectonic map has been

developed and presented. The maximum occurred events near by the each source are assigned as the maximum source magnitude.

Geological formation of the study area is considered as one of the oldest land masses of the earth's crust. Most of the study area is classified as Gneissic complex/Gneissic granulite with major inoculation of greenstone and allied supracrustal belt. The geology deposits close to the eastern and western side of the study area is coastline having the alluvial fill in the pericratonic rift. The major tectonic constituents in the southern India include the massive Deccan Volcanic Province (DVP), the South Indian Granulite Terrain (SIGT), the Dharwar craton (DC), the Cuddapah basin (CB), the Godavari graben (GG) and the Mahanadi graben (MG), the Eastern and the Western ghats on the east and west coast of India, respectively. The Eastern Ghat region in general is a quiet zone, characterized by diffused low magnitude shallow focus earthquakes and an occasional earthquake of magnitude 5 to 6 (Mw).
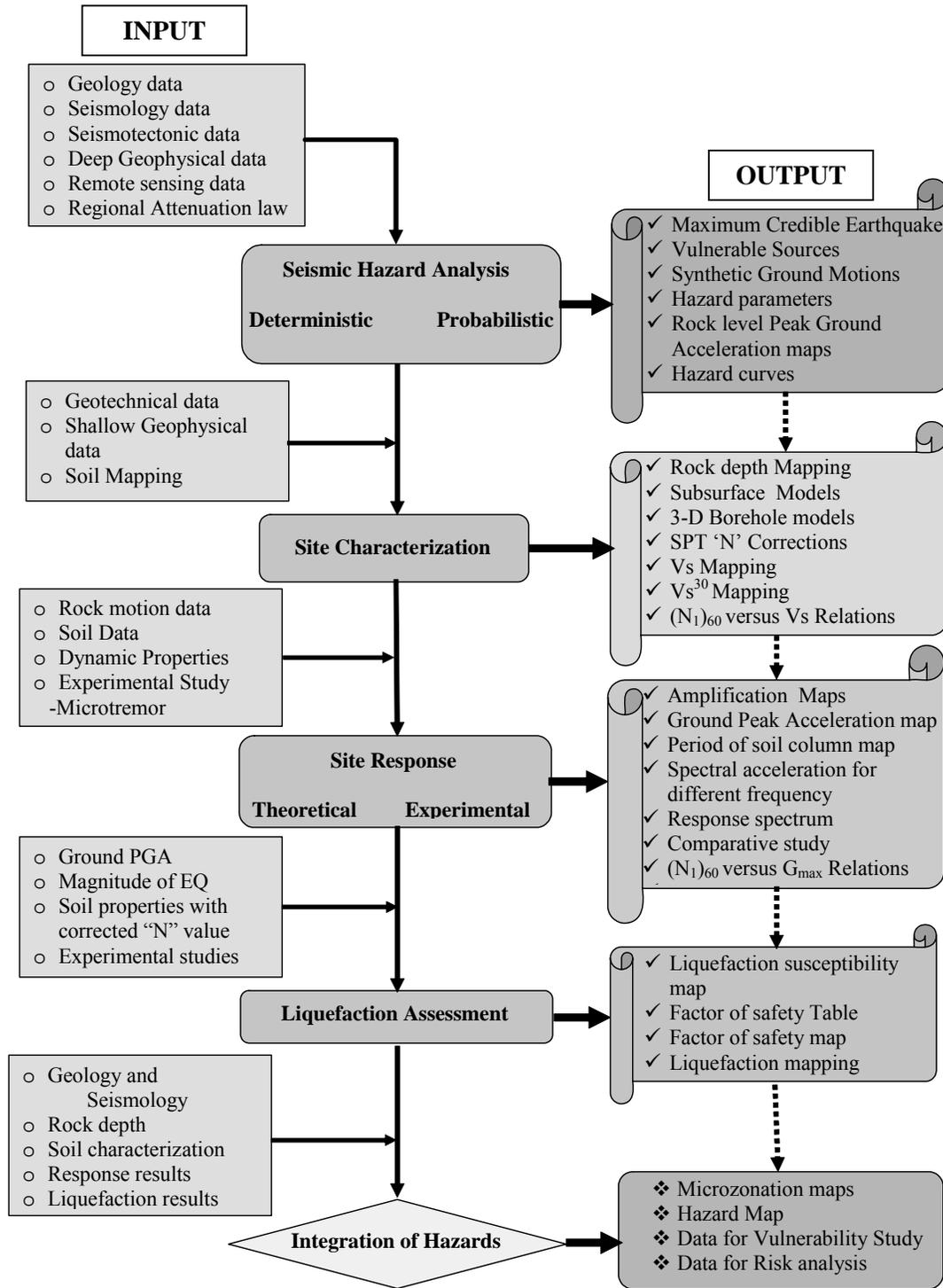
INPUT

- o Geology data
- o Seismology data
- o Seismotectonic data
- o Deep Geophysical data
- o Remote sensing data
- o Regional Attenuation law

OUTPUT

Seismic Hazard Analysis

Deterministic   Probabilistic

- ✓ Maximum Credible Earthquake
- ✓ Vulnerable Sources
- ✓ Synthetic Ground Motions
- ✓ Hazard parameters
- ✓ Rock level Peak Ground
     Acceleration maps
- ✓ Hazard curves

- o Geotechnical data
- o Shallow Geophysical
     data
- o Soil Mapping

Site Characterization

- ✓ Rock depth Mapping
- ✓ Subsurface Models
- ✓ 3-D Borehole models
- ✓ SPT 'N' Corrections
- ✓ Vs Mapping
- ✓ Vs^{30} Mapping
- ✓ $(N_1)_{60}$ versus Vs Relations

- o Rock motion data
- o Soil Data
- o Dynamic Properties
- o Experimental Study
     -Microtremor

Site Response

Theoretical   Experimental

- ✓ Amplification Maps
- ✓ Ground Peak Acceleration map
- ✓ Period of soil column map
- ✓ Spectral acceleration for
     different frequency
- ✓ Response spectrum
- ✓ Comparative study
- ✓ $(N_1)_{60}$ versus G_{max} Relations

- o Ground PGA
- o Magnitude of EQ
- o Soil properties with
     corrected "N" value
- o Experimental studies

Liquefaction Assessment

- ✓ Liquefaction susceptibility
     map
- ✓ Factor of safety Table
- ✓ Factor of safety map
- ✓ Liquefaction mapping

- o Geology and
          Seismology
- o Rock depth
- o Soil characterization
- o Response results
- o Liquefaction results

Integration of Hazards

- ❖ Microzonation maps
- ❖ Hazard Map
- ❖ Data for Vulnerability Study
- ❖ Data for Risk analysis

Figure 1 Flow Chart for Seismic Hazard and Microzonation
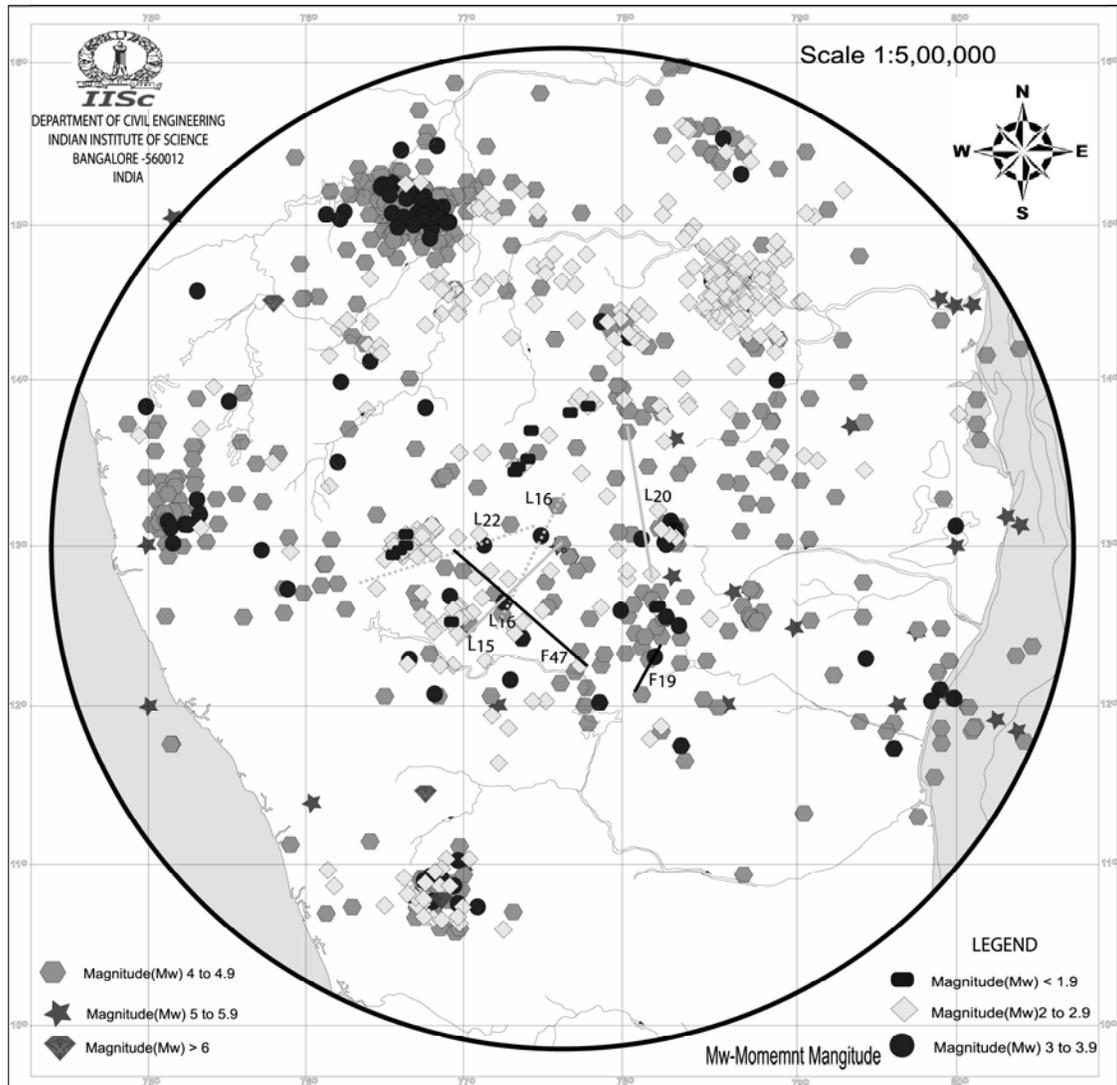
Figure 2 *Seismotectonic map of Map of Bangalore region six seismogenic sources*

The Indian shield region is marked by several rift zones and shear/thrust zones. Although this region is considered to be a stable continental region, this region has experienced many earthquakes of magnitude of 6.0 since the 18th Century and some of which were disastrous (Ramalingeswara Rao, 2000). Among them are the Mahabaleshwar (1764), Kutch (1819), Damooh hill (Near Jabalpur, 1846), Mount Abu (1848), Coimbatore (1900), Son-Valley (1927), Satpura (1938), Koyna, (1967), Latur (1993), and Jabalpur earthquake (1997). Nath (2006) highlighted that the most common cause for the Indian shield appears to be the compressive stress field in the Indian shield oriented NNE-SSW on an average as a consequence of the relentless India-Eurasia plate collision forces. Sridevi Jade (2004) highlighted that southern peninsular India moves as a rigid plate with about 20 mm/year velocity in the NNE direction (using Global positioning system measurement at Indian Institute of Science, Bangalore).

In general, for the evaluation of 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. The seismic sources are broadly classified as point source, line source and area sources. The seismic sources for this study were identified as line sources and mapped using geological, deep geophysical and remote sensing studies. The well defined and documented seismic sources are published in the Seismotectonic Atlas-2000 published by Geological Survey of India (SEISAT, 2000). Geological survey of India has compiled all the available geological, geophysical and seismological data for the entire India and has published a seismotectonic map in the year 2000. Seismotectonic atlas contains 43 maps in 42 sheets of 3° x 4° sizes with scale of 1:1 million, which also describes the tectonic frame work and seismicity. This has been prepared with the intention that it can be used for the seismic hazard analysis of Indian cities. Ganesha Raj and Nijagunappa (2004) have also mapped major lineaments for Karnataka state with lengths more than 100 km using satellite remote sensing data and correlated with the earthquake occurrences. They have highlighted that there are 43 major lineaments and 33 earthquake occurrences with magnitude above 3 (since 1828) in the study area. About 23 of these earthquakes were associated with 8 major lineaments, which they have named as active lineaments. Both the above data have been used for the generated newly seismotectonic map of the study area (Sitharam et al, 2006 and Sitharam and Anbazhagan, 2007).

These sources matches well with major seismic sources considered by Bhatia et al (1997) for Global Seismic Hazard Assessment Program (GSHAP). The preferred fault plane solutions for the region generally indicate north-east south-west orientation with left-lateral strike slip motion. Alternate set of solution indicated in region is the thrust faulting along north-west orientation. GSHAP has delineated sources 70, 71 and 74 based on localized concentration of seismicity, along the Eastern Ghat region. The seismic source 72 is delineated to account some recent concentrated seismic activity in down south, near Trivandrum (Kerala state) along the western margin. It appears that this region has also been active in the historical times. In addition, the region around Latur is numbered as a seismic source zone 76. The source 69 covers the Godavari Graben region which had experienced a moderate sized earthquake of Magnitude 5.3 (known as Bhadrachalam earthquake), in the year 1969. The region around Bellary and Coimbatore have been demarcated as source zones 75 and 73 respectively on account of having experienced moderate sized earthquakes in the past (Bhatia et al, 1997).

Study Area for Microzonation

Bangalore city covers an area of over 220 square kilometers and it is at an average altitude of around 910 m above mean sea level (MSL). It is the principal administrative, industrial, commercial, educational and cultural capital of Karnataka state, in the South India (Figure 3). It experiences temperate and salubrious climate and an annual rainfall of around 940 mm. 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 sq km. These tanks were once distributed throughout the city for better water supply facilities and are presently in a dried up condition, the residual silt and silty sand forming thick deposits over which buildings/structures have been erected. These soil conditions may be susceptible for site amplification during excitation of seismic waves. The population of Bangalore region is over 6 million. It is situated on a latitude of 12° 58' North and longitude of 77° 37' East. Bangalore city is the fastest growing city and fifth biggest city in India. Bangalore possesses many national laboratories, defence establishments, small and large-scale industries and

Information Technology Companies. These establishments have made Bangalore a very important and strategic city. Because of density of population, mushrooming of buildings of all kinds from mud buildings to RCC framed structures and steel construction and, improper and low quality construction practice, Bangalore is vulnerable even against average earthquakes (Sitharam et al, 2006). The recent studies by Ganesha Raj and Nijagunappa (2004), Sitharam et al. (2006) and Sitharam and Anbazhagan

(2007) have suggested that Bangalore need to be upgraded from the present seismic zone II (BIS, 2002) to zone III based on the regional seismotectonic details and hazard analysis. Hence sub soil classification for the Bangalore region is important to evaluate seismic local site effects for an earthquake.
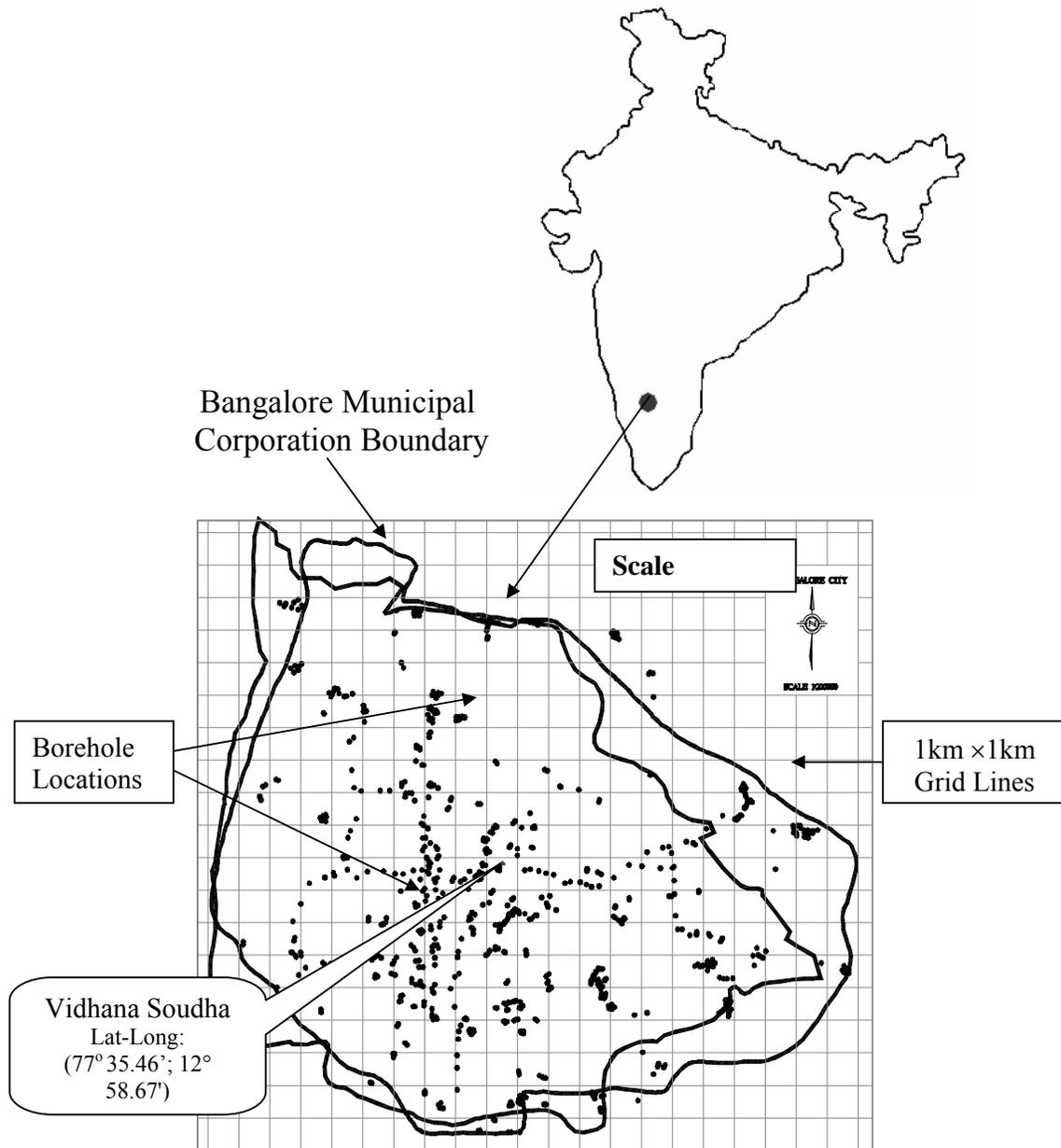

Figure 3: *Study area with SPT borehole locations*

Deterministic Seismic Hazard Analysis

Deterministic Seismic Hazard Analysis (DSHA) for Bangalore has been carried out by considering the past earthquakes, assumed subsurface fault rupture lengths and point source synthetic ground motion model. The seismic sources for region have been collected by considering seismotectonic atlas map of India and lineaments identified from satellite remote sensing images. Analysis of lineaments and faults help in understanding the regional seismotectonic activity of the area. Maximum Credible Earthquake (MCE) has been determined by considering the regional seismotectonic activity in about 350 km radius around Bangalore. Earthquake data are collected from IMD, USGS, NGRI, CESS, BARC, ASC and other public domain sites. 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 of the area. Using these details, and, attenuation relation developed for southern India by Iyengar and Raghukanth (2004), the peak ground acceleration (PGA) has been estimated. A parametric study has been carried out to find the fault subsurface rupture length 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 for the subsurface length corresponding to 3.8% of the total length of fault. Assuming 3.8 % of the total length of fault as the subsurface rupture length, the expected maximum magnitude for each source has been evaluated and PGA is estimated for these magnitudes. Further seismological model developed by Boore (1983, 2003) SMSIM program has been used to generate synthetic ground motions from seismogenic sources identified in the above two methods. Typical ground motion and spectral acceleration at rock level is shown in Figures 4 and 5. From the above three approaches maximum PGA of 0.15g was estimated for Bangalore. This value was obtained for a maximum credible earthquake (MCE) having a moment magnitude of 5.1 from a source of Mandya-Channapatna-Bangalore lineament. Considering this lineament and MCE, a synthetic ground motion has been generated for 850 borehole locations (Figure 3) and they are used to prepare PGA map at rock level (Figure 6).
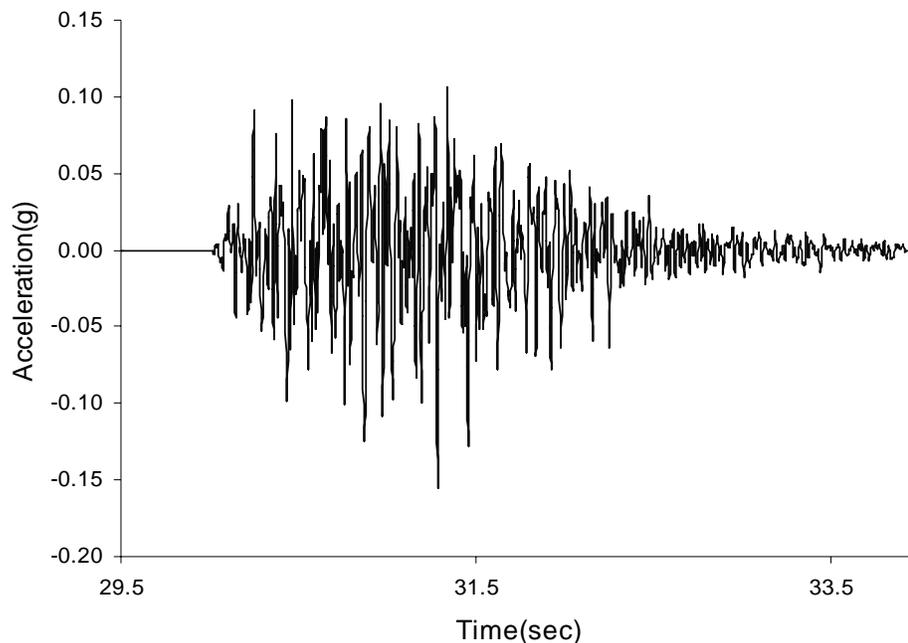
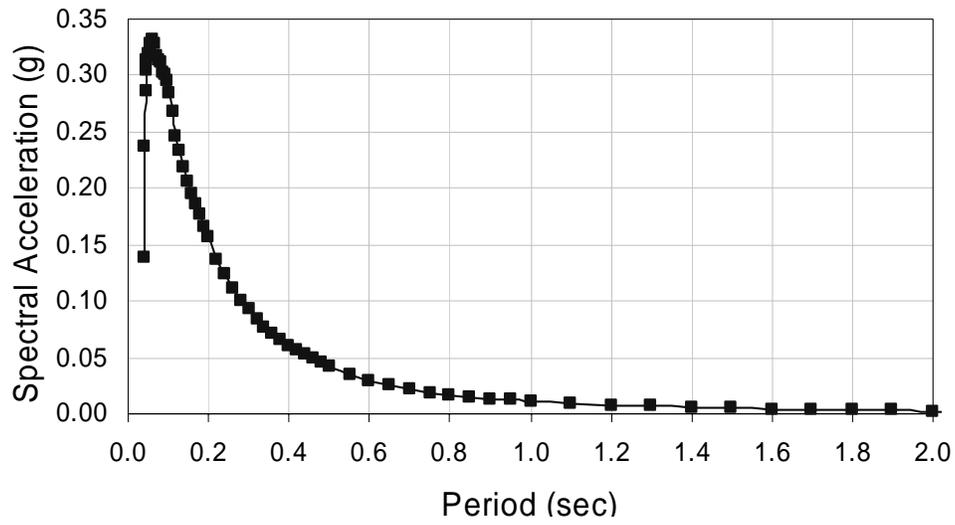**Figure 4** *Typical synthetic ground motion for rock site*

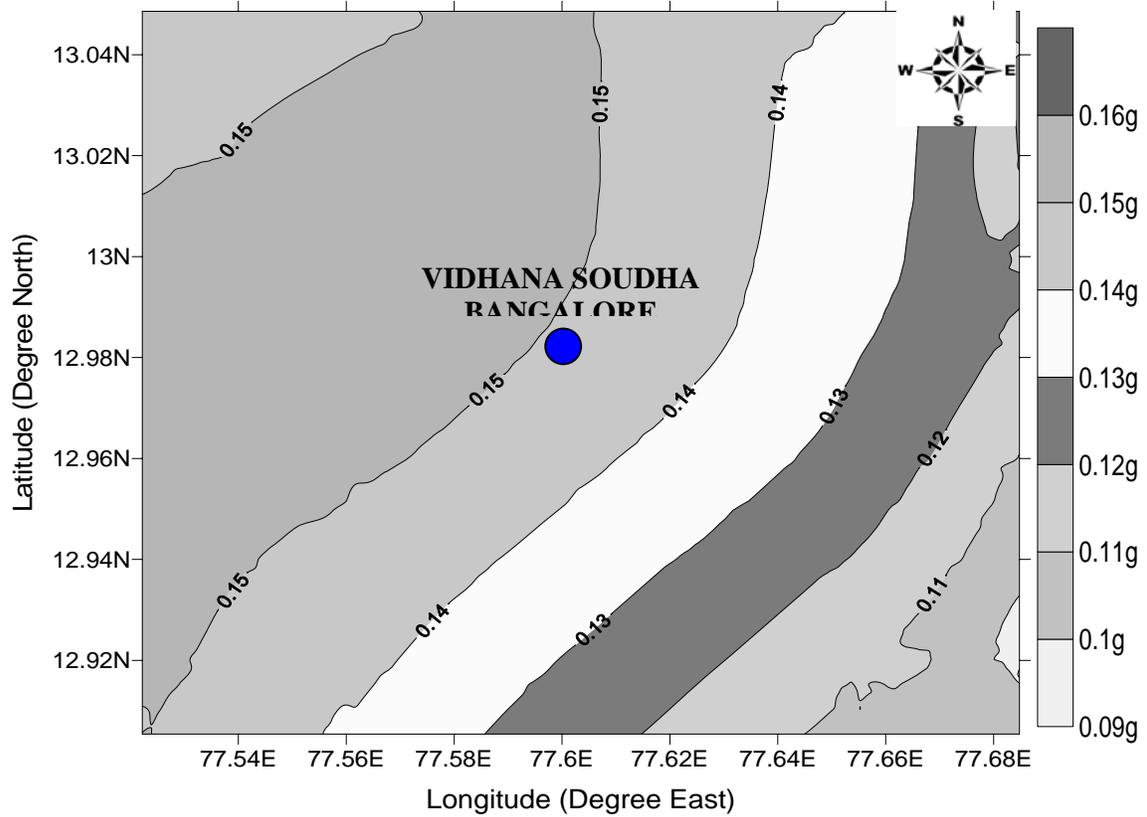**Figure 5**: *Typical Response spectra at Rock level*

Figure 6: *Rock Level PGA Map for Bangalore*

Probabilistic Seismic Hazard Analysis

Analyses have been carried out considering the seismotectonic region covering a circular area with a radius of 350km keeping Bangalore as the center. Seismic hazard parameter 'b' has been evaluated considering the available earthquake data using (1) Gutenberg–Richter (G-R) relationship and (2) Kijko and Sellevoll (1989, 1992) method utilizing extreme and complete catalogs. The 'b' parameter was estimated to be 0.87 from G - R relation and 0.87± 0.03 from Kijko and Sellevoll method. The obtained results are comparable with the 'b' values published earlier for southern India. Further, probabilistic seismic hazard analysis for Bangalore region has been carried out considering six seismogenic sources. From the analysis, mean annual rate of exceedance and cumulative probability hazard curve for Peak Ground Acceleration (PGA) and Spectral Acceleration (SA) have been generated. The mean annual rate of exceedance versus peak ground acceleration for all the sources at rock level is shown in Figure 7. Cumulative mean annual rate of exceedance versus spectral acceleration for period of 1 second and 5% damping (represented as hazard curve) is shown in Figure 8. In addition, Uniform Hazard Response Spectrum (UHRS) at rock level is also developed for the 5 % damping corresponding to 10 % probability of exceedance in 50 years. The peak ground acceleration (PGA) value of 0.121g obtained from the present investigation and it is comparable to PGA values obtained from deterministic seismic hazard analysis (DSHA) for the same area by Sitharam et al (2006) and Sitharam and Anbazhagan (2007). However, the PGA value obtained from the current investigation is higher than the Global Seismic Hazard Assessment Program (GSHAP) maps of Bhatia et al (1997) for the shield area. The study brings that the probabilistic and deterministic approaches will lead to similar answers complementing each other and provides additional insights to the seismic hazard assessment.
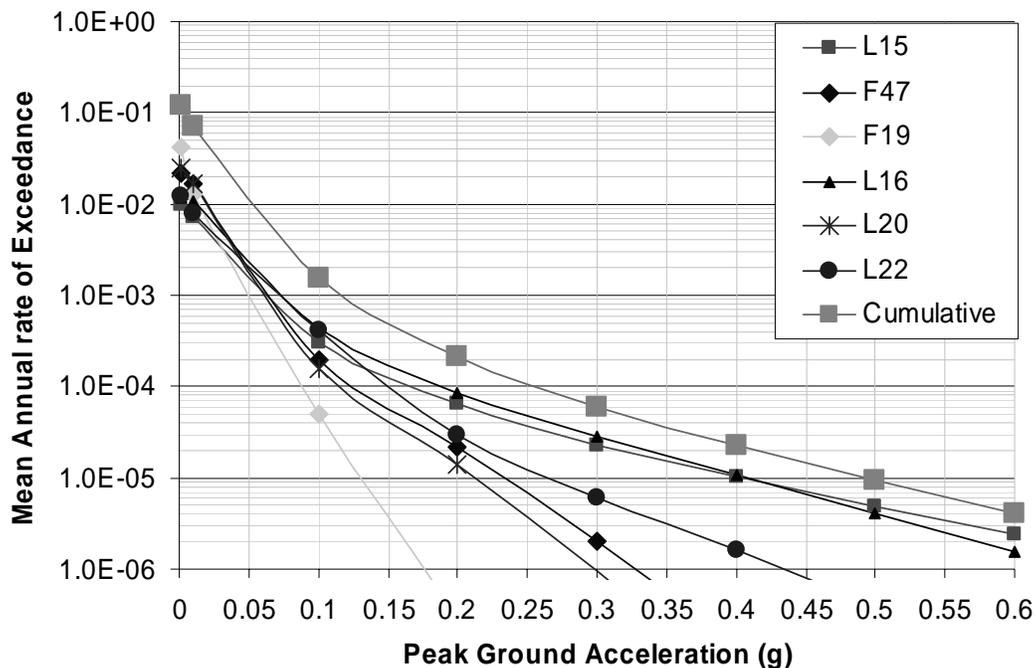

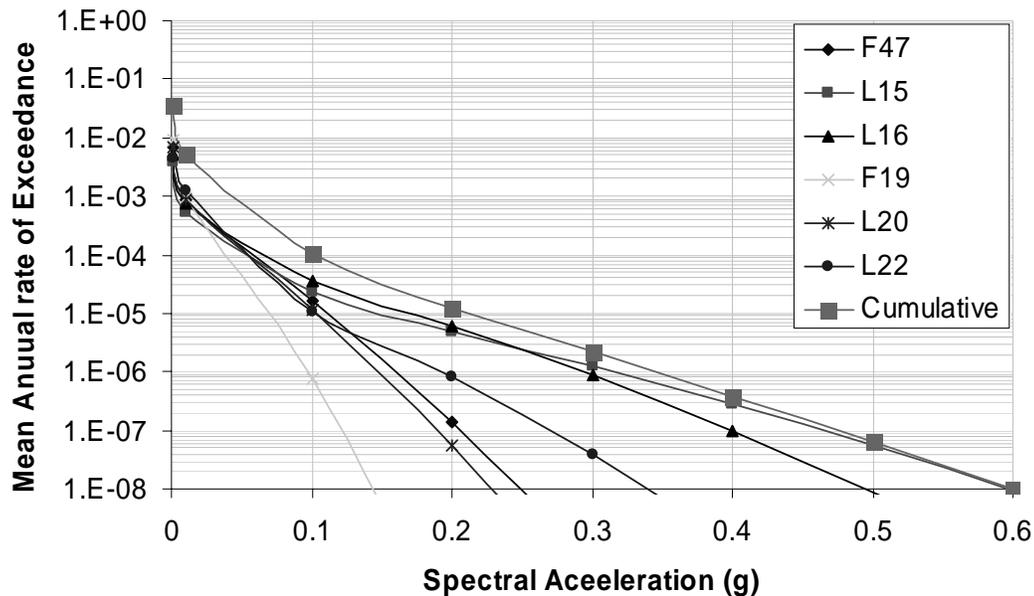**Figure 7:** *Hazard curves for different sources at the rock level for Bangalore*

Figure 8: *Spectral acceleration at the rock level corresponding to a period of 1s and 5% damping for Bangalore*

Site Characterization using geotechnical data (SPT)

The 3-D subsurface model with geotechnical data has been generated with development of base map of Bangalore city (220sq.km) 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). GIS database for collating and synthesizing geotechnical data available with different sources and 3-dimensional view of soil stratum presenting various geotechnical parameters with depth in appropriate format has been developed. Figure 9 shows the GIS model of borehole locations with respect to water features. Figure 10 shows the isometric view of some boreholes by overlapping of layers to get a 3-D projection. In the context of prediction of reduced level of rock (called as "engineering rock depth" corresponding to about Vs > 700 m/sec) in the subsurface of Bangalore and their spatial variability evaluated using geostatistical models such as ordinary kriging technique, Artificial Neural Network (ANN) and Support Vector Machine (SVM). Observed SPT 'N' values are corrected by applying necessary corrections, which can be used for engineering studies such as site response and liquefaction analysis.

From the 3-D subsurface model of geotechnical bore log data developed by Sitharam et. al, (2007), authors have identified that the overburden thickness of study area varies from 1m to about 40m. Subsurface profile information like unit weight, ground water level, SPT 'N' values are obtained from borehole data collected and compiled in the study area for the development of geotechnical subsurface model. With their wide distribution of data in the study area, these bore holes are considered to represent the typical features of soil profiles. Based on the nature of soils, classification of soils has been done for general identification of soil layers. Layer thickness and type of material are summarized in Table1. 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) Bore hole 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; Skempton, 1986; Youd et al., 2001 and Cetin et al., 2004). First, corrected 'N' value i.e., $(N_1)_{60}$ are obtained using the following equation:

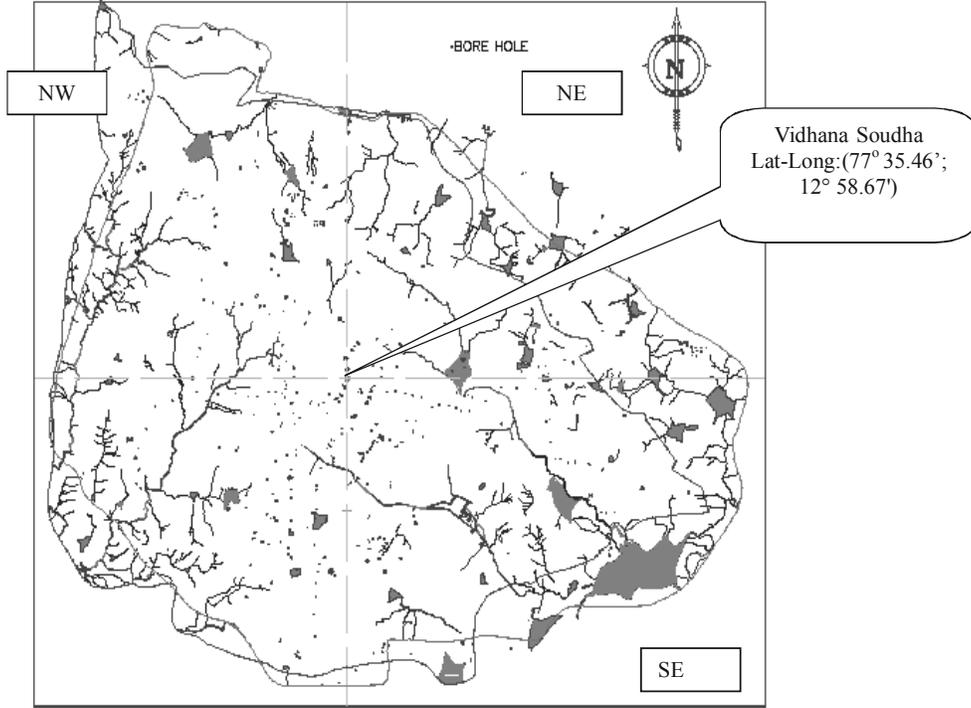$$(N_1)_{60} = N \times (C_N \times C_E \times C_B \times C_S \times C_R) \tag{1}$$

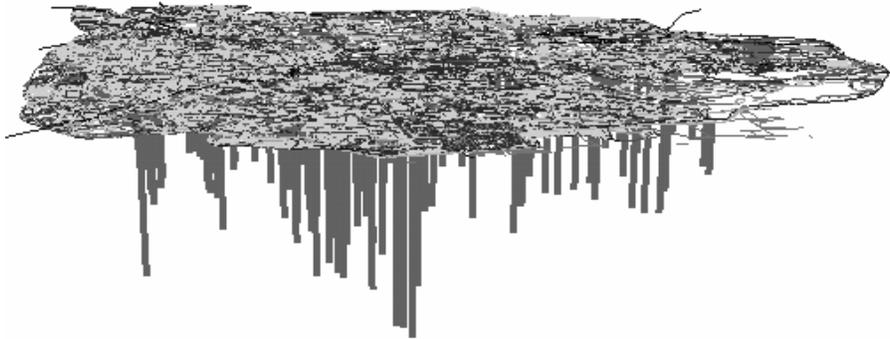**Figure 9** *GIS model of borehole locations with respect to water features*

Figure 10: *GIS model of borehole locations in 3-D view*

Then this corrected 'N' values $(N_1)_{60}$ is further corrected for fines content based on the revised boundary curves derived by Idriss and Boulanger (2004) for cohesionless soils as described below:

$$(N_1)_{60cs} = (N_1)_{60} + \Delta(N_1)_{60} \tag{2}$$

$$\Delta(N_1)_{60} = \exp\left[1.63 + \frac{9.7}{FC + 0.001} - \left(\frac{15.7}{FC + 0.001}\right)^2\right] \tag{3}$$

FC = percent fines content (percent dry weight finer than 0.074mm).

A typical "N" correction calculation table for a borehole data is shown in Table 2.

Table 1 Soil Distribution in Bangalore

Layer	Soil Description with depth and Direction			
	Northwest	Southwest	Northeast	Southeast
First Layer	Silty sand with clay 0-3m	Silty sand with gravel 0-1.7m	Clayey sand 0-1.5m	Filled up soil 0-1.5m
Second layer	Medium to dense silty sand 3m-6m	Clayey sand 1.7m-3.5m	Clayey sand with gravel 1.5m-10m	Silt sandy with clay 1.5m-9m
Third Layer	Weathered Rock 6m-17m	Weathered Rock 3.5m-8.5m	Silty sand with Gravel 10m-15.5m	Sandy clay 9m-17.5m
Fourth layer	Hard Rock Below the 17m	Hard Rock Below 8.5m	Weathered rock 15.5m-27.5m	Weathered Rock 17.5m-38.5m
Fifth Layer	Hard Rock	Hard Rock	Hard Rock Below 27.5m	Hard Rock Below 38.5m

Site Characterization Using Shear Wave Velocity Profiles By Masw

Site characterization has also been carried out using measured shear wave velocity with the help of shear wave velocity survey using MASW. MASW (Multichannel Analysis of Surface Wave) is a geophysical method, which generates a shear-wave velocity (*Vs*) profile (i.e., *Vs* versus depth) by analyzing Raleigh-type surface waves on a multichannel record.

MASW system consisting of 24 channels Geode seismograph with 24 geophones of 4.5 Hz capacity were used in this investigation. The shear wave velocity of Bangalore subsurface soil has been measured and correlation has been developed for shear wave velocity (Vs) with the standard penetration tests (SPT) corrected 'N' values. About 58 one-dimensional (1-D) MASW surveys and 20 two-dimensional (2-D) MASW surveys has been carried out with in 220 sq.km Bangalore urban area. The test locations are selected such a way that these represent the entire city subsurface information (Figure 11). Most of the survey locations are selected in flat ground and also in important places like parks, hospitals, schools and temple yards etc. The optimum field parameters such as source to first and last receiver, receiver spacing and spread length of survey lines are selected in such a way that required depth of information can be obtained. All tests has been carried out with geophone interval of 1m, source has been kept on both side of the spread and source to the first and last receiver were also varied from 5m, 10m and 15m to avoid the effects of near-field and far-field. These source distances will help to record good signals in very soft, soft and hard soils. The exploration services section at the Kansas Geological Survey (KGS) has suggested offset distance for very soft, soft and hard soil as 1m to 5m, 5m to 10m and 10m to 15m respectively (Xu et al., 2006).

Table 2 Typical "N" correction Table for borelog

Borehole 4						Correction Factors For					Water Table = 1.4 m/19-11-2005		
Depth	Field	Density	T.S	E.S	C_N					$(N_1)_{60}$	F.C	$\Delta(N_1)_{60}$	Corrected N value
	N Value					Hammer Effect	Bore hole Dia	Rod Length	Sample Method				
m	N Value	kN/m³	kN/m²	kN/m²							%		$(N_1)_{60cs}$
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

T.S - Total Stress
E.S - Effective Stress
C_N – Correction for overburden correction
$(N_1)_{60}$ – Corrected 'N' Value before correction for fines content
F.C – Fines content
$\Delta(N_1)_{60}$ – Correction for Fines content
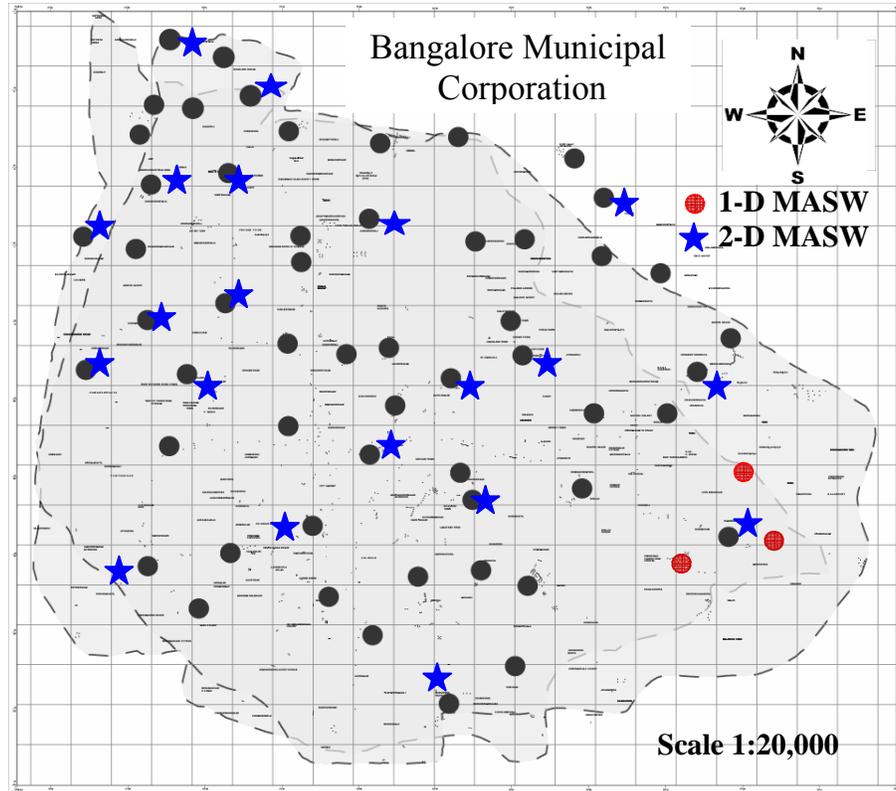$(N_1)_{60cs}$ – Corrected 'N' Value

Figure 11 *Study area with Marked MASW Testing Locations*

Dispersion curves and shear velocity 1-D and 2-D have been evaluated using SurfSeis software. The average shear wave velocity for the depth "d" of soil is referred as V_H. The average shear wave velocity up to a depth of H (V_H) is computed as follows:

$$V_H = \sum d_i / \sum (d_i / v_i) \tag{4}$$

Where $\sum d_i$ = cumulative depth in m.

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

$$Vs^{30} = \frac{30}{\sum_{i=1}^{N} (d_i / v_i)} \tag{5}$$

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. Vs^{30} is accepted for site classification as per NEHRP (National Earthquake Hazard Research Programme) 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 (4) for each location. A simple spread sheet has been generated to carry out the calculation, as shown in Table 3. The Vs average has been calculated for every 5m depth interval up to a depth of 30m and also average Vs for the soil overburden has been calculated. Usually, for amplification and site response study the 30m average Vs is considered. However, if the rock is found within a depth of about 30m, near surface shear wave

Table 3 Typical average shear wave velocity calculation

Depth (m)	Vs (m/s)	Soil thickness [d] (m)	Average Vs Soil-7.2m	Average Vs-5m	Average Vs-10m	Average Vs-15m	Average Vs-20m	Average Vs-25m	Average Vs-30m
-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							

Table 4: Site Classes for average shear wave velocity

Site Class	Range of average shear wave velocity (m/s)
A	$1500 < Vs^{30}$
B	$760 < Vs^{30} = 1500$
C	$360 < Vs^{30} = 760$
D	$180 < Vs^{30} = 360$
E	$Vs^{30} < 180$

velocity of soil has to be considered. Otherwise, Vs^{30} obtained will be higher due to the velocity of the rock mass. In Bangalore the soil overburden thickness varies from 1m to about 40m. Hence, for overburden soil average Vs has also been calculated based on the soil thickness corresponding to the location, which is also shown in column 4 of Table 3. Using 1-dimensional shear wave velocity, the average shear wave velocity of Bangalore soil has been evaluated for depths of 5m, 10m, 15m, 20m, 25m and 30m (Vs^{30}) depths. Figure 12 shows the map of average shear wave velocity for a depth of 30m. The calculated average shear wave velocities are grouped according to the NEHRP site classes (Table 4) and map has been generated. The sub soil classification has been carried out for local site effect evaluation based on average shear wave velocity of 30m depth (Vs^{30}) of sites using NEHRP and UBC classification. Bangalore falls into "site class D" type of soil. Mapping clearly indicates that the depth of soil obtained from MASW is closely matching with the soil layers in the bore logs.
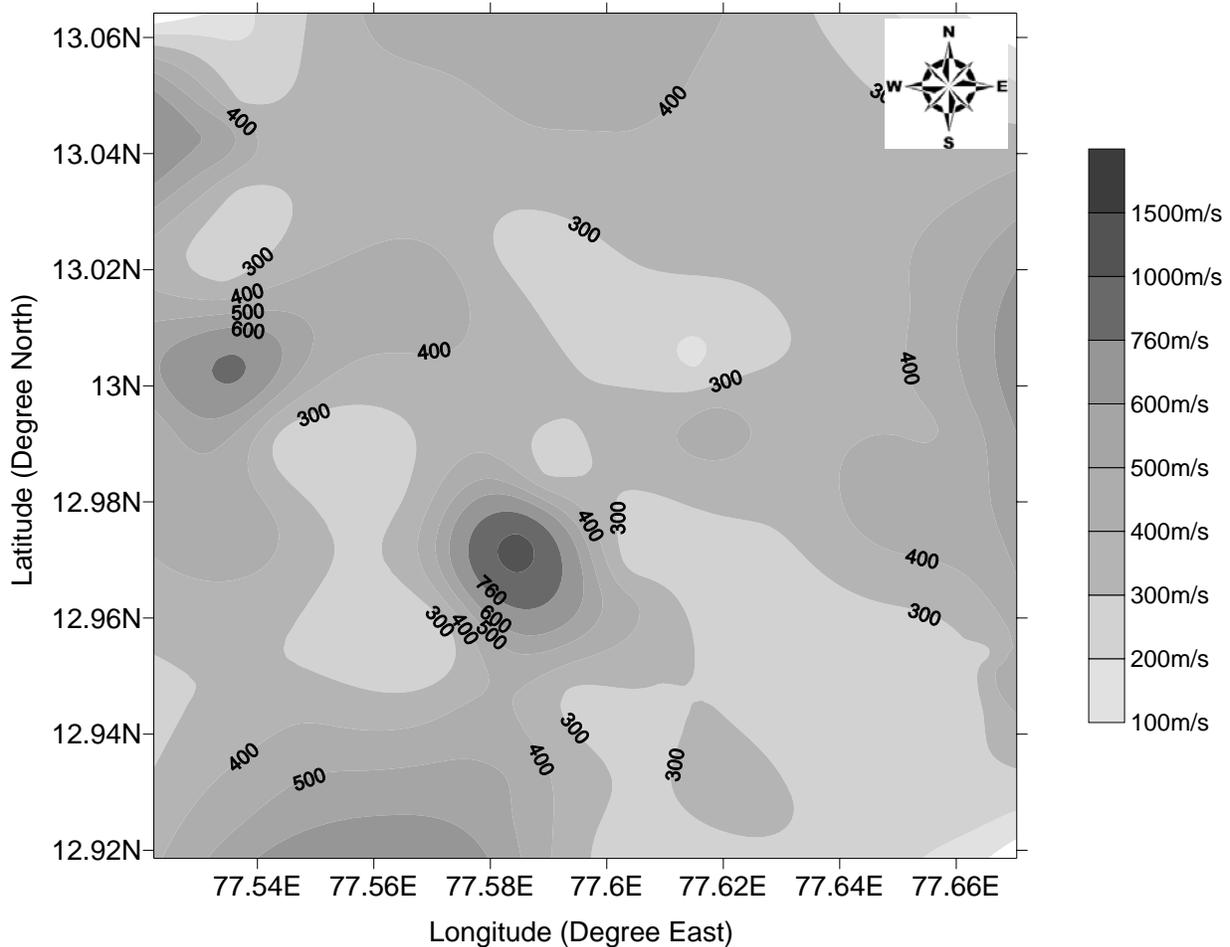
Figure 12 *Average shear wave velocity for 30m Depth*

Mapping of Subsurface Layers

2-D MASW test has been carried out at 20 locations with minimum length of 12m. Inbuilt kriging operation has been used to make interpolation of each mid point velocity and generate the 2-D *Vs* profile for a mid point of first spread line to mid point of last spread line. Typical 2-D velocity profile is shown in Figure 13. From Figure 13, it is clear that shallow depth shear wave velocities are with in

the range of 360m/s. When depth increases, the shear wave velocities also increase. General observation from the 2-D Vs profiles, material layers of velocity 300m/s and above is dipping, falling and tilting, which may be due to the undulation and variation in original ground elevation. Also there is no considerable ground layering anomaly present in the subsurface and few locations where filled up soil is found (earlier tank beds which are encroached for habitation).
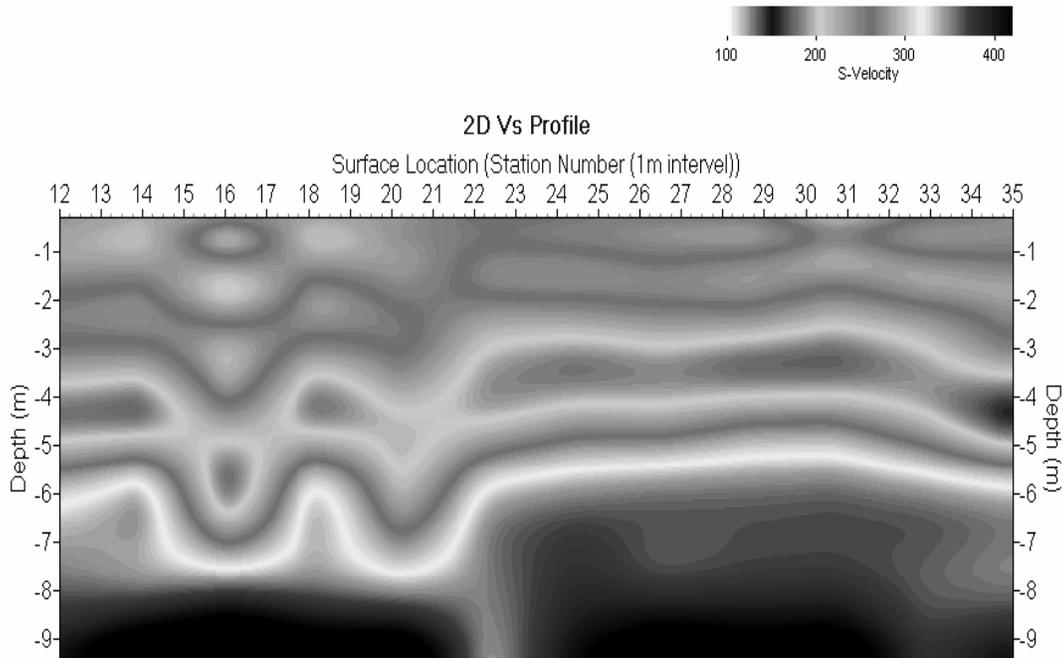

Figure 13: 2-D spatial variation of shear wave velocity

Correlation between $(N_1)_{60cs}$ AND V_S

The measured shear wave velocity at 38 locations were close to SPT boreholes, which are used to generate the correlation between the shear wave velocity and corrected 'N' values using a power fit. Prediction of ground shaking response at soil sites requires knowledge of shear modulus of the soil, which is directly expressed in terms of shear wave velocity. It is preferable to measure Vs directly by using field tests. However, presently it is not feasible to make Vs measurements at all the locations. Hence to make use of abundant available penetration measurements to obtain Vs values, correlation between Vs and penetration resistance are being done. Velocity calculated using 1-D MASW which represents Vs at mid point of each survey line, has been used for this purpose. About 162 data pairs of Vs and SPT corrected below count have been used for the regression analysis. The Vs values are selected from the 1-D MASW results corresponding to SPT "N" value at different depths. The regression equation developed between Vs and $(N_1)_{60cs}$ is given in equation 6 (with regression coefficient of 0.84):

$$Vs = 78[(N_1)_{60cs}]^{0.40} \tag{6}$$

Where, Vs is the shear wave velocity in m/s and $(N_1)_{60cs}$ is the corrected SPT 'N' value.

Japan Road Association (JRA, 1980) equations (equation 7 -for clayey soil and equation 8- for sandy soil), relating Vs and N_{60} are given below:

$$Vs = 100(N_{60})^{1/3} \quad \text{(JRA, 1980)- For clayey soil} \tag{7}$$

$$Vs = 80(N_{60})^{1/3} \quad \text{(JRA, 1980)} \quad \text{- For Sandy soil} \tag{8}$$

The coefficients are close to the value for the sandy soil. From the comparison between JRA equations with newly developed equation (6), it is clear that the fitted equation lies between the JRA equations for sandy and clay equations for wide range of "$(N_1)_{60cs}$" values, because the soil overburden in Bangalore has sand and silt with some percentage of clay content. Also, developed relationship between shear wave velocity and corrected 'N' values corresponds well with the published relationships of Japan Road Association.

Local site effects and Site Response

Bangalore city, a fast growing urban center, with low to moderate earthquake history and highly altered soil structure (due to large reclamation of land) is been the focus of this work. 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 sq km. In the present study, an

attempt has been made to assess the site response using geotechnical, geophysical data and field studies. The subsurface profiles of the study area within 220sq.km area was represented

by 160 geotechnical bore logs (Figure 14) and 58 shear wave velocity profiles obtained by MASW survey. The data from these geotechnical and geophysical technique have been used to study the site response. These soil properties and synthetic ground motions for each borehole locations are further used to study the local site effects by conducting one-dimensional ground response analysis using the program SHAKE2000. The non-linearity of the shear modulus and damping is accounted for by 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 as discussed above. The degradation curves for sand and rock used for the present work are those proposed by Seed and Idriss (1970) and Schnabel (1973) respectively. The response and amplification spectrum have been evaluated

for each layer of borehole location. The map shows the peak acceleration at ground surface, amplification factor, period of the soil column, peak spectral acceleration, frequency corresponding to the peck spectral acceleration and the response spectrum at the ground surface of frequency of 1.5Hz, 3Hz, 5Hz, 8Hz and 10Hz for a 5% damping ratio. The microzonation maps prepared indicates a medium variation in amplification potential. There is a need for quantifying the number of times the PHA value at bedrock is amplified by the time it reaches the ground surface as stated in the previous section. The term "Amplification Factor" is hence 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 PHA 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 SHAKE 2000. With the amplification factors varying from 1 to 4.7 and period of soil column from 0.08 to 4.5 seconds, the region is moderately amplifying. The amplification factor map for Bangalore City is shown in Figure 15. The spectral acceleration (SA) values for all the locations at 1.5 Hz, 3 Hz, 5Hz, 8 Hz and 10 Hz are computed and SA corresponding to a frequency of 8Hz is shown in Figure 16. A peculiar feature of the study region is that it has reclaimed land from silted lakes/tanks leading to significant variations in ground response.
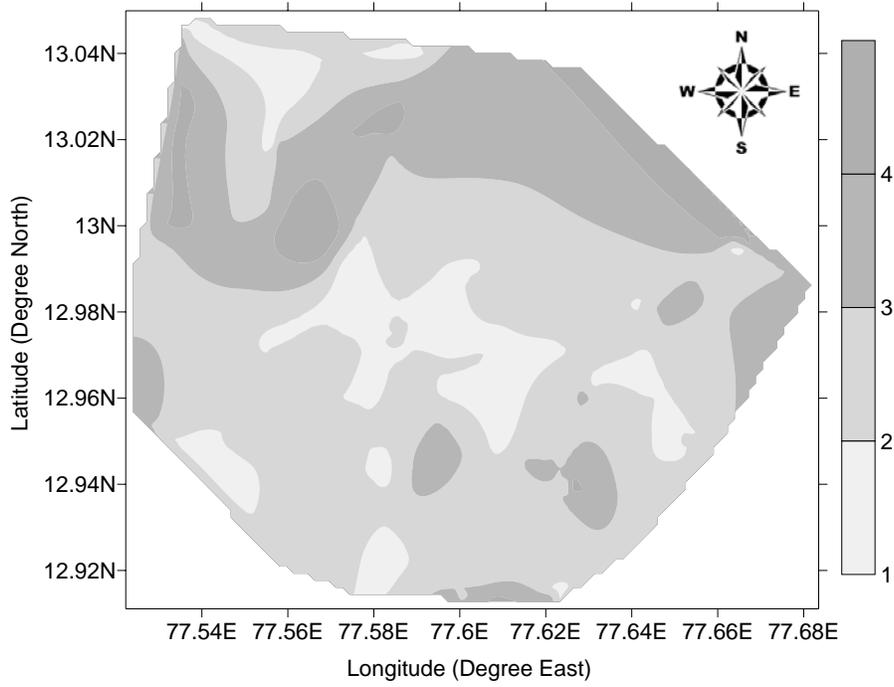
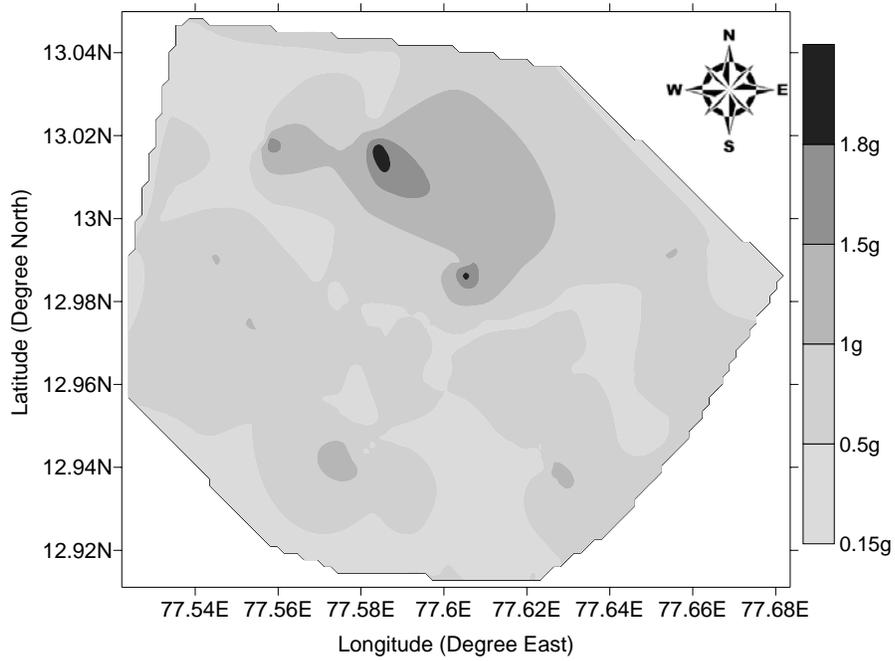**Figure 15** *Amplification Factor map for Bangalore City*

Figure 16 *Spectral Acceleration Map of Bangalore City at 8 Hz Frequency*

Site Response study using shear wave velocity

Growth of geophysical methods particularly SASW (spectral analysis of surface wave) and MASW are being increasingly used for the site response study and microzonation of cities world wide. Shear wave velocities (Vs) measured using geophysical method are widely used to get better results of site response studies than SPT data. Because, wave propagation theory shows that ground motion amplitude depends on the density and shear wave velocity of subsurface material (Bullen, 1965; Aki and Richards, 1980). Usually density has relatively little variation with depth but shear wave velocity is the logical choice for representing site conditions. The response spectrum for 5% damping at the ground surface obtained for 160 borehole locations and 58 MASW survey locations clearly indicate that the range of spectral acceleration (SA) at different frequencies varied from 0.01 to 2.17g. Response parameter obtained using MASW data is comparable with the results of SPT. However results from MASW is lower than the results from SPT. Peak spectral acceleration values at lower period using MASW data is lower than SPT data, but the higher period values matches well for both the 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 one is shown in Figure 18.
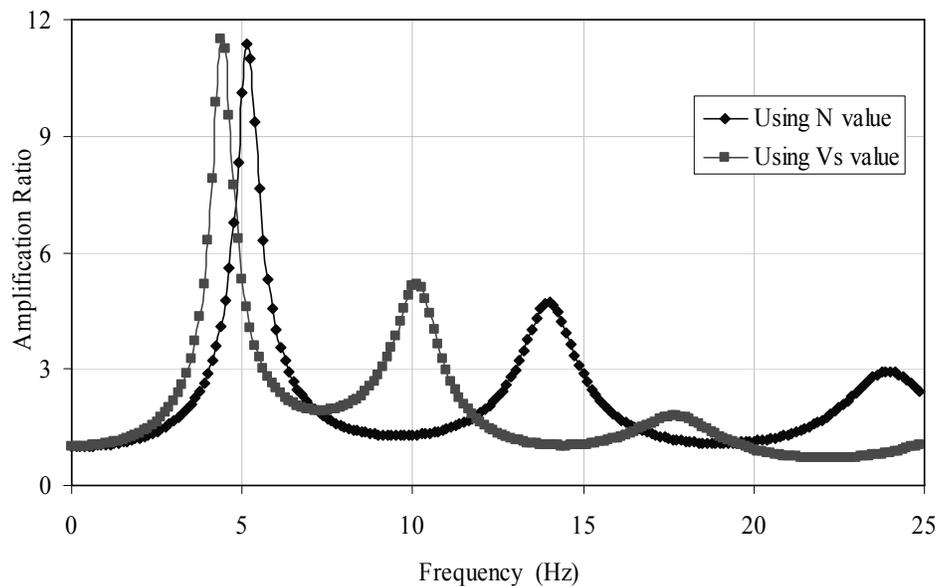

Figure 18 *Typical Amplification Ratio Using Both Data*

Predominant Frequency of Soil using site Response study

A single parameter widely used to categorize the soil for a ground motion is the predominant frequency, which is mainly, depends on the soil column height and its properties. The predominant frequency is defined as 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 of each borelog are estimated using both SPT data and MASW data. Results shows that predominant frequencies are similar from both analysis and varies from 3Hz to 12Hz using SPT data and 3.5Hz to 12Hz using MASW data. To find the variation of predominant frequencies from both method, the site response study (SHAKE2000 analyses) 33 points by SPT and MASW methods are considered. Predominant frequencies corresponding to these locations are presented in Figure 19. Figure 19 shows that predominant frequencies obtained from both

data are comparable; values above the symbol are obtained using SPT data and below the symbol are obtained using MASW data. Table 5 shows that most of the study area has higher predominant frequency (3 Hz to 12.5 Hz) from both methods.
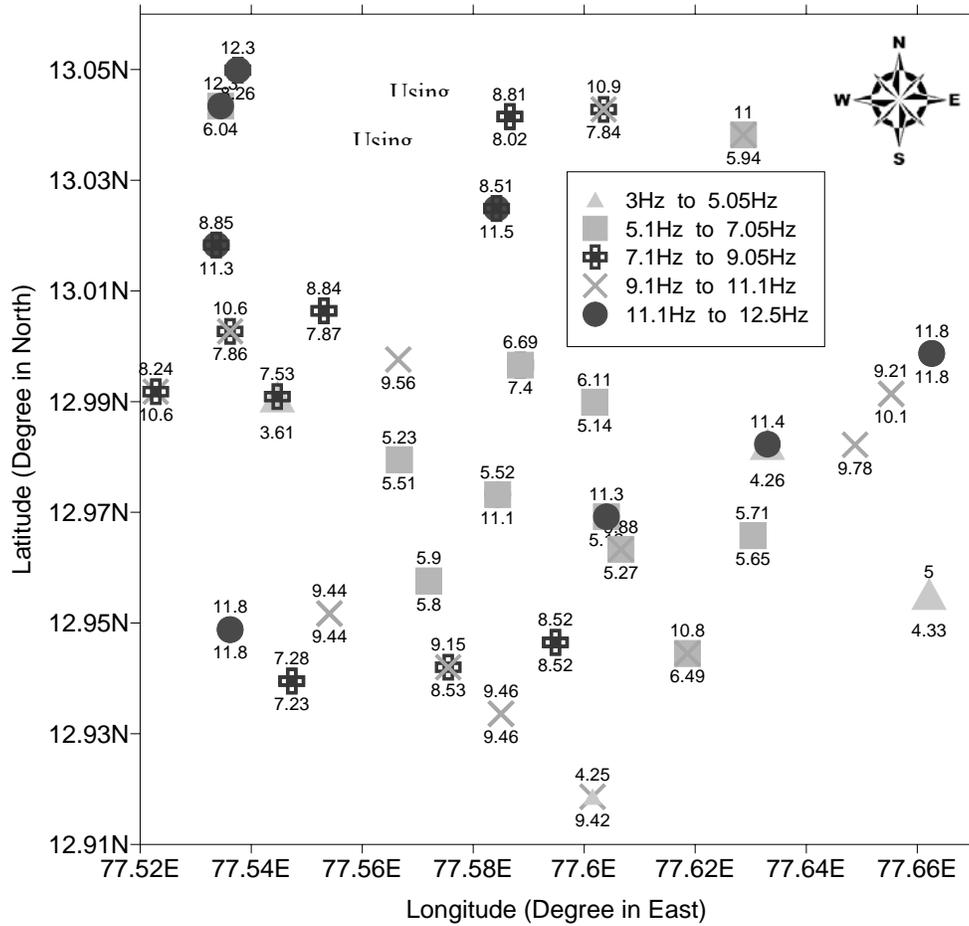

Figure 19 *Predominant Frequencies using SPT and MASW Data*

Table 5 Predominant frequency Ranges

Predominant Frequency Range (Hz)	Symbols	Numbers of sites	
		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
9.0 to 11.0	✕	9	7
11.1 to 12.5	●	8	5

Correlation between (N$_1$)$_{60cs}$ and G$_{max}$

Ground response study using SPT data and MASW data for same locations clearly shows that results obtained from SPT data are higher than MASW data result. Even though input motion, densities, thickness of layer and analysis procedures are same for both results, variation in the output may be due to another important input of dynamic soil properties. In SHAKE2000 dynamic soil properties such as shear modulus are evaluated based on the inbuilt equation (equation 13 in SHAKE2000) developed by Imai and Tonouchi (1982) which is given below:

$$G_{\max}(kips / ft^2) = 325[(N_1)_{60cs}]^{0.68} \text{ (Imai and Tonouchi, 1982)} \tag{9}$$

The shear wave velocity is back calculated from the well known equation of $G = \rho Vs^2$. In response study using MASW data, shear modulus (G$_{max}$) is calculated by accounting the both density as well as in-situ shear wave velocities, which is given below:

$$G_{\max} = \rho V_s^2 \tag{10}$$

Where

ρ density measured from the undisturbed sample in SPT boreholes

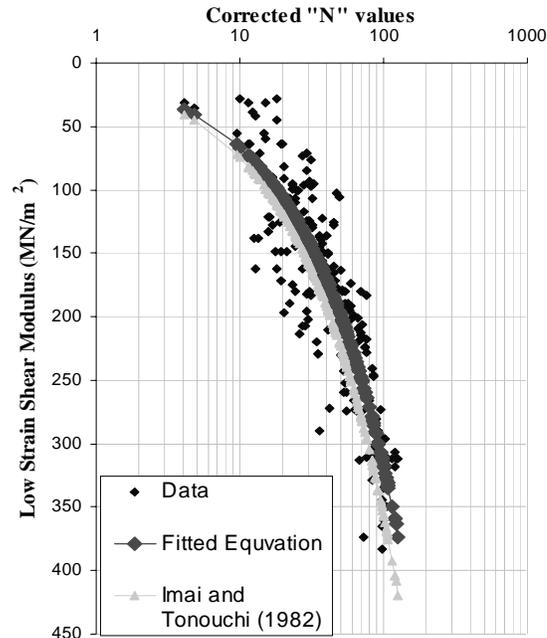*Vs* shear wave velocity measured using the MASW testing.

Figure 20 *Comparison of shear modulus equations*

Dynamic properties obtained from SPT test correspond to high strain values when compared to MASW test which gives properties at low shear strains. Also the factor affecting G$_{max}$ depends on soil parameters, but in SHAKE2000, G$_{max}$ is calculated based on the inbuilt equation developed for some region. From this study it is felt that Shake programme can be effectively used by using G$_{max}$ equation for the region or the in-situ shear wave velocity for shake analysis. Studies show that the site response obtained from SHAKE2000 using MASW data is reasonably good when compared to using SPT data. The SPT data can be effectively used for site response analysis, if regional G$_{max}$ equation is developed.

To fulfill this requirement an attempt has been made to correlate the measured G_{max} (calculated from measured shear wave velocity and densities of each layer) of each borehole to corrected SPT-N values. About 38 locations MASW data were very close to the SPT bore hole. From 38 locations about 195 data pairs of *Vs* and SPT corrected blow count have been used for the regression analysis. The regression equation developed between *Vs* and $(N_1)_{60cs}$ is given in equation 11:

$$G_{max} = 13.86\left[(N_1)_{60cs}\right]^{0.68} \tag{11}$$

Where, G_{max} –Low strain maximum shear modulus in MN/m^2,

$(N_1)_{60cs}$ – Corrected SPT "N" Value.

Power regression fitting gives the highest R squared value of 0.87. The comparison between Imai and Tonouchi (1982) equations (equation 9) with newly developed equation (11) are given in Figure 20. Fitted equation (11) matches up to a corrected SPT-N [$(N_1)_{60cs}$] value of 30 with Imai and Tonouchi (1982) equation. Beyond the "$(N_1)_{60cs}$" values of 30 fitted equation G_{max} is lower than the Imai and Tonouchi (1982) equation.
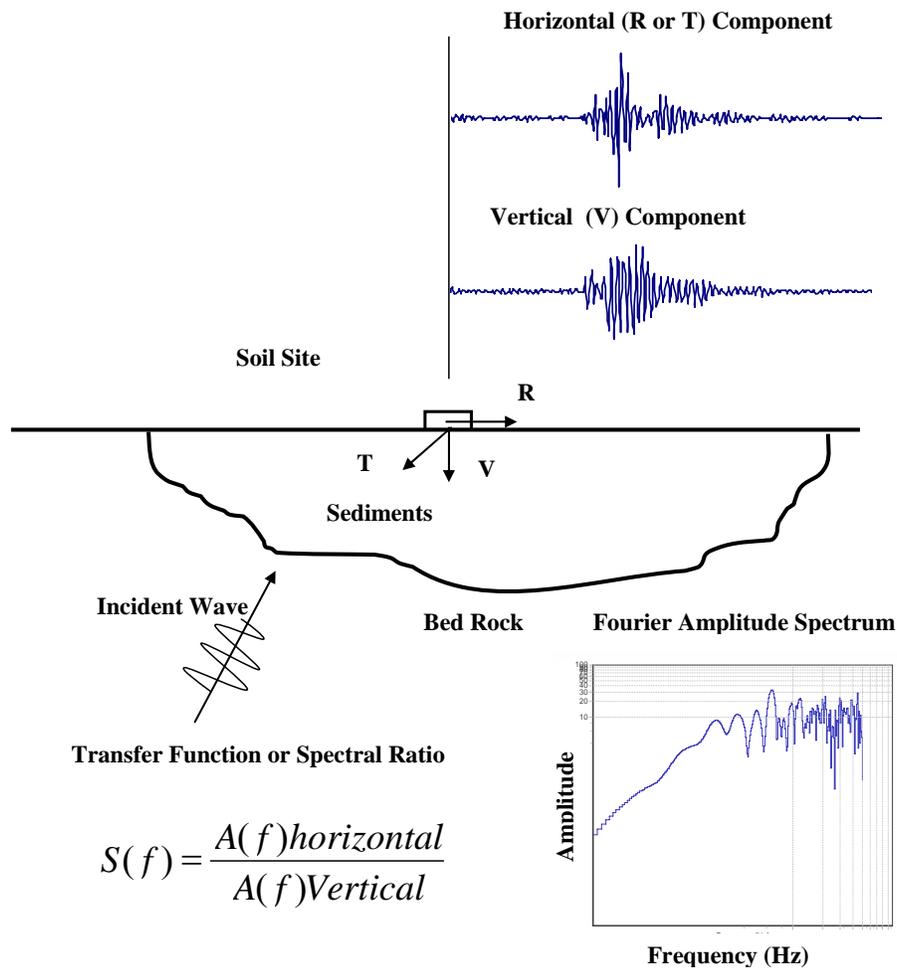

Figure 21(a) *Horizontal to Vertical Spectral Ratio Technique –*

Site Response Using Micro Tremor (Jointly with NGRI)

The site response studies also carried out experimentally based on recording the ambient noise for a selected period of duration. The noise was recorded at 54 different locations in 220sq.km area of Bangalore city using L4-3D short period sensors (CMG3T) equipped with digital data acquisition system. In this study, Nakamura method was adopted by NGRI for obtaining the transfer function at various sites in Bangalore. The general layout of the Horizontal to Vertical Spectral Ratio technique (HVAR) is shown in Figure 21(a). The surface sources for the ambient noise generate Rayleigh waves which affect the vertical and horizontal motion equally in the surface layer. The spectral ratio of the horizontal component to the vertical component of the time series provides the transfer function at a given site. The dominant peak is well correlated with the fundamental resonant frequency. The predominant frequencies obtained from experimental result range between 1.2 Hz -11 Hz, which matches well with the 1-dimensional ground response analysis presented earlier.

Comparison of Predominant Frequency

Even though the Microtremor and MASW was carried out separately, about 43 points are comparatively closer to each other. These points are further used to compare the predominant frequency of Bangalore soil. Site response studies using SPT and MASW data shows that the predominate frequency of Bangalore soil varies from 3Hz to 12Hz. But a microtremor studies shows that the predominant frequency of Bangalore soil varies from 1.5Hz to 12Hz. The predominant frequency estimated from Microtremor and site response using MASW is shown in Figure 21(b). From Figure 21(b) the values above the symbol obtained using MASW site response study and values below the symbols are obtained using microtremor. Figure Figure 21(b) also clearly shows that in most of the locations predominant frequency from both the method matches well. Most of the study area has predominant frequency of 3 Hz to 12 Hz from site response using SHAKE and microtremor studies, which is shown in Table 4.
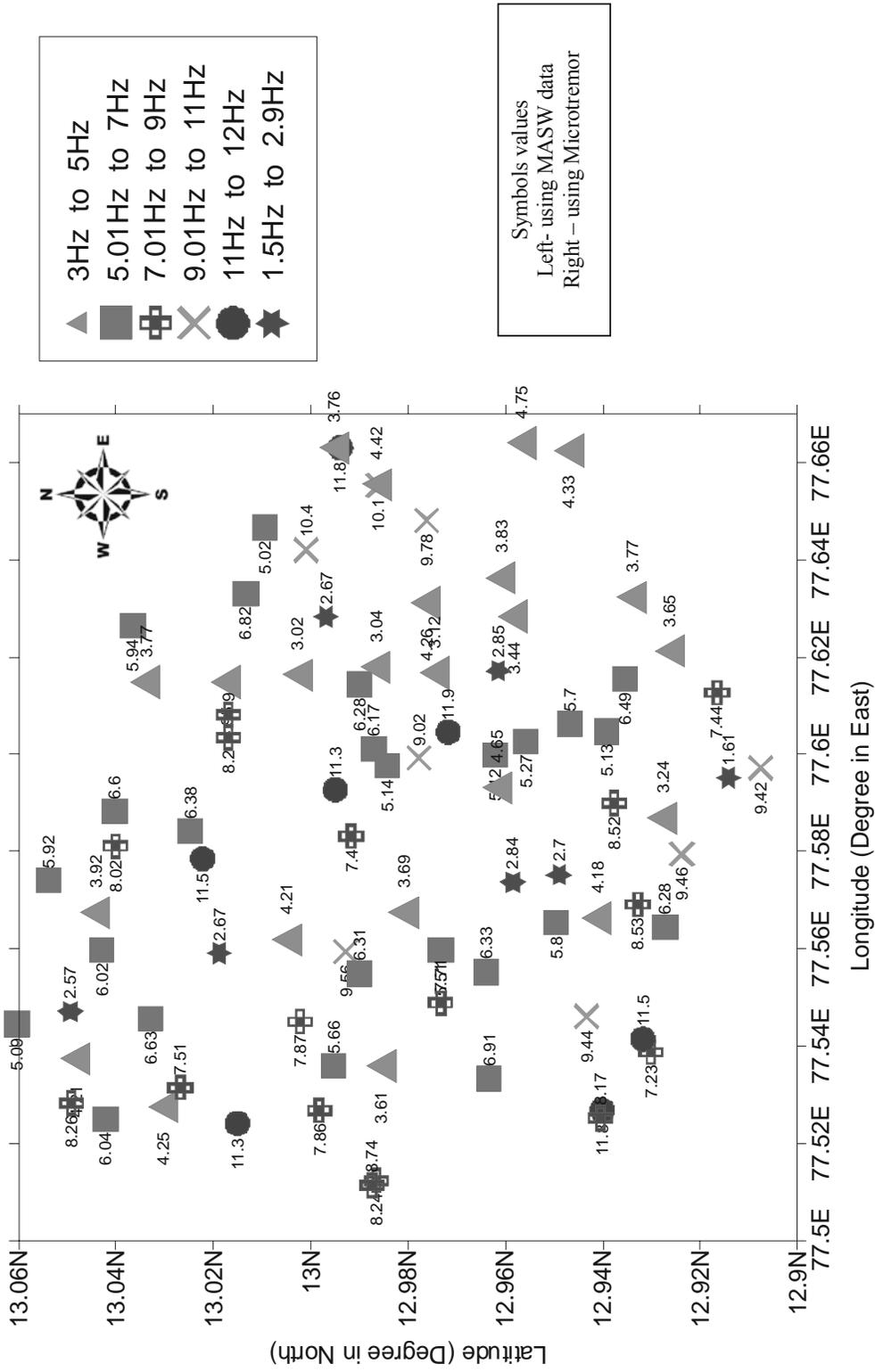
Table 4 Predominant Frequency using site response study and Microtremor

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
9.0 to 11.0	✕	6	2
11.1 to 12.5	●	4	3
1.5 to 2.9	★	-	7

Liquefaction Hazard Assessment

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 layer has 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 and amplified peak ground acceleration. Cyclic Resistant Ratio (CRR) is arrived using the corrected SPT 'N' values and soil properties. In the cyclic stress approach, the generation of pore pressure related to the cyclic shear stresses and earthquake loading represented same. The earthquake loading can be evaluated using Seed and Idriss (1971) simplified approach as given below:

$$\text{Cyclic stress ratio (CSR)} = 0.65\left(\frac{a_{max}}{g}\right)\left(\frac{\sigma_{vo}}{\sigma_{vo}'}\right)r_d \tag{12}$$

Figure 21(b) *Predominant frequency from Microtremor and Site Response using Shear wave Velocity*

In this equation $0.65 \dfrac{a_{max}}{g}$ represents 65 % of the peak cyclic shear stress, a_{max} is peak ground surface acceleration, g is the acceleration of gravity, σ_{vo} and σ_{vo}' are total and effective vertical stresses and r_d = stress reduction coefficient. For the calculation of stress reduction coefficient many correlations are available which are discussed in detail in the NCEER workshop report (NCEER, 1997; Youd et al 2001). NCEER, (1997) and Youd et al (2001) recommends that for routine practice and non-critical projects, the equations given by Liao and Whitman (1986) may be used to estimate average values of r_d and is given below:

$$r_d = 1.0 - 0.00765_z \quad \text{for z≤9.15 m} \tag{13}$$

$$r_d = 1.174 - 0.0267z \quad \text{for 9.15 m < z ≤ 23 m} \tag{14}$$

Cyclic resistance ratio (CRR) is arrived based on corrected 'N' value from a plot of CRR versus corrected 'N' value from a large amount of laboratory and field data. Liquefaction resistance of soil depends on how close the initial state of the soil is to the state corresponding to the "failure". The liquefaction resistance can be calculated based on the laboratories tests and in-situ tests. Cyclic resistance ratio (CRR) is arrived based on corrected "N" value as per Seed et al. (1985), Youd et al., (2001); Cetin et al., (2004). Seed et al. (1985) presents a plot of CRR versus corrected "N" value from a large amount of laboratory and field data. The corrected "N" values are used to calculate the CRR for the magnitude of 7.5 earthquake using equation proposed by Idriss and Boulanger (2005) which as given below:

$$CRR = \exp\left\{ \frac{(N_1)_{60cs}}{14.1} + \left(\frac{(N_1)_{60cs}}{126} \right)^2 - \left(\frac{(N_1)_{60cs}}{23.6} \right)^3 + \left(\frac{(N_1)_{60cs}}{25.4} \right)^4 - 2.8 \right\} \tag{15}$$

However this estimation is proposed for an earthquake magnitude of 7.5. For the present study, for the earthquake moment magnitude of 5.1 has to be considered, so the necessary Magnitude Scaling Factor (MSF) has been evaluated. The magnitude-scaling factor used in the present study for the magnitude less than 7.5 is given below (Seed and Idriss, 1982):

$$MSF = \left[\frac{10^{2.24}}{M_W^{2.56}} \right] \tag{16}$$

Factor of safety against liquefaction: The cyclic stress ratio caused by the earthquake is greater than the cyclic resistance ratio of in situ soil then liquefaction could occur. The factor of safety against liquefaction is defined as follows:

$$FS = \left(\frac{CRR_{7.5}}{CSR} \right) MSF \tag{17}$$

Factor of safety against liquefaction is calculated using stress ratios and accounting necessary magnitude scaling factor for maximum credible earthquake. A simple spread sheet was developed to carryout the calculation for each bore log. The factor of safety against liquefaction is grouped together for the purpose of classification of Bangalore (220 sq. km) area for a liquefaction hazard. Using 2-D base map of Bangalore city, the liquefaction hazard map was prepared using AutoCAD and Arc GIS packages. The results are grouped as four groups for mapping and presented in the form of 2-dimensional maps. Figure 22 shows the map of factor of safety against liquefaction (FS) for Bangalore city to the local magnitude of 5.1. About 90% of the area in Bangalore have heigher factor of safety and are non-liquefiable. This study shows that Bangalore is safe against liquefaction except at few locations where the overburden is sandy silt with presence of shallow water table.
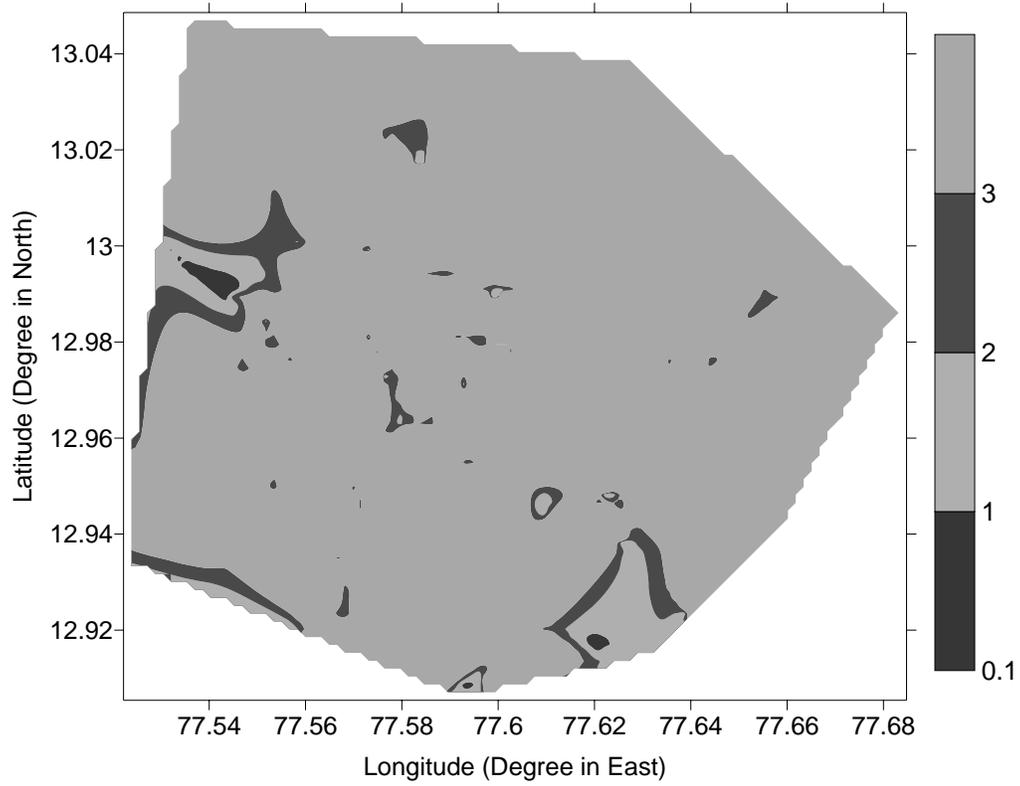
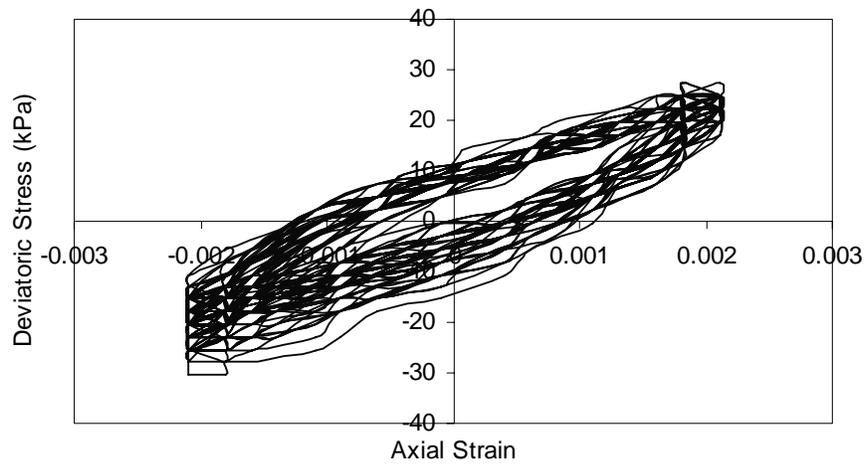**Figure 22** *Distribution Factor of safety against Liquefaction*

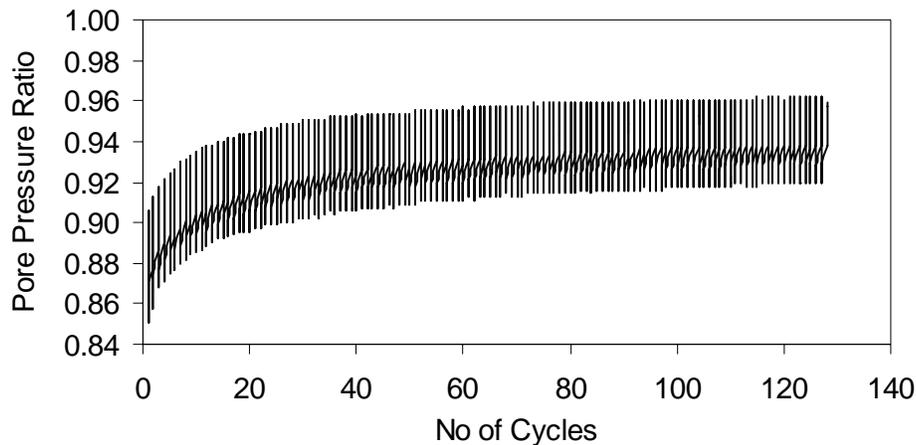**Figure 23** *Typical hysteresis loops from a Cyclic Triaxial test*

Figure 24: *Typical Pore Pressure Ratio Plot with*

Cyclic Triaxial Experiments on Undisturbed Soil Samples

Undisturbed samples were collected from few locations in (south west region) Bangalore city to verify the liquefaction potential of the soil. This is done by conducting cyclic triaxial test in the laboratory on the undisturbed soil samples collected from Boreholes locations of 482, 810 and 91. The test has been carried out as per ASTM: D 3999 (1991) in strain controlled mode. Cyclic triaxial tests are carried out with double amplitude axial strains of 0.5%, 1% and 2% with a frequency of 1Hz. A typical cyclic triaxial test results are presented in Figures 23 and 24. Figure 23 shows the variation of deviatoric stress versus strain plot for more than 120 cycles of loading (axial strain = 0.25%; applied confining pressure 100 KPa, for the undisturbed sample corresponding to depth 3m below GL, in-situ density of the soil sample 2.0 gm/cc with in-situ moisture content 15%, at 3.0m depth). Figure 24 shows the pore pressure ratio versus number of cycles. From these plots it is clear that even after 120 cycles, the average pore pressure ratio is about 0.94 and deviatoric stress versus strain plots has not become flat, indicating no liquefaction. The resistance to liquefaction is very high. The calculated factor of safety against liquefaction results, for this borehole is also very high indicating no liquefaction. These results match well with the lab test results (Sitharam et al 2007).

Summary

This study shows that, expected peak ground acceleration (PGA) at rock level for Bangalore is about 0.15g using DSHA. Seismic parameter 'b' value is estimated as 0.87, which is slightly higher than the published values which may be due to increase in seismotectonic activity of the region. PSHA used to quantify the uncertainty involved in the hazard analysis, which also gives similar peak ground acceleration of 0.136g. Generally PSHA estimates a lower PGA values compared to that of PGA values obtained from DSHA. Mean annual rate of exceedance for particular acceleration is obtained for both PGA and spectral accelerations. Uniform hazard spectra at rock level and return period have been evaluated. Site characterization using SPT data has been carried out and 3-D subsurface model has been generated using GIS. Field SPT 'N' values are corrected by applying necessary corrections for further use in engineering applications. Site characterization also carried out using measured shear wave velocity using MASW and average shear wave velocity at each 5m interval up to a depth of 30m was evaluated and presented. Based on soil average shear wave velocity and 30m average shear wave velocity, as per NEHRP and IBC, Bangalore can be classified as "Site class D". Correlation between corrected SPT 'N' values and measured shear wave velocity has been developed. 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 2 Hz to 12Hz. The results of site response studies using SPT data and MASW data are comparable. Ground response parameters evaluated using MASW data are slightly lower values when compared to the parameters obtained using SPT data. Correlation between corrected SPT 'N' values and low strain shear wave modulus has been developed. Field study of microtremor also shows similar values of predominant frequencies for these sites. Predominant frequency obtained from these three methods matches very well. Liquefaction hazard map has been generated using factor of safety against Liquefaction. Which is evaluated based on SPT borehole information. At few locations undisturbed soil samples were collected and liquefaction testing has been carried out using laboratory cyclic triaxial testing. 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

References

1) Aki, K. and Richards, P.G. (1980), "Quantitative seismology", *W.H. Freeman, San,* Vol. 1

2) Ansal, A., Laue, J., Buchheister, J., Erdik, M., Springman, S.M., Studer, J. and Koksal, D. (2004), "Site Characterization and Site Amplification for a Seismic Microzonation Study in Turkey", *Proceedings 11th International Conference on Soil Dynamics and Earthquake Engineering, 3rd International Conf. On Earthquake Geotechnical Engineering, April 2004; Berkeley, California, USA,* pp 1-8.

3) Bhatia, S. C., Ravi Kumar, M., and Gupta, H.K. (1997)," A Probabilistic Seismic Hazard Map of India and Adjoining Regions", *http://www.seismo.ethz.ch/gshap/ict/india.html*, pp 1-12.

4) Boore, D. M. (1983), "Stochastic simulation of high-frequency ground motions based on seismological models of the radiated spectra", *Bull. Seism. Soc. Am.,* Vol. 73, 1865-1894.

5) Boore, D. M. (2003), "Simulation of ground motion using the stochastic method", *Pure and Applied Geophysics,* Vol. 160, pp 635-675.

6) Bullen, K.E. (1965), "An introduction to the theory of seismology", *Cambridge Univ. Press, Cambridge, U.K.*

7) Cetin, K.O, Seed, R.B., Kiureghian, A.D., Tokimatsu, K., Harder, L.F. Jr., Kayen, R.E., and Moss, R.E.S. (2004), "Standard penetration test-based probabilistic and deterministic assessment of seismic soil liquefaction potential", *Journal of Geotechnical and Geoenvironmental Engineering,* Vol. 12, pp 1314-1340.

8) Dobry, R., R. D., Borcherdt, C. B., Crouse, I. M., Idriss, W. B., Joyner, G. R. Martin, M. S., Power, E. E., Rinne and R. B. Seed, (2000), "New site coefficients and site classification system used in recent building seismic code provisions", *Earthquake Spectra,* Vol. 16, pp 41–67.

9) Ganesha Raj. K., and Nijagunappa, R. (2004)," Major Lineaments of Karnataka State and their Relation to Seismicity" *Remote Sensing Based Analysis, Jr.Geol.Soc.India,* Vol.63, pp.430-439.

10) Idriss, I. M. and Boulanger, R. W. (2005), "Evaluation of Liquefaction Potential, Consequences and Mitigation" *Invited Expert Lectures, Proc. Indian Geotechnical Conference-2005, 17-19 December 2005, Ahmedabad, INDIA,* pp 3-25.

11) Idriss, I. M., and Boulanger, R. W. (2004), "Semi-empirical procedures for evaluating liquefaction potential during earthquakes." *Proc., 11th International Conference on Soil*

Dynamics and Earthquake Engineering, and 3rd International Conference on Earthquake Geotechnical Engineering, D. Doolin et al., eds., Stallion Press, Vol. 1, pp 32-56.

12) Imai. T and Tonouchi. K, (1982), "Correlation of N-value with S-wave velocity and shear modulus", Proceedings, 2nd European Symposium on Penetration Testing, Amsterdam, pp 57-72.

13) Kanli, A.I., Tildy, P., Pronay, Z., Pinar, A. and Hemann, L. (2006), "Vs^{30} mapping and soil classification for seismic site effect evaluation in Dinar region , SW Turkey", *Geophysics J. Int,* Vol. 165, pp 223-235.

14) Kijko, A. and Sellevoll, M. A. (1989), "Estimation of earthquake hazard parameters from incomplete data files. Part I Utilization of extreme and complete catalogs with different threshold magnitudes" *Bull. Seismol. Soc. Am.,* Vol. 79, pp 645–654.

15) Kijko, A. and Sellevoll, M. A. (1992), "Estimation of earthquake hazard parameters from incomplete data files. Part II. Incorporation of magnitude heterogeneity," *Bulletin of the Seismological Society of America, Feb 1992,* Vol.82, pp 120 - 134.

16) Liao, S. S. C., and Whitman, R. V. (1986), ''Catalogue of liquefaction and non-liquefaction occurrences during earthquakes.'' *Res. Rep., Dept. of Civ. Engrg., Massachusetts Institute of Technology, Cambridge, Mass.*

17) Nath,S.K. (2006), "Seismic Hazard and Microzonation Atlas of the Sikkim Himalaya", *published by Department of Science and Technology, Government of India, India.*

18) Ramalingeswara Rao, B. (2000), "Historical Seismicity and deformation rates in the Indian Peninsular Shield", *Journal of Seismology,* Vol. 4, pp 247-258.

19) Schnabel, P. B., (1973), "Effects of Local Geology and Distance from Source on Earthquake Ground Motion," *Ph.D. Thesis, University of California, Berkeley, California.*

20) Seed, H. B., and I. M. Idriss, (1971), "Simplified procedure for evaluating soil liquefaction potential," *Journal of the Soil Mechanics and Foundation Division, ASCE,* Vol.97, No.9, pp 1249-1274.

21) Seed, H. B., and Idriss, I. M., (1970), "Soil Moduli and Damping Factors for Dynamic Response Analyses," Rep. No. EERC-70/10, *Earthquake Engineering Research Center, University of California, Berkeley, California*

22) Seed, H. B., Idriss, I. M., and Arango, I. (1983), "Evaluation of Liquefaction potential Using Field Performance Data," *Journal of Geotechnical Engineering,* Vol. 109, No. 3, March, pp 458-482.

23) Seed, H.B., and I.M., Idriss, (1982), "Ground Motions and Soil Liquefaction during Earthquakes, Monogr.5", *Earthquake Engineering Research Institute, University of California, Berkeley.*

24) Seismotectonic Atlas of India-(2000), *published by Geological Survey of India.*

25) Sitharam, T. G. and Anbazhagan, P. (2007), "Seismic Hazard Analysis for the Bangalore Region", Natural Hazards, Vol. 40, pp 261–278.

26) Sitharam, T. G., Anbazhagan, P. and Ganesha Raj, K. (2006), "Use of remote sensing and seismotectonic parameters for seismic hazard analysis of Bangalore", *Natural Hazards Earth System Sci.,* Vol. 6, pp 927–939.

27) Skempton, A. W. (1986), "Standard Penetration Test Procedures." *Geotechnique,* Vol.36, No.3, pp.425-447.

28) Sridevi Jade, (2004), "Estimation of plate velocity and crustal deformation in the Indian sub-continent using GPS geodesy", *Current Science,* Vol.86, pp 1443-1448.

29) Wells, D.L., Coppersmith, K.J. (1994), "New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement", *Bull. Seismol. Soc. Am. 4 (84), 975– 1002.*

30) Xu, Y., Xia, J., and Miller, R.D., (2006), "Quantitative estimation of minimum offset for multichannel surface-wave survey with actively exciting source", *Journal of Applied Geophysics,* vol 59, No. 2, pp117-125.

31) Youd, T.L., Idriss, I.M., Andrus, R.D., Arango, I., Castro, G., Christian, J.T., Dobry, R., Liam Finn, W.D., Harder Jr., L.H., Hynes, M.E., Ishihara, K., Koester, J.P., Liao, S.S.C, Marcuson, W.F., Marting, G.R., Mitchell, J.K., Moriwaki, Y., Power, M.S., Robertson, P.K., Seed, R.B, And Stokoe, K.H. (2001), "Liquefaction Resistance of Soils: Summary from the 1996 NCEER and 1998. NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils", *Journal of Geotechnical and Geoenvironmental Engineering,* pp 817 – 833.