Site Characterization and Site Response Studies Using Shear Wave Velocity

P. Anbazhagan[1] and T.G. Sitharam[2]

1. Lecturer, Department of Civil Engineering, Indian Institute of Science, Bangalore-12., India, email: anbazhagan@civil.iisc.erent.in
2. Professor, Department of Civil Engineering, Indian Institute of Science, Bangalore-12., India

ABSTRACT: *The complete microzonation and site response studies require the characterization of subsurface materials considering local subsurface profiles of the site or region. The general site characterization comprises of the evaluation of subsurface features, material types, material properties and buried/hollow structures, by which it is determined whether the site is safe against earthquake effects. In this study, an attempt has been made to characterize the Bangalore Mahanagar Palike (BMP) area of about 220km^2 using the shallow geophysical method, Multichannel Analysis of Surface wave (MASW), which identifies each type of seismic wave on a multichannel record using the refraction survey and produces shear-wave velocity (Vs) profiles. The study area of BMP has been characterized as per NEHRP (National Earthquake Hazards Reduction Program) and IBC (International Building Code) site classification using an average shear wave velocity (Vs^{30}) of 30m, obtained from MASW. In the study area, 58 one-dimensional (1-D) MASW survey has been carried out and respective velocity profiles are obtained. The major part of the BMP area can be classified as "site class D", and "site class C" and a smaller part in and around Lalbagh Park is classified as" site class B". Further site response has been carried out using measured shear wave velocity and synthetic ground motion developed by Sitharam and Anbazhagan [11]. Site response study shows that due to soil condition, large modification of wave amplitudes are observed resulting in higher peak ground acceleration when compared to rock level acceleration.*

Keywords: MASW; Average shear wave velocity; Site class; Site response

1. Introduction

Mapping of shear wave velocity profile has been widely used in seismic hazard and microzonation studies. A complete site characterization is essential for the seismic site classification and site response studies, which can be used together for seismic microzonation. Site characterization should include an evaluation of subsurface features, subsurface material types, subsurface material properties and buried/hollow structures to determine whether the site is safe against earthquake effects such as site amplification and liquefaction. Site characterization should provide the following data:

- Site description and location
- Geotechnical data/properties
- Soil conditions.

As part of the site characterization, experiments were carried out and data is interpolated and represented in the form of maps. The representation maps can be further used for the site classification and seismic studies. A number of geophysical methods have been proposed for near-surface characterization and measurement of shear wave velocity by using a great variety of testing configurations, processing techniques, and inversion algorithms. The most widely used techniques are *SASW* (Spectral Analysis of Surface Waves) and *MASW* (Multichannel

Analysis of Surface Waves). The spectral analysis of surface wave (*SASW*) method has been used for site investigation for several decades by Nazarian et al [16], Al-Hunaidi [17], Ganji et al [18], Stokoe et al [19] and Tokimatsu [20]. In *SASW* method, the spectral analysis of a surface wave is generated by an impulsive source and recorded by a pair of receivers. Evaluating and distinguishing signal from noise with only a pair of receivers by this method is difficult. Thus to eliminate inherent difficulties, a new technique incorporating multichannel analysis of surface waves using active sources, *MASW*, was developed [26, 29, 30]. The *MASW* has been found to be a more efficient method for unraveling the shallow subsurface properties [26, 29, 31]. Multichannel Analysis of Surface wave (*MASW*) is increasingly being applied to earthquake geotechnical engineering for microzonation and site response studies. *MASW* is widely used in geotechnical engineering for the measurement of shear wave velocity, evaluation of dynamic properties, identification of subsurface material boundaries, and spatial variations of shear wave velocities and material. *MASW* is a non-intrusive and less time consuming geophysical method. It is a seismic method that can be used for geotechnical site characterization of near surface materials [24, 25, 26, 27, 29]. *MASW* identifies each type of seismic wave on a multichannel record, based on the normal pattern recognition technique that has been used in oil exploration for several decades. The identification leads to an optimum field configuration that assures the highest signal-to-noise ratio (*S/N*). Effectiveness in signal analysis is then further enhanced by diversity and flexibility in the data processing step [23]. In this study, an attempt has been made to characterize Bangalore site using geophysical experimental data. About 58 locations *MASW* field test has been carried out and one dimensional shear wave velocity is obtained. These results are used for site classification of *BMP* area as per *NEHRP* and *IBC*.

Many earthquakes have amply demonstrated effect of site amplification due to soil conditions and the damages caused to build environment during the last century. The widespread 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) in Japan, Kocaeli earthquake (1999) in Adapazari, Turkey and Bhuj earthquakes (2001) in India are important examples of site specific amplification of ground motion, even at locations far away (100-300*km*) from the epicenter [1]. The 2001 Gujarat-Bhuj earthquake in India is another example, with notable damage at a distance of 250*km* from the epicenter [5, 15]. These damages have resulted from the effect of soil condition on the ground motion that translates to higher amplitude; and the spectral content and duration of ground motion which is also modified. As seismic waves travel from bedrock to the surface, the soil deposits is subjected to certain changes based on the characteristics of the waves, such as amplitude and frequency content. This process can transfer large accelerations to structures causing huge destruction, particularly when the resulting seismic wave frequency matches with the resonant frequencies of the structures. Site-specific ground response analysis aims to determine this effect of local soil conditions on amplification of seismic waves and estimating the ground response spectra for 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. Bangalore, a fast growing urban center with low to moderate intensity earthquake history [11] and highly altered soil formation, (due to large reclamation of land from tank/lake beds) has been the focus of our study. In the present study, shear wave velocity from *MASW* and the generated synthetic ground motion using the synthetic ground motion model developed by the authors for Bangalore are used to study the site effects [11]. The soil properties and synthetic ground motion for each location is used to study the local site effects using 1-*D* ground response analysis program *SHAKE*2000. The results obtained from site specific ground response analysis has been used to prepare hazard maps of Bangalore, which shows the peak acceleration at ground surface, amplification factor, peak spectral accelerations (*PSA*) at ground surface, frequency corresponding *PSA* and spectral accelerations corresponding to 1.5, 3, 5, 8 and 10*Hz* frequency and also predominant frequency of the soil column.

2. General Setting of the Study Area

Bangalore city covers an area of approximately 696.17km^2 (Greater Bangalore). The area of study is limited to Bangalore Metropolis area (Bangalore Mahanagar Palike) of about 220km^2. Bangalore is situated on a latitude of 12º 58' North and longitude of 77º 36' East and 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 and lies in the South- Western part of India. Bangalore city is the fastest growing city and fifth biggest city in India. Besides political activities, Bangalore possesses many national laboratories, defense establishments, small and large-scale industries and Information Technology Companies. 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 $220km^2$. These tanks were once distributed throughout the city for better water supply, but are presently in a dried up condition. The residual silt and silty sand form thick deposits over which buildings/structures have been built. By 1961, Bangalore had become the 6th largest city in India with a population of 1,207,000. Between 1971 and 1981, Bangalore's growth rate was 76%, the fastest in Asia. In 1889, open space in Bangalore was four times of the built up area and by 1980 the built up area was four times the open space area. This indicates the rapid growth of infrastructure in the city. By 1988 the electronic city had been developed and Bangalore emerged as India's software capital. Consequently, there was a huge construction boom in the 1990's. Blessed with a strong educational and technological base and agreeable climate, Bangalore is still witnessing a tremendous growth in industry, trade and commerce leading to a rapid growth of the city and large-scale urbanization. The population of Bangalore region is over 6 million. 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 [10-11].

Bangalore city lies over a hard and moderately dense Gneissic basement dated back to the Achaean 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 region 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 migmatite intrusion formed within the granitic one extends for approximately 7.3*kms* running parallel with Krishna Rajendra Road/ Kanakpura Road from Puttanna Chetty Road in Chamrajpet till Bikaspura Road in the south. A 2.25*km* Quatrzite formation is found in Jahahalli East. Dike swarms are seen around the western outskirts of the city (west of the Outer Ring Road), most of them striking approximately $N15^oE$. However random east west trending ones are also seen. They appear to strike parallel to the strike of the vertical foliation of the country rock at that area. These basic intrusives which mark the close of the Archean era (Lower Proterozoic; 1600-2500*mya*) mainly constitute of hard massive rocks such as Gabbro, Dolerite, Norite and Pyroxenite. Bangalore city is subjected to a moderate annual soil erosion rate of 10*Mg/ha* [13]. 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. 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 [12].

3. Measurements of Shear Wave Velocity

MASW system consisting of 24 channels Geode seismograph with 24 vertical geophones of 4.5*Hz* capacities, has been used for measuring shear wave velocity. The seismic waves are created by impulsive source of 15 pound (sledge hammer) with 300*mm*x 300*mm* size hammer plate with ten shots. Receivers capture these waves and the captured Rayleigh wave is further analyzed using SurfSeis software to obtain *Vs* profiles. Test locations are selected based on three criteria: 1) Sampling the range of soil types and conditions, 2) Flat surface free from noise, and) important places, see Figure (1). A typical testing arrangement in the field is shown in Figure (2). SurfSeis is designed to generate *Vs* data (either in 1-*D* or 2-*D* format) using a simple three-step procedure: i) preparation of a Multichannel record (some times called a shot gather or a field file), ii) dispersion-curve analysis, and iii) inversion. The term “multichannel record” indicates a seismic data set acquired by using a recording instrument with more than one channel using geode seismograph. *MASW* has been effectively used with highest signal-to-noise ratio (*S/N*) of surface waves. 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. These are in conformity with the recommendations of Park et al [28]. These source

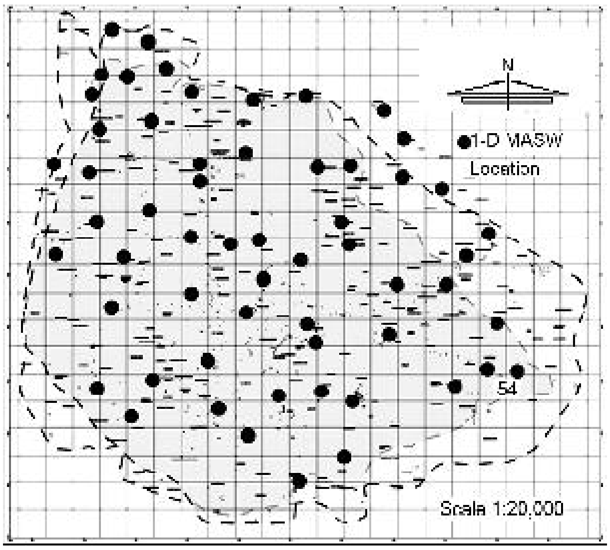

Figure 1. MASW testing locations in Bangalore.

Figure 2. A typical testing arrangement in the field.

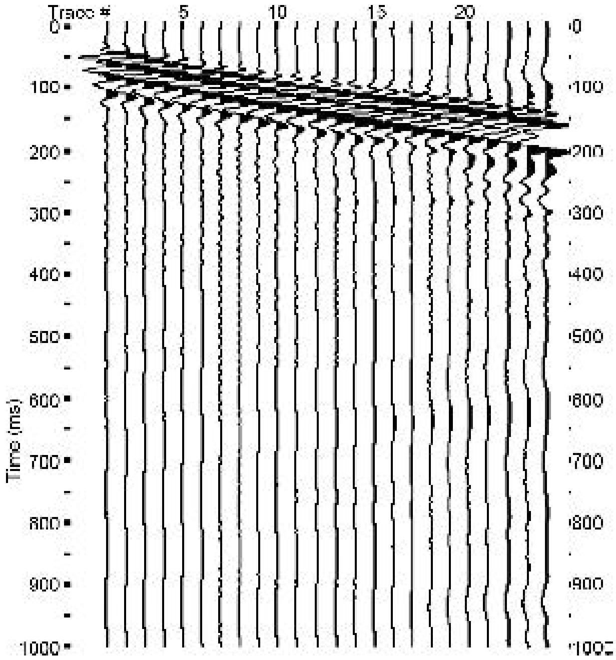

Figure 3. Typical seismic waves recorded in geode seismograph.

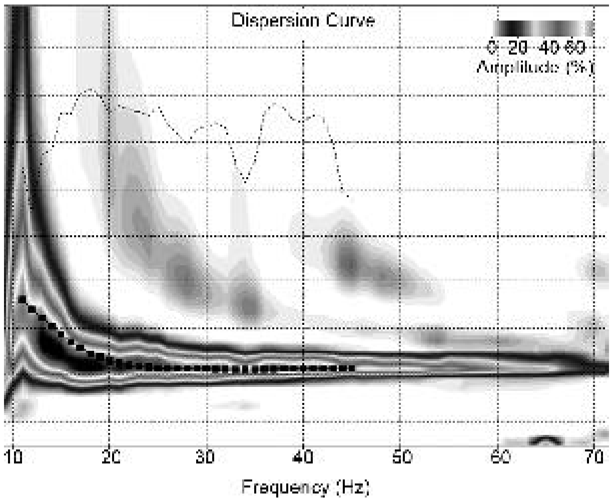

Figure 4. Typical dispersion curve from MASW record.

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 1*m* to 5*m*, 5*m* to 10*m* and 10*m* to 15*m* respectively [30]. Typical recorded surface wave arrivals for source to first receiver distance of 5*m*, with recording length of 1000*ms* is shown in Figure (3).

The recorded seismic waves are further used to generate a dispersion curve, which is generally 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. The lowest analyzable frequency in this dispersion curve, which is around 5*Hz*, and highest frequency of 75*Hz* has been considered. Typical dispersion curve is shown in Figure (4). Each dispersion curve obtained for corresponding locations has a very high signal to noise ratio of about 80 and above. A shear wave velocity profile has been calculated using an iterative inversion process that requires the dispersion curve developed earlier as input. A least-squares approach allows automation of the process [29], which is inbuilt in SurfSeis. Shear wave velocity has been updated after completion of each iteration with parameters such as Poisson's ratio, density, and thickness of the model remaining unchanged. An initial earth model is specified to begin the iterative inversion process. Typical 1-dimensional shear wave velocity profile is shown in Figure (5).

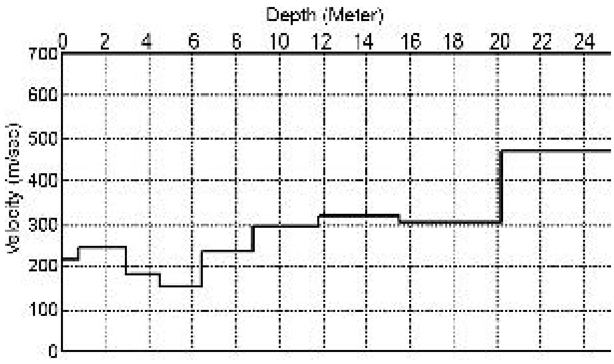

Figure 5. Typical 1-dimentional shear wave velocity profile.

4. 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 is referred as V_H. The average shear wave velocity up to a depth of H (V_H) is computed as follows:

$$V_H = \sum d_i / \sum (d_i / v_i) \quad (1)$$

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

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

$$Vs^{30} = \frac{30}{\sum_{i=1}^{N} (d_i / v_i)} \quad (2)$$

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 30m. Vs^{30} is accepted for site classification as per *NEHRP* classification and also *IBC* classification [21, 22, 24]. About 75% data are available at more than 30m depths and in these locations Vs^{30} has been calculated using respective layer thickness and shear wave velocity as per Eq. (2). But for the remaining locations, the data is available for less than 30m, (2 locations-up to 20m depth, remaining data are above 25m depth) and for these, Vs^{30} is calculated by assuming that shear wave velocity of the last layer remains constant up to 30m depth. A simple spread sheet has been generated to carry out the calculation, as shown in Table (1). Usually for amplification and site response study, the 30m average *Vs* is considered. The calculated average shear wave velocities are grouped according to the *NEHRP* site classes and a map has been generated using Arc *GIS* package, see Table (2). Figure (6) shows the map of average shear wave velocity for a depth of 30m. Figure (6)

Table 1. Typical average shear wave velocity calculation.

Depth (m)	*Vs* (m/s)	Soil Thickness [d_i] (m)	Average *Vs*-30m
-1.22	316	-1.2	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	

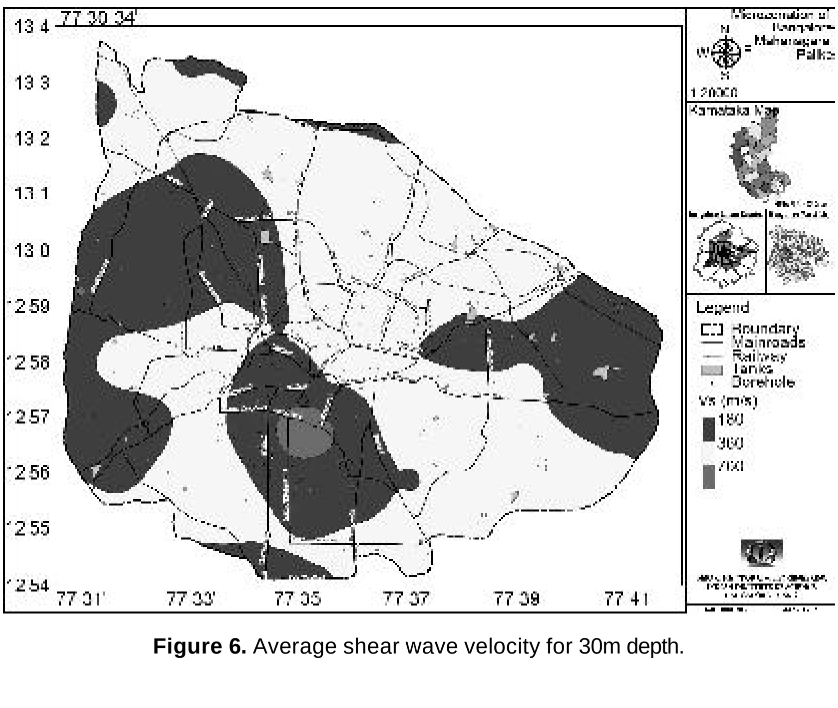

Figure 6. Average shear wave velocity for 30m depth.

Table 2. Site Classes for average shear wave velocity.

Site Class	Range of Average Shear Wave Velocity (m/s)
A	$1500 < Vs^{30}$
B	$760 < Vs^{30} \leq 1500$
C	$360 < Vs^{30} \leq 760$
D	$180 < Vs^{30} \leq 360$
E	$Vs^{30} < 180$

clearly shows that the *BMP* area can be characterized as three groups for seismic local site effects. Major parts of the *BMP* fall in "site class *D*" and "site class *C*" whereas, a very small part fall on "site class *B*" where bedrock outcrop is also identified (Lalbagh Park).

5. 1-D Ground Response Analysis Using Equivalent Linear Approach

A ground response analysis consists of studying the behavior 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 *SHAKE* 2000 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. These are obtained using an iterative procedure to get the values for modulus and damping compatible with the effective strains in each layer. In this approach, first, a known time history of bedrock motion is represented as a Fourier series, usually using the Fast Fourier Transform (*FFT*). 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. Using 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 horizontal displacement due to the vertically propagating harmonic s-waves in each material is given by:

$$u_s(z_s, t) = A_s e^{i(\omega t + k_s^* z_s)} + B_s e^{i(\omega t + k_s^* z_s)} \quad (3)$$

$$u_r(z_r, t) = A_r e^{i(\omega t + k_s^* z_s)} + B_s e^{i(\omega t + k_s^{''} z_s)} \quad (4)$$

In the equations, subscripts *s* and *r* refers to soil and rock respectively.

Where *u* is the displacement, ω is the circular frequency of the harmonic wave and k^* is the complex wave number. No shear stress can exist at the ground surface ($z_s = 0$), so:

$$\tau(0,t) = G_s^* \gamma(0,t) = G_s^* \frac{\partial u_s(0,t)}{\partial z_s} = 0 \quad (5)$$

Where $G_s^* = G(1-2i\beta)$ is the shear modulus of the soil. The soil surface amplitude can be obtained as the product of the rock outcrop amplitude and the transfer function, which is defined as the ratio of the soil surface amplitude to the rock outcrop amplitude. The response of the soil layer to a periodic input motion is obtained by the following steps [6]:

Schnabel et al [7] explained that within a given layer (layer *j*), the horizontal displacements for the two motions (motions *A* and *B*) may be given as:

$$u_r(z_j, t) = \left(A_j e^{ik_j^* z_j} + B_j e^{-ik_j^* z_j} \right) e^{i\omega t} \quad (6)$$

Thus, at boundary between layer *J* and layer *J*+1, compatibility of displacements requires that:

$$A_{j+1} + B_{j+1} = A_j e^{ik_j^{''} z_j} + B_j e^{-ik_j^{''} z_j} \quad (7)$$

Continuity of shear stresses requires that:

$$A_{j+1} + B_{j+1} = \frac{G_j^* K_j^*}{G_{j+1}^* K_{j+1}^*} \left(A_j e^{ik_j^{''} z_j} + B_j e^{-ik_j^{''} z_j} \right) \quad (8)$$

The effective shear stress of equivalent linear analysis is calculated as:

$$\gamma_{eff} = R_{\gamma}\gamma_{max} \tag{9}$$

Where γ_{max} is the maximum shear strain in the layer and R_{γ} is a strain reduction factor often taken as:

$$R_{\gamma} = \frac{M-1}{10} \tag{10}$$

In which, M is the magnitude of the earthquake.

Soil behavior under irregular cyclic loading is modeled using modulus reduction (*G/G max*) and damping ratio (β) *vs.* strain curves. 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 as discussed above. The degradation curves for sand and rock used for the present work are those proposed by Seed and Idriss [9] and Schnabel [8] respectively. These curves are shown in Figures (7) and (8) respectively. These are included in the *SHAKE* database and can be selected as input using option command.

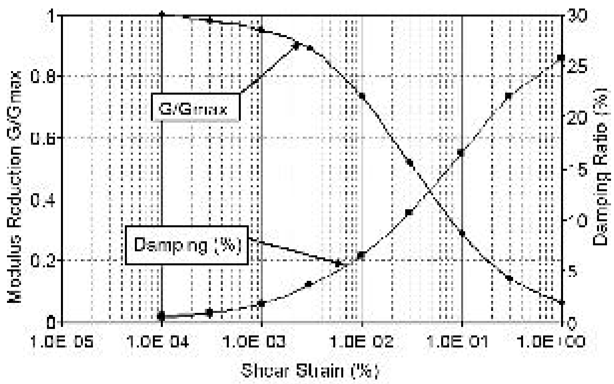

Figure 7. Shear modulus reduction and damping ratio curves considered for sand [9].

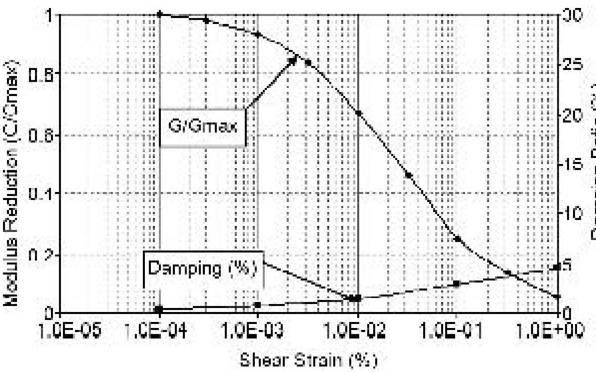

Figure 8. Shear modulus reduction and damping ratio curves considered for rock [8].

6. Synthetic Input Ground Motion

Indian peninsular shield, which was once considered to be seismically stable, has experienced many earthquakes in the recent past. Large numbers of earthquakes with different magnitudes have occurred in this region. The seismic hazard analysis for Bangalore city by considering possible earthquake sources is presented by Sitharam et al [10] and Sitharam and Anbazhagan [11]. The authors have identified potential seismic source within a distance of 350*km* radius around Bangalore using the available data on faults, lineaments and earthquake reported. They highlighted that Mandya- Chennapatana-Bangalore lineament is the seismic source which may produce a maximum credible earthquake 5.1 in moment magnitude 5.1. Since recorded strong motion data are not available for study area, authors have developed synthetic ground motion model using Boore [2-3] *SMSIM* program considering regional seismotectonic parameters. The same model has been used to generate the synthetic ground motion at 58 *MASW* locations and it is used as input ground motion to site response study. A typical synthetic ground motion in terms of acceleration, velocity and displacement is shown in Figure (9). The most commonly used measure of amplitude for a particular

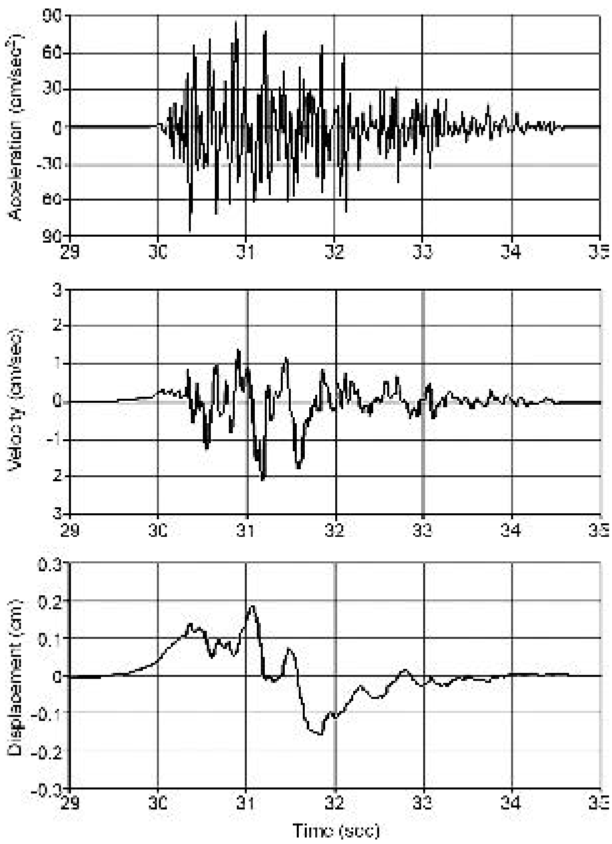

Figure 9. Typical input ground motion used for the analysis.

ground motion is peak ground acceleration (*PGA*). The *PGA* for a given component of motion is simply the largest (absolute) value of horizontal acceleration obtained from the accelerogram. Here only horizontal motion has been synthetically generated corresponding to peak value of acceleration at rock level. For further discussion in the site response study, the values of *PGA* at rock level at each borehole locations are evaluated and a rock level *PGA* map has been generated as shown in Figure (10).

7. Ground Response Analysis

The input rock motions at bed rock level were generated for all the *MASW* test locations considering the hypo central distance calculated test points to the Mandya-Channapatna-Bangalore lineament and used as an input for the corresponding *Vs* locations for site response study. The input motion for the location 54, see Figure (1), is shown in Figure (11). The rock motion obtained from synthetic ground motion model is assigned at the bedrock/engineering rock level, based on shear wave as input in *SHAKE* to evaluate peak acceleration values and acceleration time histories at the top of each sub layer. Response spectra at the top of the bedrock and at ground surface, amplification spectrum between the first and last layer and Fourier spectrum at a frequency step of 0.125*Hz* are obtained. Typical results obtained for borehole location 54 are illustrated in Figures (12) to (14). The variation of peak acceleration with depth is shown in Figure (12), from 9*m* depth to surface. The wave amplitude has increased and this may be attributed to the soft material having shear wave velocity less than 200*m/s.* Beyond 9*m* the velocity gets increased resulting in a decrease in the amplitude of waves. The peak acceleration from

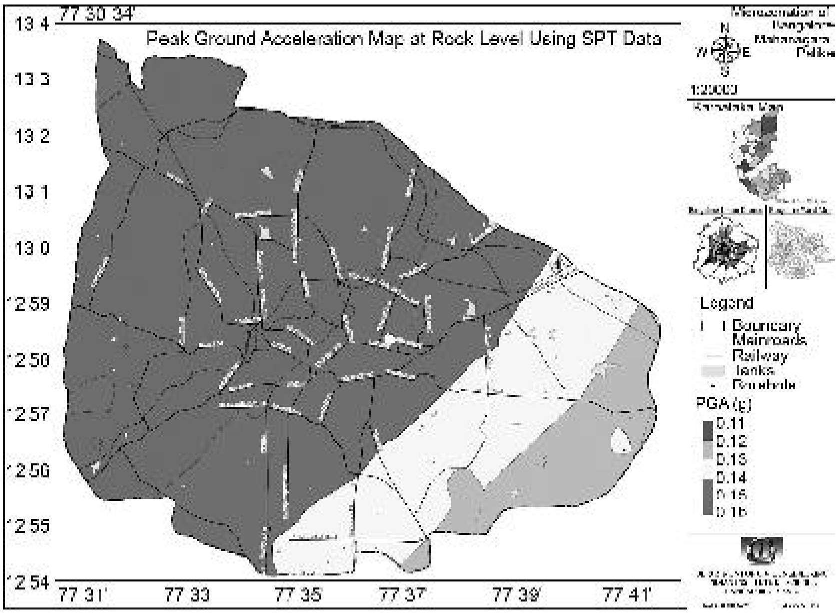

Figure 10. Rock level peak ground acceleration map.

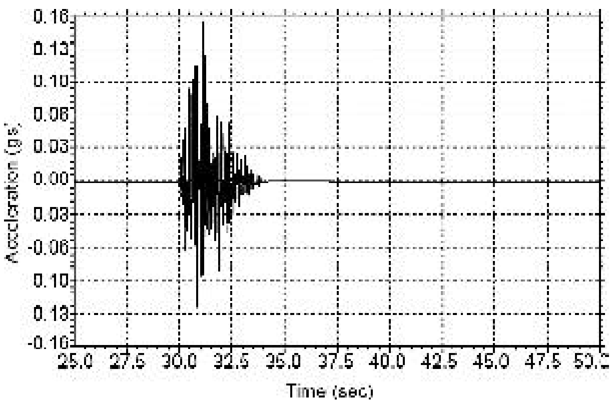

Figure 11. Typical input ground motion used in SHAKE2000.

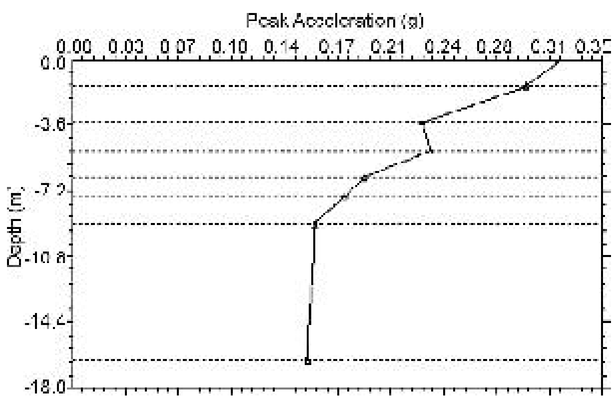

Figure 12. Variation of peak acceleration with depth.

these plots is used to prepare map showing peak horizontal acceleration at ground surface. The response spectrum of soil is shown in Figure (13), in which the first peak of 1.2*g* occurs at 0.1*s* and second peak of 1.0*g* occurs at 0.18*s*. Similar two peaks identified in amplitude spectrum is shown in Figure (14). Similar plots, stress-strain time history and Fourier amplitude spectrum have been obtained for all the points. These are compiled and presented in the form of maps depicting variation of different parameters and are discussed in the next section. The parameters obtained from the analysis are presented as maps, which are developed using the software Surfer using natural neighbor interpolation technique to depict the variation of various parameters in the study area. These ground response parameters are added as layers in the *GIS* platform, and finally hazard parameters maps are prepared in the *GIS*.

8. Peak Acceleration at Ground

The peak acceleration at ground surface for each location is obtained from variation of peak acceleration with depth plots, which is used to prepare the peak acceleration map at ground surface and is shown in Figure (15). The *PGA* value ranges from 0.125*g* to 0.507*g*. They are not evenly distributed due to variation in the soil profile at various locations. The ground surface acceleration is considerably large in the areas of tank beds, resulting from the thick layers of silty sand. From the Figures (10) and (15) it very clear that, *PGA* at rock surface is influenced by the distance, but *PGA* at ground surface is influenced by local site soil condition. Ground motions with high peak accelerations are usually more destructive than motions with lower peak accelerations, thus indicating that regions in the zones having *PGA* greater than 0.3*g* are seismically more unstable than the other regions. However, very high *PGA* that last

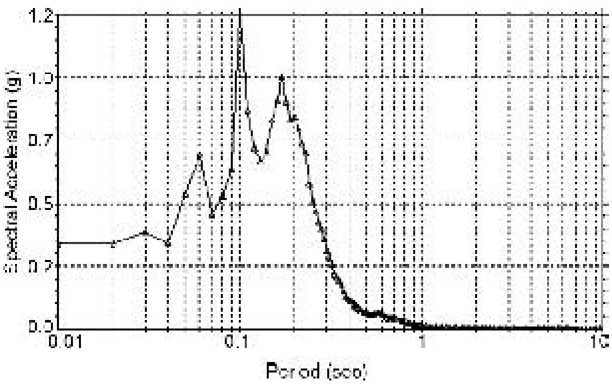

Figure 13. Response spectrum for 5% damping at ground surface.

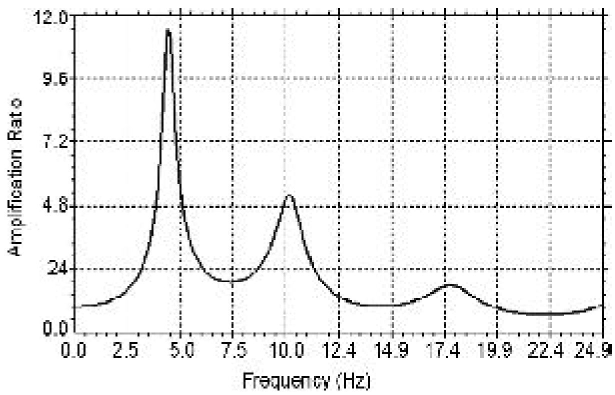

Figure 14. Amplification spectrum between the bedrock and ground surface.

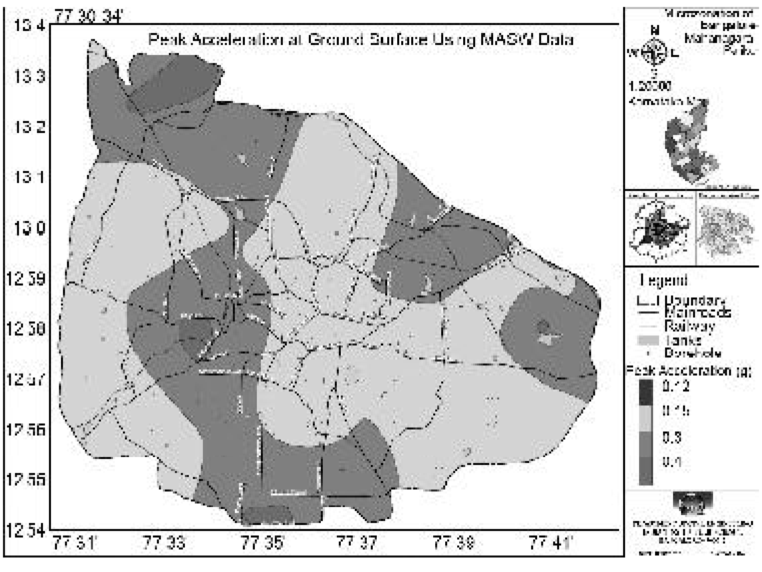

Figure 15. Peak acceleration at ground surface from site response study.

only for a very short period of time and having very high frequencies, may cause little damage to structures. Hence a better estimate of the regions of high seismic vulnerability, can be made by identifying regions susceptible to higher amplification of the bedrock motion. The amplification potential of the soil profile to seismic waves should thus be quantified as discussed in the subsequent section.

9. Amplification Map

The term "Amplification Factor" is hence used here to refer to the ratio of the peak acceleration at the ground surface to the peak acceleration at the bedrock. This factor is evaluated for all locations using the *PGA* at bedrock obtained from the synthetic acceleration time history and the peak ground surface acceleration obtained as a result of ground response analysis using *SHAKE*2000. The amplification factor thus calculated, ranges from 1 to 4. Quantitative amplification factors are obtained and these results are used to prepare the amplification map. Bangalore city can be divided into four zones based on the range of amplification factors assigned to each zone as shown in Table (3). The amplification factor map for Bangalore city is shown in Figure (16). Larger amplification factor was found where the shear wave velocity is lower and in a filled up areas. Lower amplification values indicate lesser amplification potential and hence lesser seismic hazard. It can be observed that the amplification factor for most of Bangalore region is in the range of 2 to 3.99. This is in agreement with Sitharam et al [14], where in, authors have qualitatively studied amplification susceptibility rating based on the average shear wave velocity of 30*m* (Vs^{30}) depth using *SPT* "*N*" values. They classified borehole soil profiles based on Finn's [4] approach and concluded that most parts of Bangalore city has moderate amplification potential.

Table 3. Zones and amplification factor range.

Zone	Amplification Factor
1 (I)	1.00-1.99
2 (II)	2.00-2.99
3 (III)	3.00-3.99
4 (IV)	>4

10. Result and Discussion

The frequency content of an earthquake motion will strongly influence the effects of ground motion and hence the *PGA* value on its own, can not characterize the ground surface motion. A response spectrum is used extensively in earthquake engineering practice to indicate the frequency content of an earthquake motion. A response spectrum describes the maximum response of a (*SDOF*) single-degree-of-freedom system to a particular input motion as a function of the natural frequency/period and damping ratio of the *SDOF* system. The combined influence of acceleration, amplitudes and frequency components of the movement are represented in a single graph. Since the time history of the seismic excitation in a certain site is characterized by the corresponding response spectrum, the differences among the time histories of the movements at different places can be analyzed by the comparison of their response spectra. The acceleration-time histories at various depths are

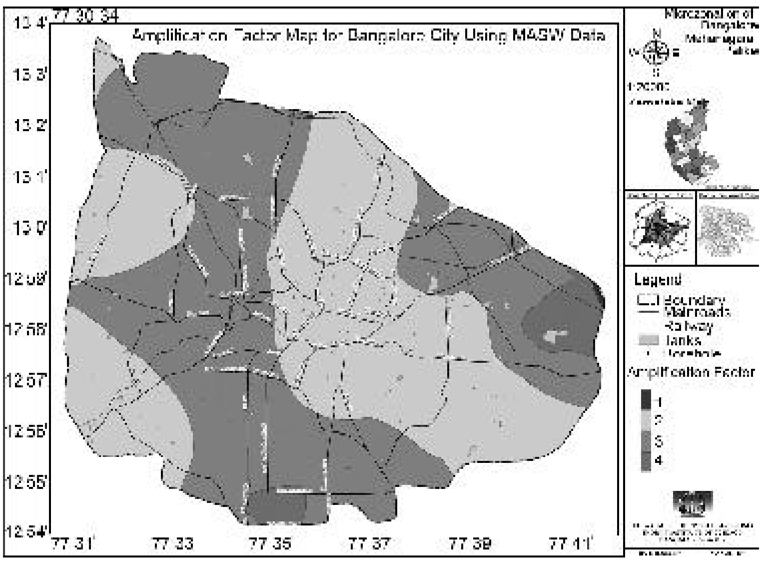

Figure 16. Amplification map of Bangalore.

obtained as a result of ground response analysis and these motions can be characterized by the corresponding response spectra. The ground surface response spectra for 58 locations were plotted with 5% critical damping value. The spectral acceleration (*SA*) values for all the locations at 1.5*Hz*, 3*Hz*, 5*Hz*, 8*Hz* and 10*Hz* are computed and presented in Figures (17) to (21). The above frequencies from 1.5*Hz* to 10*Hz* were selected as they represent the range of natural frequencies of tall buildings to single storey buildings [5, 32].

The earthquake amplitudes are represented usually by the peak ground acceleration; however for the structural designs and building code the most widely used parameter is spectral acceleration and corresponding period/frequency. Peak spectral acceleration (*PSA*) and frequency corresponding to *PSA* of each borelog from site response study has been computed. Peak spectral acceleration varies from 0.04*g* to 2.0*g* which is shown in Figure (22). The northern part of the study area has larger spectral acceleration when compared to the western part. Figure (23) shows that the frequency corresponding to the *PSA* varies from 3*Hz* to 19*Hz*. A major part of the study area has the frequency range of 5*Hz* to 15*Hz*. Predominant frequency of soil is widely used to categorize the soil for a ground motion, and mainly depends on 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

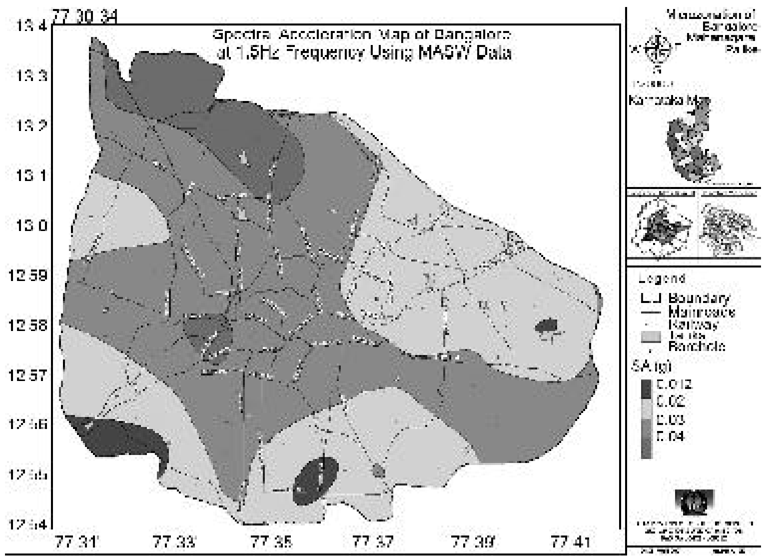

Figure 17. Spectral acceleration with 5% damping at 1.5Hz frequency.

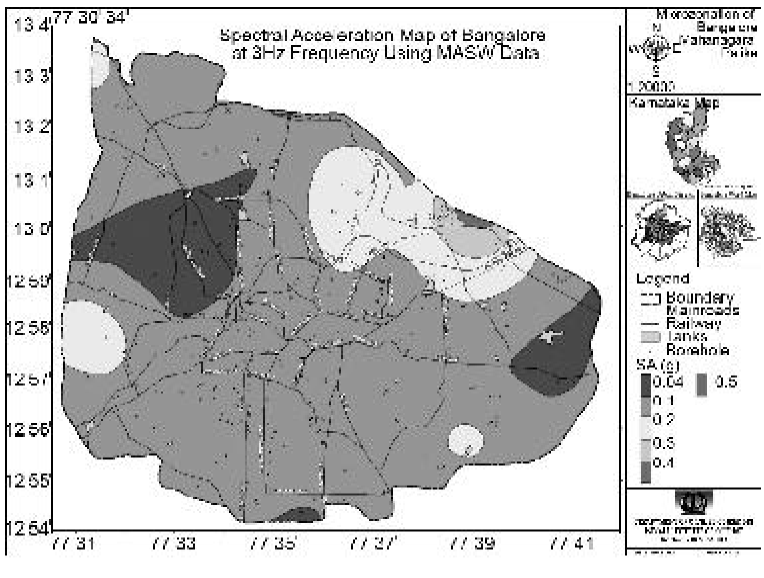

Figure 18. Spectral acceleration with 5% damping at 3Hz frequency.

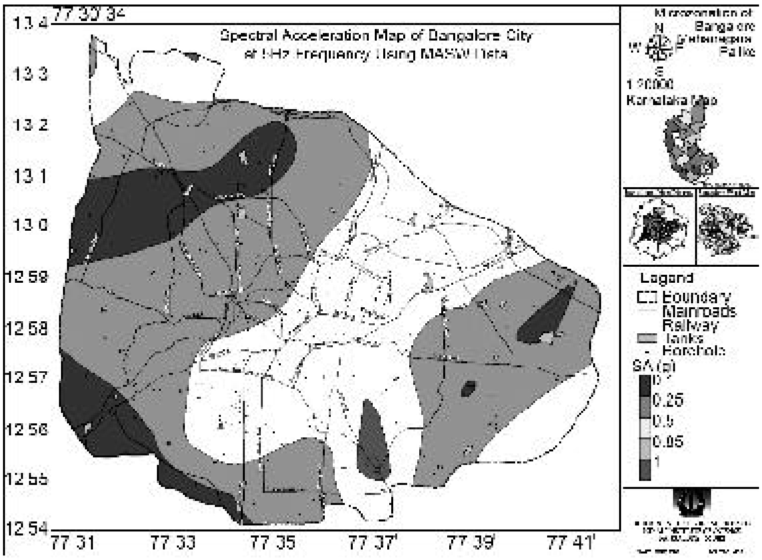

Figure 19. Spectral acceleration with 5% damping at 5Hz frequency.

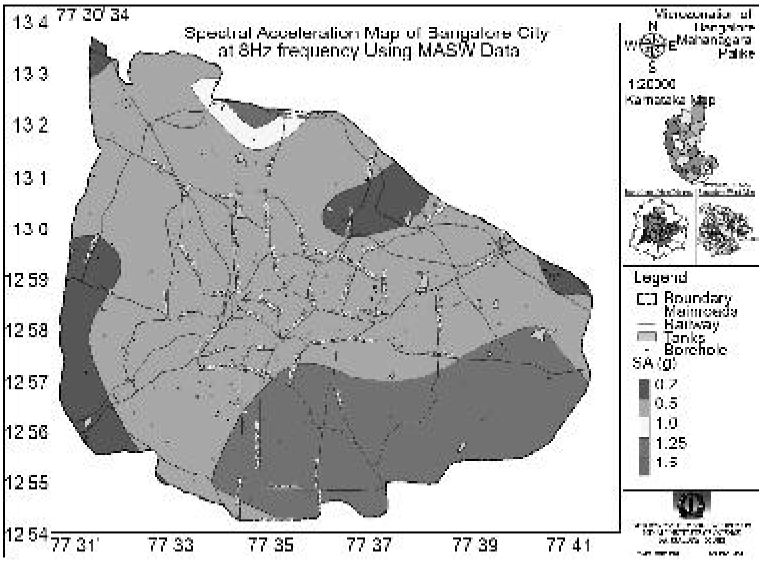

Figure 20. Spectral acceleration with 5% damping at 8Hz frequency.

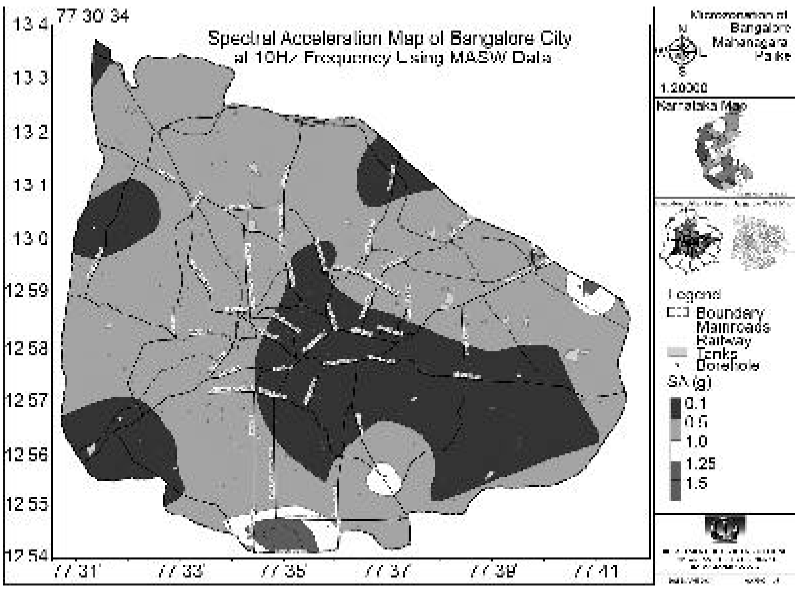

Figure 21. Spectral acceleration with 5% damping at 10Hz frequency.

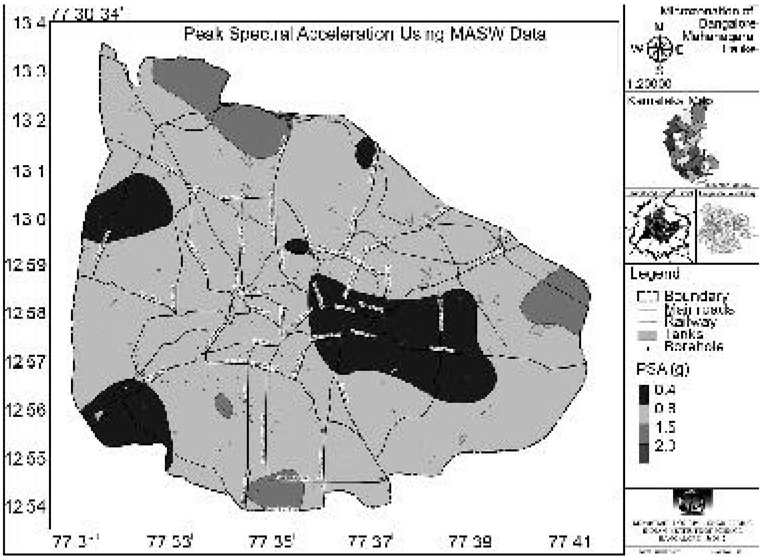

Figure 22. Peak spectral acceleration with 5% damping.

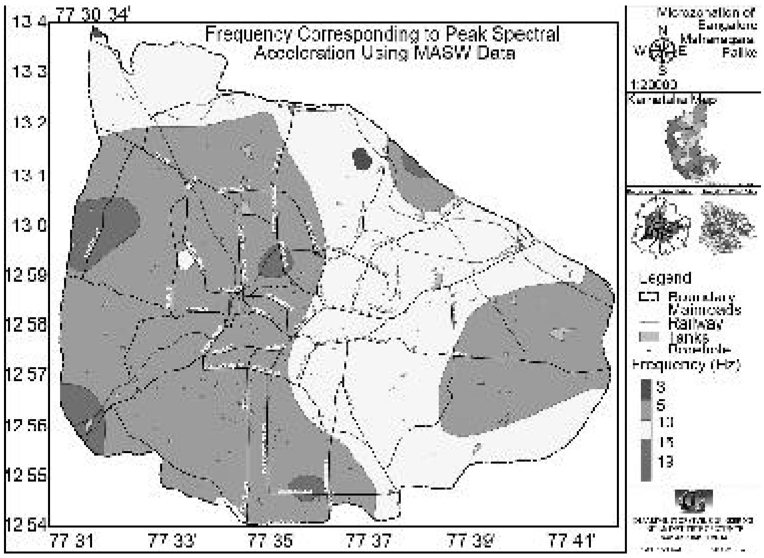

Figure 23. Frequency corresponded to peak spectral acceleration.

estimated using *SHAKE*2000. Predominant frequencies are estimated from Fourier amplitude spectrum obtained from each locations and varies from 3.45*Hz* to 12*Hz*, see Figure (24). The study presents different ground response parameters and these values are the maximum values calculated for a worst scenario earthquake based on deterministic hazard estimation. Uncertainty associated will earthquake and site response is not included in this analysis.

11. Conclusions

This study shows that the study area can be divided as three classes based on the measured shear wave velocity as per *NEHRP* and *IBC* recommendations. Most of the area is classified as “Site class *D*” and “Site class *C*” and meager portion is classified as “Site class *B*” using average 30*m*-depth shear wave velocity. The measured shear wave velocity is used to evaluate amplification factor of Bangalore using the ground response analysis by Shake2000. Ground level peak acceleration shows that based on soil characteristics the rock level acceleration gets magnified. The study shows that most of the areas in Bangalore have an amplification factor of 2 to 4, which may be attributed to soil characteristics of Bangalore. Majority of the soil deposits in this area is silty and sand with clay, which are residual and silted in lakes. To represent the range of natural frequencies of tall buildings to single storey buildings, spectral acceleration map has been developed for 1.5*Hz*, 3*Hz*,

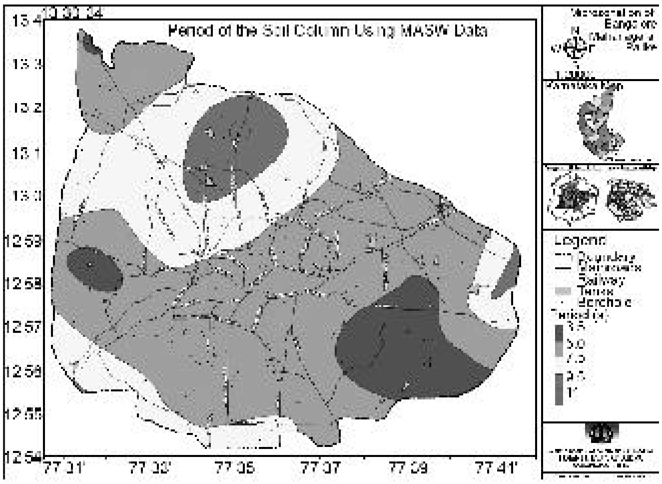

Figure 24. Predominant frequency of soil columns.

5*Hz*, 8*Hz*, and 10*Hz* and presented in this study. From this study, it is found that peak spectral acceleration for study area varies from 0.04*g* to 2.0*g* and corresponding frequency varies from 3*Hz* to 19*Hz*. The predominant frequency obtained from Fourier spectrum varies from 3.5*Hz* to12*Hz*, which most likely affects single storey to ground plus 3 storey buildings. Hence a detailed vulnerability and risk study is needed for Bangalore, where most of the buildings are less than 3 storey in the study area.

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