Site Characterization Using Geotechnical and Geophysical Techniques - Applicability of 30m Average Concept in Shallow Bedrock Region of Bangalore, India

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Received: 13/12/2011
Accepted: 19/06/2012

ABSTRACT

In this study, a shallow region of engineering bedrock in Bangalore, India, was chosen to investigate the application of 30 m based site classification scheme. About 370 bore logs previously drilled up to the bedrock were selected from a geotechnical database. Equivalent N values for 30 m were estimated using measured standard penetration test (SPT) N values, which mean that the study area may be classified as site class C and D. In the study area, a geophysical test and a multi-channel analysis of the surface wave (MASW) were conducted at 58 locations. The shear wave velocities were measured and then used to estimate the equivalent 30 m shear wave velocities (Vs30), upon the results of which the study area was then classified as class B, C, and D sites. The average 30 m SPT N and Vs values were included rock N and Vs values when the depth of the rock is less than 25 m. Therefore, an attempt was made to estimate the equivalent SPT N values and shear wave velocity of the thickness of the overburden soil up to the engineering bedrock and compared with 30 m values. This study shows that, by excluding the N and Vs values of the bedrock, this area can be classified as site class D. There were large spatial site class variations between the site classifications based on the 30 m and engineering bedrock. If the area had clearly defined engineering bedrock within 30 m, then average 30 m SPT N values and the shear wave velocity would mean a higher classification. Site response analysis carried out considering selected SPT N and Vs profiles by giving regional synthetic ground motion at 30 m and engineering bedrock. Response spectrum and amplification values are much higher than 30 m based spectrum and amplifications. Separate site classification scheme needs to be developed for the shallow bedrock region with response spectrum and amplification values.

Keywords:
Site classes; SPT-N values; MASW; Shear wave velocity; Engineering bedrock

1. Introduction

Wide spread destruction from earthquakes, particularly the Guerrero earthquake (1985) in Mexico City, the Spitak earthquake (1988) in Leninakan, the Loma Prieta earthquake (1989) in the San Francisco Bay area, the Kobe earthquake (1995), and the Kocaeli earthquake (1999) in Adapazari are important examples of specific amplification of local ground motion, at locations far away (100-300 km) from the epicentre [1]. The earthquake at Gujarat-Bhuj, India, in 2001 is another example where there was a notable damage at 250 km from the epicentre. These failures were caused by the influence of soil overburden layers and ground motions are translated to higher amplitudes with modification in the spectral content and duration of the rock motion [2]. Specific ground response analysis of the site aims to determine these effects by considering local soil conditions. Seismic microzonation of urban areas requires multi-disciplinary contributions and a comprehensive understanding of the effects of earthquakes due to local soil conditions. The process of estimating the effect of earthquakes due to soil layers under the earthquake loading requires an understanding of the properties of sub-surface materials. The characteristics of sub-surface materials are the key parameters affecting the applicability and feasibility of any microzonation study. Classification of sub-surface materials according to strength and thickness is called by seismic site characterization.

A general site characterization should describe the site, provide geological and hydro-geological data, characterise the aquifer, describe the condition and strength of the soil, give a risk assessment and reveal the presence and distribution of any contaminants. With a site characterization in seismic microzonation; however, the first six parameters alone are important. It must give detailed information about the mechanical and geometrical parameters of the subsurface, the effects of the proposed project on its environment, and an investigation of existing structures or lifelines below the subsurface. This data can thus be used to select a site, design the foundation and earthworks, and study the effects of the earthquake. How a soil deposit responds during an earthquake depends on the frequency of the base motion, the geometry and material properties of the soil above the bedrock. The geometries and material properties of soil are directly or indirectly quantified and represented by many researchers as a part of seismic microzonation. Seismic site classifications are widely used to quantify site effects and spectral acceleration.

In this study, the site characterization of the urban centre at Bangalore was conducted using the geotechnical and geophysical data. The SPT "N" values were used to estimate equivalent SPT N values for 30 m depth $(\overline{N_{30}})$. A geophysical survey of MASW was conducted at 58 selected locations to measure one dimensional shear wave velocities (Vs) with depth, and these shear wave velocities were used to estimate Vs^{30}. The study area was divided into class C and D sites based on $\overline{N_{30}}$ and class B, C, and D sites based on Vs^{30}. Because this area has clearly defined engineering bedrock at a shallow depth (within 40 m), a site classification with SPT N and Vs values up to engineering bedrock was attempted. Further site specific response analysis has been carried out considering selected SPT N and Vs profiles and by giving regional synthetic ground motion data at 30 m and engineering bedrock. The results of both site classifications and site specific response spectra and amplification values for the shallow engineering bedrock region are discussed in this paper.

2. Site Characterization Methods

A geographic distribution of site class based on Vs^{30} is useful for seismic zonation studies, because the amplification factors were defined as a function of Vs^{30}, such that the conditions of the ground on the site shaking can be taken into account [3]. Mostly, the seismic site characterization maps are prepared by considering the average SPT N or Vs values of the top 30 m of ground. Surface level acceleration using site classes and probabilistic approach has been presented by Raghu Kanth and Iyengar [4], Anbazhagan et al [5], Vipin et al [6]. In spite of the strong correlation between top 30 m shear wave velocities and relative amplification, these site classifications are still being researched [7]. In the initial stages of seismic microzonation, surface geology was used for site classification, but it was later proved that using geological units as the only criterion for seismic site characterization is not appropriate [1]. In addition, Wills and Silva [8] suggested that using the shear wave velocity rather than geological units, despite the extensive field investigations, required determining the shear wave velocities. In recent times, many seismic site characterizations were carried out using geotechnical and geophysical field studies. Nath [9] used geology to represent the subsurface characteristics and produced a Seismic Hazard and Microzonation Atlas of the Sikkim Himalaya. Mohanty et al [10] followed the same procedure using geology to develop a first order Seismic microzonation of Delhi. The use of geotechnical data, particularly borehole with SPT N is becoming a common practice because of the mass of data available and clear knowledge of the type of materials with penetration resistant (strength). The SPT data for site characterization and site response study is being used in India, Seismic Microzonation of Jabalpur Urban Area [11], Delhi seismic microzonation studies [12-13] and an estimation of the site response at Chennai [14] are few examples. Geophysical methods for seismic site characterization have been used in India, especially in the Jabalpur [11] Dehradun [15] and Delhi seismic microzonation studies [12]. Here the shear wave velocities were measured and used to estimate the site effects of the respective regions. Shafiee and Azadi [16] characterised the shear wave velocity of geological materials in Tehran and presented a distribution of shear wave velocity to 30 m (Vs^{30}). They have also used the same method to develop a site classification map of Tehran. Masashi et al [17] has presented the site classification of Japan based on mapping the average shear wave velocity using the Japanese engineering geomorphologic classification. Kockar and Akgun [18] used SPT N and Vs to conduct a site characterization of the Ankar basin in Turkey. They emphasised the point that the site classification of deep soils using SPT and shear wave velocities were almost the same. Bala et al [19] presented the site classification of Romania using 30 m and 50 m average shear wave velocities and reported that they both gave similar results. Kockar et al [3] carried out site classification of the Ankara Basin in Turkey using geology, shear wave velocity, and the International Building Code and Turkish Seismic codes. They have stated that a site classification utilising 30 m shear wave velocity was different in assigning site classes which only used the top soil. Lee et al [20] suggested the average shear wave velocity of 100-200 m depth as a site parameter to estimate acceleration at surface. Yaghmaei-Sabegh and Tsang [21] presented an efficient approach of site classification based on artificial neural networks (ANN) and representative horizontal to vertical spectral ratio (HVSR) curves.

3. Study Area and Geotechnical Data

Bangalore city covers approximately 696.17 km^2 (Greater Bangalore). The study area was limited to the Bangalore Metropolis (Bangalore Mahanagar Palike, BMP) which is about 220 km^2. Bangalore is situated on latitude 12^o 58' North and a longitude of 77^o 36' East, on an average altitude of 910 m above mean sea level (MSL). A map of Bangalore covering an area of 220 km^2 with different entities was developed using GIS with different layers at a scale of 1:20000. This map has several layers of information some of which are the boundaries (Outer and Administrative), Contours, Highways, Major roads, Minor roads, Streets, Railroads, Water bodies, Drains, Landmarks and Bore locations. A study area of Bangalore with several layers is shown in Figure (1). Figure (1) shows the boreholes and water features like tanks, lakes and drains within the corporate boundary of Bangalore, along with outer boundary circumscribing the ring road [22].

Geotechnical bore log data from previous

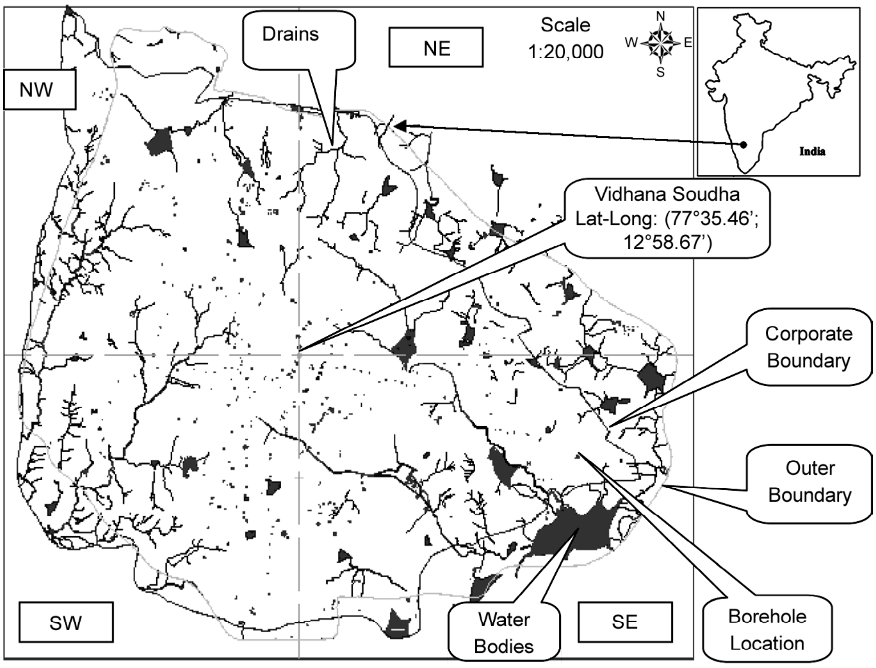

Figure 1. GIS model of borehole locations along with water body features.

geotechnical investigations of several major projects in Bangalore from 1990-2006 were collected from the archives of the Torsteel Research Foundation in India (TRFI) and the Indian Institute of Science (IISc). Bore holes of more than 15 m were drilled for several grade separator projects, and bore holes less than 15 m were drilled for residential and commercial complexes soil investigations. Bore holes for important projects were drilled up to 30 to 40 m deep and more than 3 m deep in very hard rock whilst others were terminated wherever bedrock was encountered. These bore holes were distributed spatially throughout the city of Bangalore, but more densely in areas of high land use, see Figure (1). The bore-hole database contains details of the N values, the water table, the density, the distribution of grain according to their size, the Atterberg limits, and the strengths of the soil and rock. SPT N values are measured as per IS 2131 [23] and soil properties are measured as per IS1498 [24]. These tests are very common and widely used in geotechnical engineering in India to find out design parameters. A typical bore log with SPT N values is shown in Figure (2). A generalized profile of the soil for general classification was obtained and is given in Table (1). These data are used for the site response and liquefaction analysis for the microzonation of Bangalore [25-28].

Bore Log-4

BH No BH-4 Date of Commencement 8.2.03

Ground Water Table Not Encountered Date of Completion 14.2.03

Depth Below GL (m)	Soil Description	Thickness of Layer	Legend	Soil Classification	Samples Type	Depth (m)	SPT N Values
0 1.5 3.0	Reddish/Brownish Silty Sand with Clay	3		SM	SPT UDS* SPT	1.5 2.5 3	N=11 N=26
4.0 5.0 6.0	Brownish Medium Dense to Very Dense Silty Sand	3		SM	UDS* SPT SPT	4 4.5 6	 N=52 Rebound
7.0 9.0 10.0 11.0 12.0 14.0 15.0 17.0	Weathered Rock 7.5 to 8.0m CR-58%, RQD-52% 8.0 to 9.5m CR-73%, RQD-34% 9.5 to 11.0m CR-62%, RQD-50% 11.0 to 12.5m CR-72%, RQD-54.66% 12.5 to 14.0m CR-60%, RQD-41% 14.0 to 15.5m CR-NIL, RQD-NIL 15.5 to 17.0m CR15%, RQD-NIL	11			SPT SPT SPT SPT	9 10.5 13.5 16.5	Rebound Rebound Rebound Rebound
18.0 20	Hard Rock 17.0 to 18.5m CR-61.33%, RQD-48% 18.5 to 20.0m CR-76%, RQD-52%	3			SPT SPT	18	Rebound

Note:

Bore hole Terminated at 26.0m SPT-Standard Penetration Test CR-Core Recovery

UDS-Undisturbed Sample RQD-Rock Quality Designation GL-Ground Level

Figure 2. Typical borelog with SPT N values.

Table 1. General soil distribution in Bangalore (after Anbazhagan and Sitharam, 2008).

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 3-6m	Clayey Sand 1.7-3.5m	Clayey Sand with Gravel 1.5-4m	Silty Clay 1.5-4.5m
Third Layer	Weathered Rock 6-17m	Weathered Rock 3.5-8.5m	Silty Sand with Gravel 4-15.5m	Sandy Clay 4.5-17.5m
Fourth Layer	Hard Rock Below the 17m	Hard Rock Below 8.5m	Weathered Rock 15.5-27.5m	Weathered Rock 17.5-38.5m
Fifth Layer	Hard Rock	Hard Rock	Hard Rock Below 27.5m	Hard Rock Below 38.5m

4. Site Characterization Using Geotechnical Data

The Standard Penetration Test (SPT) is one of the oldest, most popular, and commonly used in situ test for exploration in soil mechanics and foundation engineering because the equipment and test procedure are simple. They are particularly useful for seismic site characterizations, site response, and liquefaction studies towards seismic microzonation. In most cases, the specific site response analysis, shear wave velocity, and shear modulus (G_{max}) of layers are estimated using relationships based on the SPT N values [29-30].

In this study, about 370 bore logs drilled up to engineering bedrock were selected from the database of 850 bore logs based on rock characterization test results. Engineering bedrock has a shear wave velocity of around 700 m/sec [31] and an SPT "N" value of more than 100 for 5 cm of penetration [22]. They are widely used for placing engineering structures. Anbazhagan and Sitharam [31] mapped the depth of weathered and engineering bedrock in the study area based on the shear wave velocity and SPT N values. They emphasized the fact that the depth of the rock mapped using V_s compared very well with the depth of rock identified from drilled bore holes. The depth of the engineering bedrock was generated using 370 borehole data, shown in Figure (3), and it varies from 1 m to about 40 m in the study area. Figure (3) also shows that the soil overburden in the southeastern and central parts of the study area was more than 30 m deep but less than 1 m deep in the northern and southwestern parts. The average thickness of overburden in the study area was from 10 m to 15 m.

4.1. Site Classification

Site classifications based on SPT N values are practiced in many regions using N values directly, or by converting to shear wave velocities. Ground classification of individual sites based on soil boring or *Vs* is a more direct indicator of local site effects. Site effect in terms of amplification requires knowing the shear stiffness of a soil column, expressed in terms of *Vs* [32]. Site classes are defined in terms of *Vs* up to 30 m deep, denoted by Vs^{30}, but if this measurement cannot be obtained, then standard penetration resistance $(\overline{N_{30}})$ and undrained shear strength (S_u^{30}) could be used instead [32]. *Vs* can be

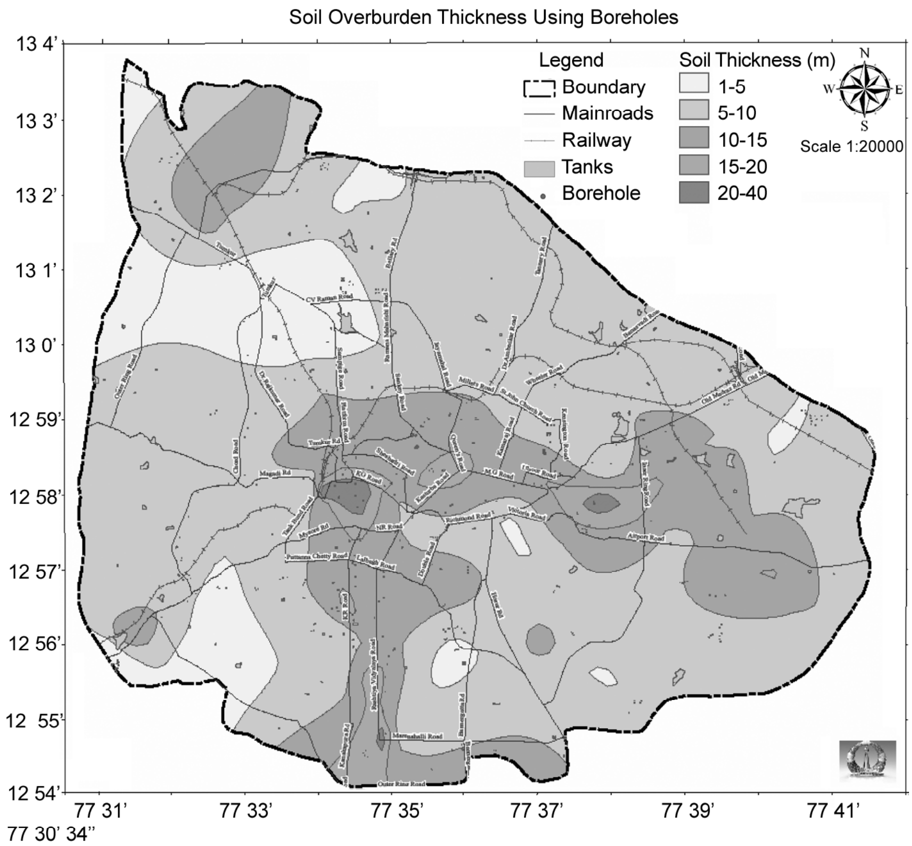

Figure 3. Rock depth/ soil overburden thickness in the study area.

directly measured in field tests or estimated from existing correlations between SPT blow-counts (SPT-N) and Vs [33]. The seismic site characterizations for calculating seismic hazards are usually carried out based on the near surface (30 m) N and Vs^{30} values. Equivalent N and Vs30 values for 30 m depths were used for site classification in the National Earthquake Hazards Reduction Program (NEHRP) recommendation and the International Building Code (IBC) classification [34-36]. To classify the study area, SPT- N values and the shear wave velocity ranges suggested by NEHRP (The Building Seismic Safety Council BSSC, 2001) [37] are, site class A ($Vs^{30} > 1.5$ km/s), site class B (0.76 km/s $< Vs^{30} = 1.5$ km/s), site class C (0.36 km/s $< Vs^{30} = 0.76$ km/s or $\overline{N_{30}} > 50$), site class D (0.18 km/s $< Vs^{30} = 0.36$ km/s or $15 < \overline{N_{30}} = 50$) and Site class E ($Vs^{30} < 0.18$ km/s or $\overline{N_{30}} < 15$) have been considered.

To classify the study area of Bangalore based on 30 m SPT 'N' values, equivalent N values were computed in accordance as follows:

$$\overline{N} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n}\left(\frac{d_i}{N_i}\right)} \qquad (1)$$

where $\sum_{i=1}^{n} d_i$ is the summation of total depth for the 30m average $(\overline{N_{30}})\sum_{i=1}^{n} d_i$ = 30 m, di and Ni denotes the thickness (in meters), and standard penetration resistance does not exceed 100 blows/0.3 m as directly measured in the field without correcting the i[th] formation or layer respectively, in a total of n layers existing in the top 30 m. A $\overline{N_{30}}$ for every borehole location was estimated. A borehole with an SPT N value of 100 was considered as the depth of engineering bedrock. Many boreholes were terminated within 30 m after an SPT-N value of 100 was recorded. In these boreholes it was assumed that after the N values reached 100, the SPT N values would remain constant up to 30 m deep to calculate $\overline{N_{30}}$ as per Boore [38]. Boore [38] suggested that the values of the lowest layer to be continued until 30 m depth to calculate 30 m average or it can be estimated using his correlation between 30 m average and average Vs till data is available. A 30 m equivalent N value map was then generated using these values, and is shown in Figure (4). Figure 4 also shows that study area can be classified as Site class C and D. A major part of the study area was a site class C, as per BSSC [37]. 30 m average N

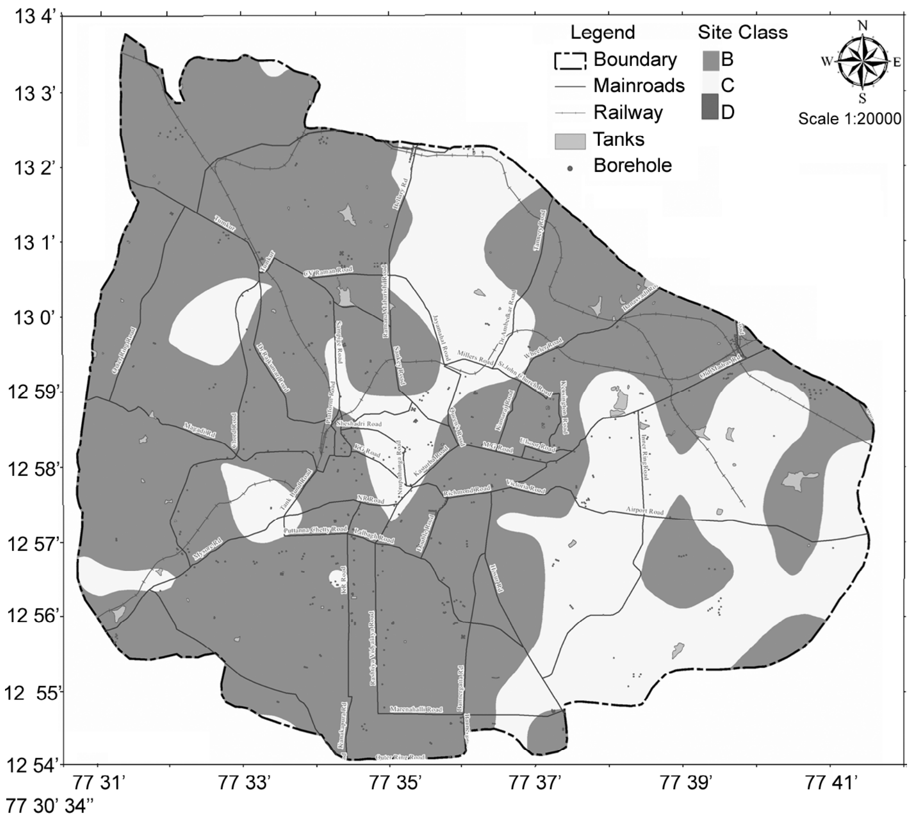

Figure 4. Site class based on 30 m equivalent SPT -N values.

values revealed that 63% of the boreholes were classified as site class C, 36% as site class D, and the remaining 1% as site class E. Because the engineering bedrock in the study area was shallow, there may be influence of an engineering bedrock N value in the 30 m average site classification, so an attempt was made to estimate the equivalent N value up to engineering bedrock by eliminating the bedrock N values. The equivalent N value up to engineering bedrock (first N of 100) was estimated and mapped. Figure (5) shows the equivalent N value up to engineering bedrock. This shows that the study area can be classified as site class C, D, and E. Site classification with N value up to engineering bedrock shows that 8% of the boreholes were classified as class C, 80% as class D, and 12% as class E. Figures (4) and (5) show that the 30 m average site classification in the region where the engineering bedrock was shallow, had stiffer site classes because the N values of the rock were added. Sites in the same location based on N values up to engineering bedrock had lower class sites.

Boreholes through dense soil and followed by engineering bedrock gave similar site classification for 30 m and engineering bedrock average values. Figure (6) shows a typical bore log with dense soil on top of engineering bedrock. The 30 m average $(\overline{N_{30}})$ was 93 and the average N values $(\overline{N_{ST}})$ of the soil was 68 for this location, so in both cases the site was a class C $(\overline{N_{30}} > 50)$. Similar class sites may be attributed to layers of soil with higher N values with a constant variation of N values beyond the N value of 100, up to 30 m. A borehole with loose to medium soil over dense soil and then engineering bedrock is shown in Figure (2). The loose to medium soil shows an $\overline{N_{ST}}$ of 30 and can be classified as class D, but if an average up to 30m gives an $\overline{N_{30}}$ of 63, it becomes class C $(\overline{N} > 50)$. Lower class sites may be attributed due to loose to medium soil present above the engineering bedrock. Similarly, loose soil over engineering bedrock results in lower class than 30 m site class. Sites with soil thickness less than 10 m may be divided into two cases: Case I sites with dense soil with high N values followed by engineering bedrock are similar class of sites where $\overline{N_{30}}$ and $\overline{N_{ST}}$. However, $\overline{N_{30}}$ value above 50 in the N based classification becomes a class C site, i.e., where 93 and 68 show the same class sites. Hence, a range of $\overline{N_{30}}$ values for sites B and A may be suggested and an upper $\overline{N_{30}}$ value for the class C site may be

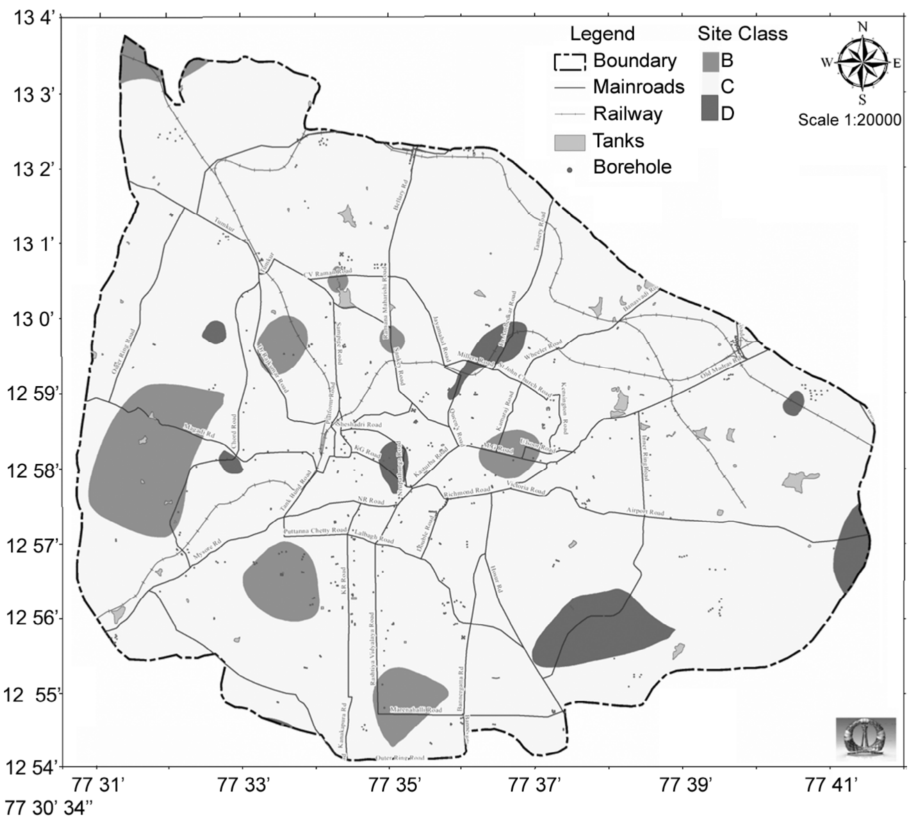

Figure 5. Site class based on equivalent Soil SPT -N values.

Bore Log-1

BH No BH-1 Date of Commencement 17.2.03
Ground Water Table Not Encountered Date of Completion 19.2.03

Depth Below GL (m)	Soil Description	Thickness of Layer	Legend	Soil Classification	Samples Type	Depth (m)	SPT N Values
0					SPT	1.5	N=60
1.0	Reddish Very Dense				UDS*	2.5	
2.0	Silty Sand with Clay			SM		3	N=48
4.0							
4.5		4.5			SPT	4.5	N=61
5.0	Greyish/Brownish			SM		6	N=102
6.0	Very Dense Silty Sand	1.5			SPT		
7.0	Soft Rock Comprision of Brownish/					7.5	Rebound
	Greyish/Whitishb Very Dense			SM			
7.5	Silty Having N Value>100	1.5			SPT	8	
8.0					SPT	9.5	Rebound
9.0	Weathered Rock				SPT	11	Rebound
10.0	7.5 to 9.0m CR-47.3%, RQD-24%				SPT	12.5	Rebound
11.0	9.0 to 10.5m CR-29.33%, RQD-16.67%				SPT	15.5	Rebound
12.0	10.5 to 12.0m CR-19%, RQD-14.33%				SPT		
15.0	Weathered Rock 15.0 to 16.5m				SPT	16.5	Rebound
16.0		9					
17.0					SPT	17	
18.0							
20.0					SPT	18	Rebound
21.0	Soft Hard Rock				SPT	19.5	Rebound
27.0					SPT	21	Rebound
27.5					SPT	27	Rebound
29.0					SPT	28.5	Rebound
30.0		12.5			SPT	30	Rebound

Note:
Bore hole Terminated at 30.0m SPT-Standard Penetration Test CR-Core Recovery
UDS-Undisturbed Sample RQD-Rock Quality Designation GL-Ground Level

Figure 6. Typical bore log with dense soil followed by rock.

incorporated into NEHRP or IBC classifications. Case II sites with loose to medium density soil over engineering bedrock had higher class sites if $\overline{N}_{30}$ was used but were lower if $\overline{N}_{ST}$ was used. Figure (7) shows a typical bore log with about 15 m of loose to medium density soil over engineering bedrock. In this case $\overline{N}_{30}$ and $\overline{N}_{ST}$ give similar site classifications. However, the same thickness of medium to dense soil over engineering bedrock gives different classifications. These results came from profiles of soil collected from Bangalore, the results of which may be investigated using more data from other regions. Further detailed site response analysis has been carried out by giving input ground motion at engineering bedrock and 30 m depth to understand response and amplification characters.

5. Site Characterization Using Geophysical Data

A number of geophysical methods using a wide variety of testing configurations, processing techniques and inversion algorithms have been proposed for near-surface characterization and measurement of shear wave velocity. The most widely used techniques are SASW (Spectral Analysis of Surface Waves) and MASW (Multi-channel Analysis of Surface Waves). The spectral analysis of surface wave (SASW) method has been used for site investigation for several decades [39-43]. MASW is found to be a more efficient method for unraveling shallow sub-surface properties [44-50], and is used in geotechnical engineering to measure the shear wave velocity and dynamic properties [51]. MASW can also be used for the geotechnical characterization of near surface materials [49-52]. Anbazhagan et al [53] recently used MASW to study ballast fouling in the railway track. MASW generates a shear-wave velocity (*Vs*) profile (i.e., *Vs* versus depth) by analyzing the Rayleigh-type surface waves

Bore Log-2

BH No BH-2 Date of Commencement 4.2.03
Ground Water Table Not Encountered Date of Completion 6.2.03

Depth Below GL (m)	Soil Description	Thickness of Layer	Legend	Soil Classification	Samples Type	Depth (m)	SPT N Values
0	Brownish/Greyish Loose to				SPT	1.5	N=6
1.5	Medium Dense			SM	UDS*	2.5	
3.0	Silty Sand with Clay						
4.0		4			SPT		N=17
6.0							
7.0	Brownish/Whitish				UDS*	5	
8.0	Dense to Vense Silty Sand			SM	SPT	6.5	N=52
9.0					SPT	8	N=39
9.5		5.5					
11.0	Soft Rock Comprising of Brownish/				SPT	9.5	Rebound
12.5	Greyish/Whitish Very Dense Silty Sand				SPT	10.5	Rebound
	Having N Value>100	3			SPT	12.5	Rebound
15.0	Weathered Rock						
	12.5 to 14.0m CR-16%, RQD-14%				SPT	15.5	Rebound
18	15.5 to 17.0m CR-26%, RQD-NIL						
	17.0 to 18.5m CR-26%, RQD-NIL				SPT	18.5	Rebound
21	20.0 to 21.5m CR-96%, RQD-67%						
23.0	21.5 to 23.0m CR-26.6%, RQD-21.33%	10.5			SPT	21.5	Rebound
24.0	Hard Rock				SPT	23	Rebound
25.0	23.0 to 24.5m CR-89%, RQD-72%						
26.0	24.5 to 26.0m CR-88%, RQD-88%	3					

Note:
Bore hole Terminated at 26.0m SPT-Standard Penetration Test CR-Core Recovery
UDS-Undisturbed Sample RQD-Rock Quality Designation GL-Ground Level

Figure 7. Typical bore log with loose-to-medium soil followed by rock.

on a multi-channel record. In this investigation, the MASW system consisted of a 24 channel Geode seismograph with 24, 4.5 Hz geophones. Seismic waves were generated by the impulsive source from a 15 pound sledgehammer hitting a 300 mm x 300 mm plate, ten times. The Rayleigh wave was analyzed further with SurfSeis software. About 58 one-dimensional (1-D) MASW surveys were conducted in the study area. The testing points in Bangalore are shown in Figure (8). An effective result from MASW depends on the highest signal-to-noise ratio (*S*/*N*) of surface waves. Optimum field parameters such as the source to first and last receiver, receiver spacing, and spread length of survey lines were such that the highest *S*/*N* ratio and required depth of information could be obtained. To obtain the highest signal to noise ratio, tests with a geophone were conducted at 1 m intervals. The source was kept on both sides of the spread line 5 m, 10 m, and 15 m apart, to avoid the effect of near and far fields. These distances conformed to the original recommendations made by Park et al [54] and Xu et al [46]; and helped to record good signals in soft, medium, and hard soils. Typical surface wave arrivals from 10 m (the source closest to the last (24th) geophone) and 15 m (the source closest to the first geophone) for a recording length of 1000 ms, is shown in Figure (9).

A dispersion curve 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. A typical dispersion curve corresponding to Figure (9b) recorded data are shown in Figure (10). 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 was calculated using an iterative inversion process that requires the input of the dispersion curve developed earlier. A least-squares approach allows the process to be automated [45], which is inbuilt in SurfSeis. After each iteration was completed, the shear wave velocity was updated, while the parameters of Poisson's ratio, density, and the thickness of the model remained unchanged. An initial earth model was specified to begin the iterative inversion process.

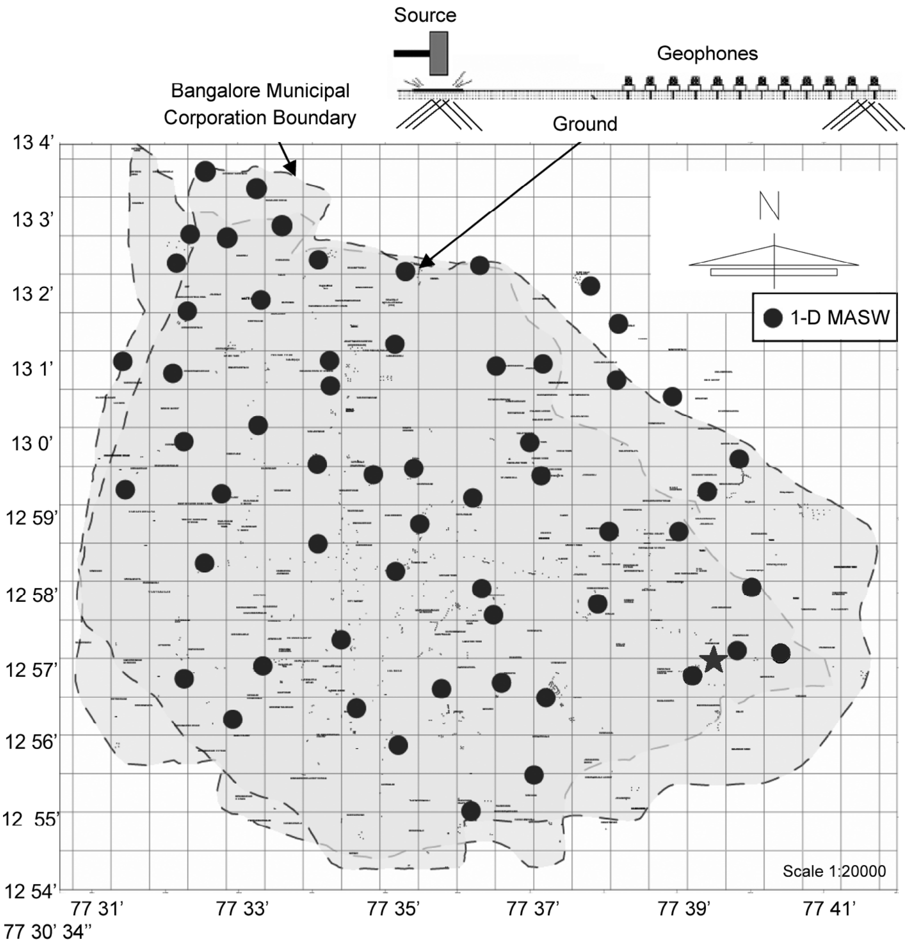

Figure 8. MASW test locations in Bangalore with field setup.

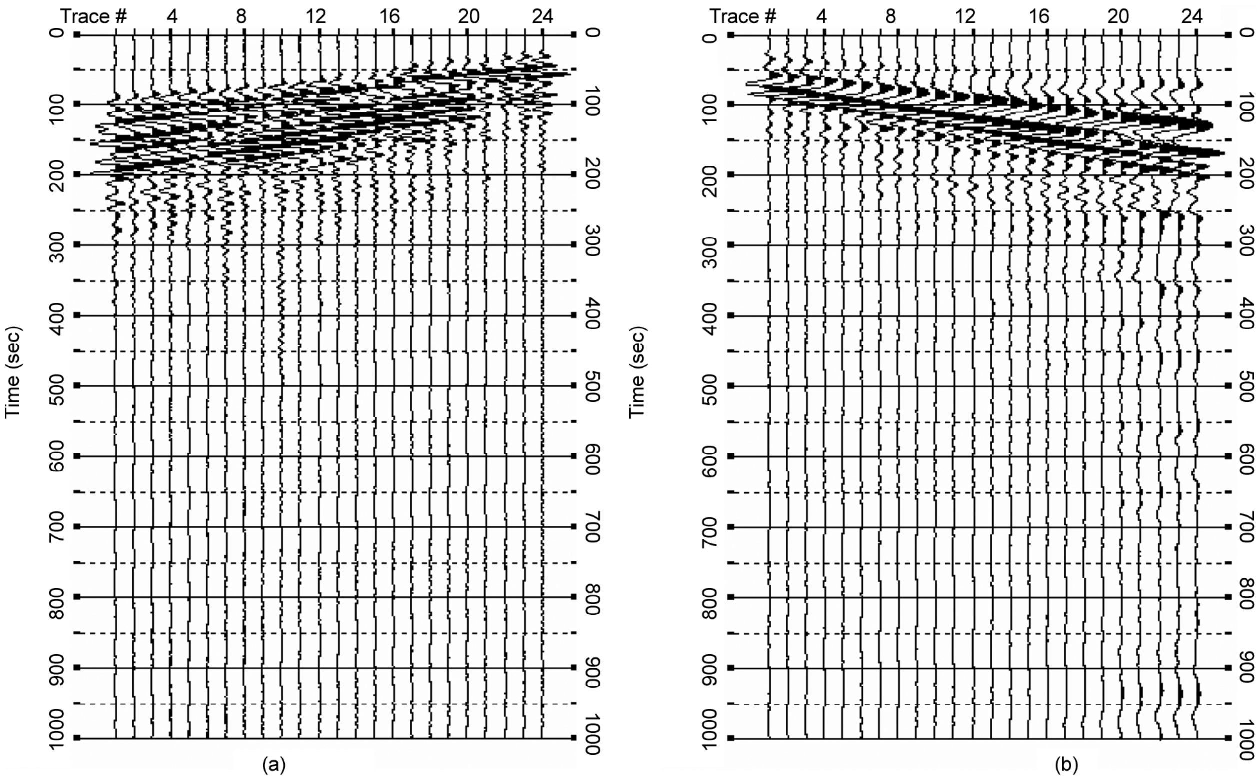

Figure 9. Example of seismic signal recorded by geophones (a) Source distance of 10m from 24th geophone and (b) Source distance of 15m from 1st geophone.

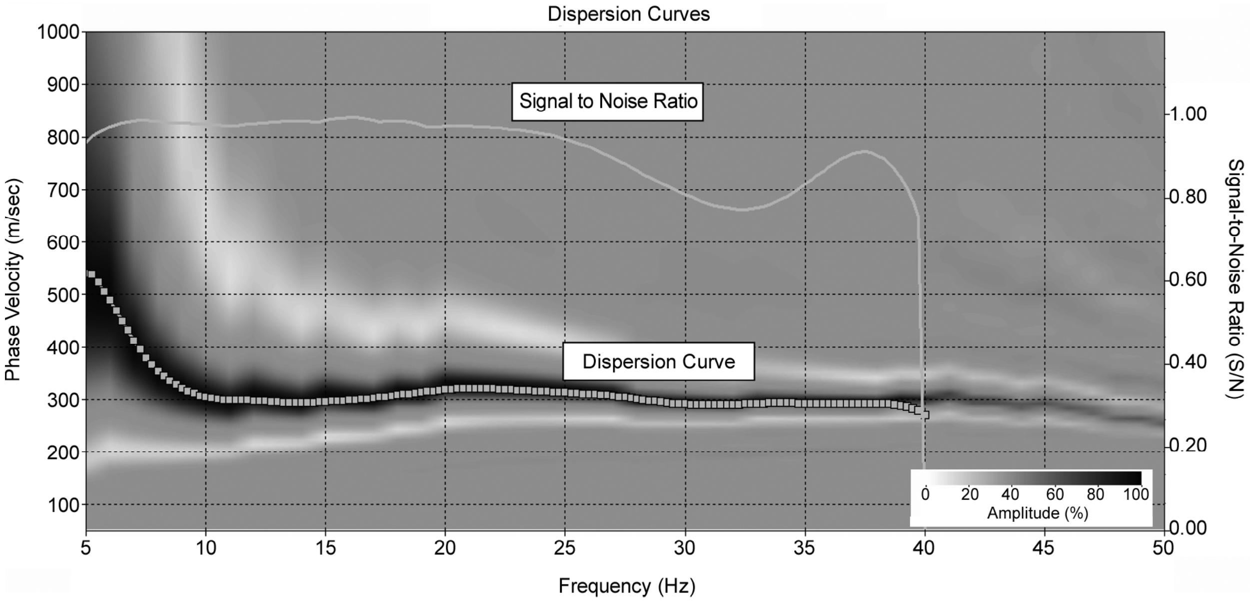

Figure 10. Examples of dispersion curves corresponding to recorded signal given in Figure (9b).

The earth model consists of the velocity (P-wave and S-wave velocity), density, and thickness parameters. A typical modeled shear wave velocity and an actual dispersion curve associated with the Rayleigh wave is shown in Figure (11). The shear wave velocities from 58 locations are given in Figures (12) to (14).

5.1. Equivalent Shear Wave Velocity of Soil

The equivalent shear wave velocity is the weighted average shear wave velocity for depth (*H*) by considering each layer and their properties with depth. The equivalent shear wave velocity for a depth of soil "*d*" is referred to as V_H. The equivalent shear wave velocity to a depth of $H\,(V_H)$ is computed as follows:

$$V_H = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{di} \left[\frac{d_i}{Vs_i} \right]} \qquad (2)$$

where $H = \sum d_i$ = cumulative depth in m, d_i and v_i

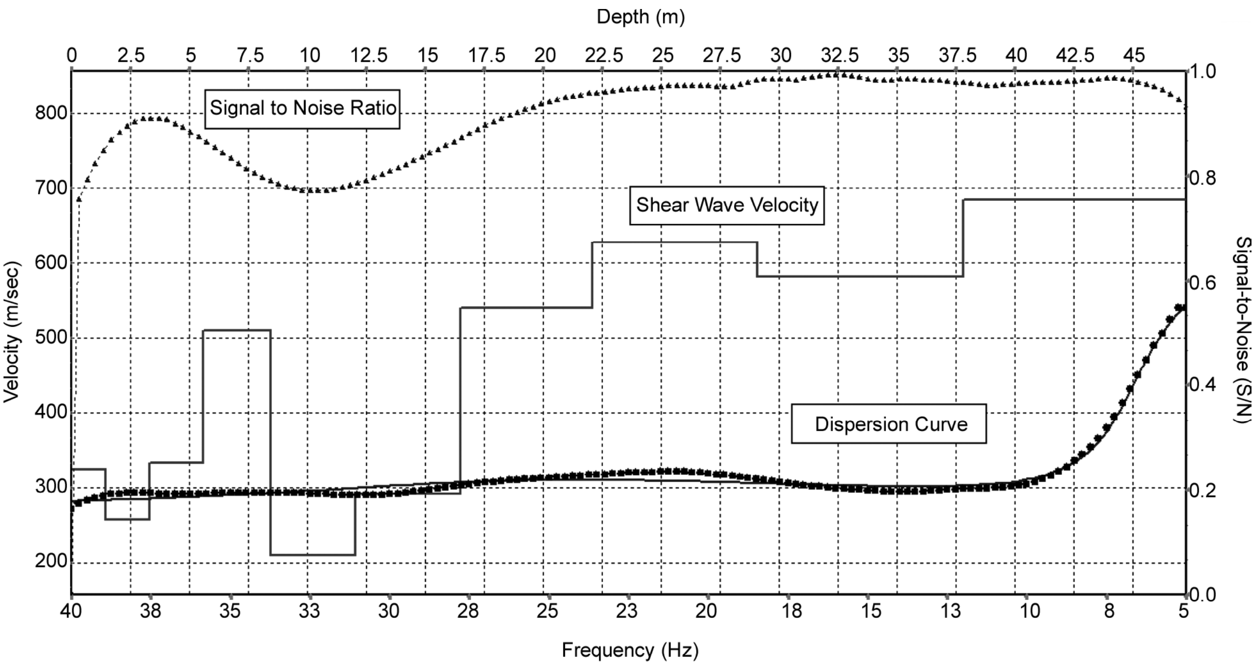

Figure 11. Typical shear velocity modeled using SurfSeis with dispersion curves.

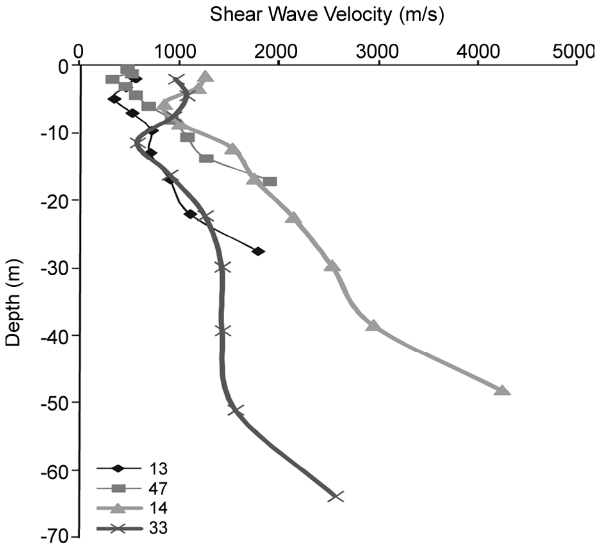

Figure 12. Shear wave velocity profiles corresponding to class B site as per NEHRP Vs 30.

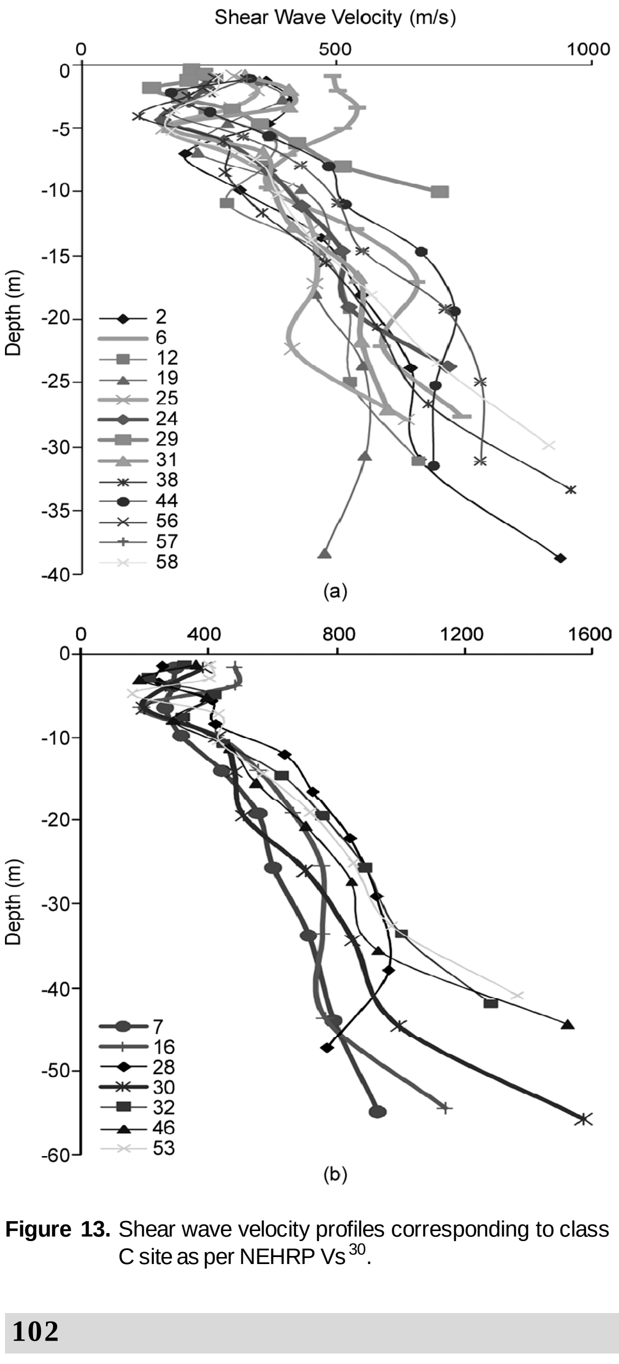

Figure 13. Shear wave velocity profiles corresponding to class C site as per NEHRP Vs 30.

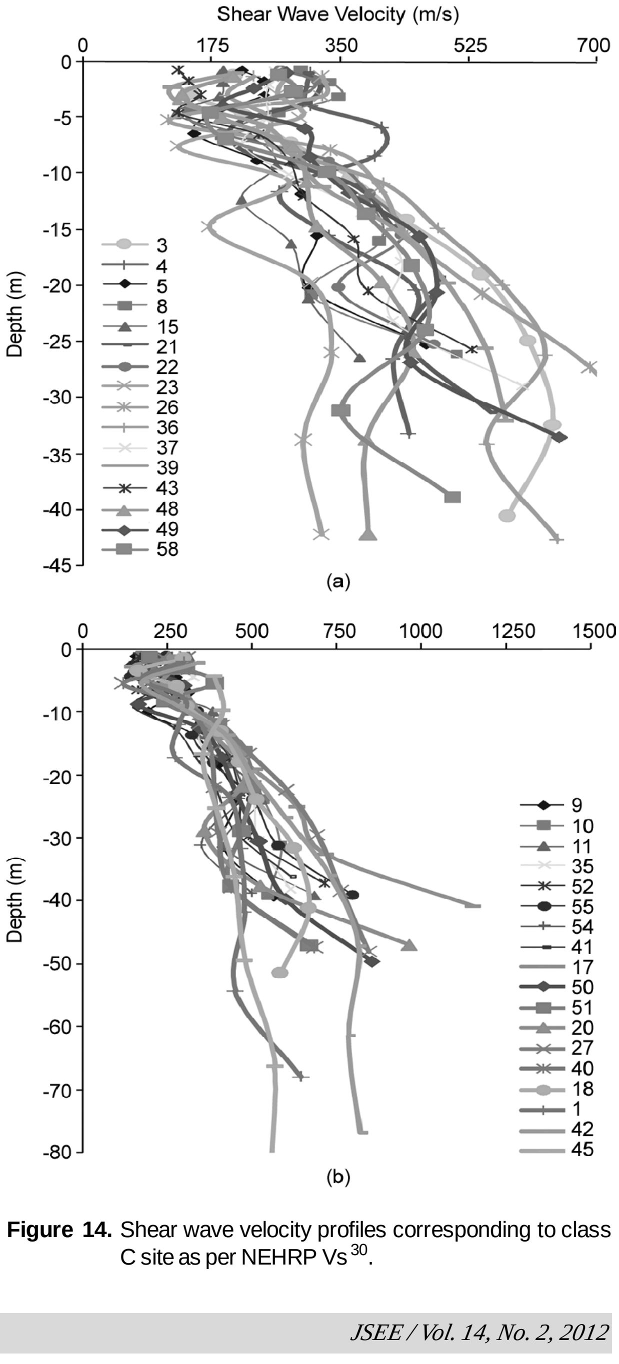

Figure 14. Shear wave velocity profiles corresponding to class C site as per NEHRP Vs 30.

denote the thickness (in meter) and shear wave velocity (at a shear strain level of 10-5 or less, m/s) of the i[th] formation or layer, respectively, in a total of n layers within a depth of *H*. About 75% of the data at more than 30 m depths were available, and in these locations, Vs^{30} was calculated using respective layer thickness and shear wave velocity as per Eq. (2). However, for the remaining locations, data is available for less than 30 m, (2 locations - up to 20 m depth, remaining data is above 25 m depth) and for these, Vs^{30} was calculated by assuming that the shear wave velocity of the last layer remains constant up to 30 m deep as per Boore [37]. The equivalent shear wave velocity (Vs^{30}) for the study area is shown in Figure (15). Figure (15) also shows that the study area can be classified into class B, C, and D sites based on 30 m average shear wave velocity. The profiles of the shear wave velocity given in Figure (12) correspond to the class B site (7% of the testing site). The minimum shear wave velocity at these locations was 320 m/s and the depth of data available was from 30 m to 65 m, except for location 47. Figure (13) shows the shear wave velocity profiles for the class C site as per NEHRP Vs^{30}. About 34% of the test locations show the site as class C. About 59% of the test locations can be classified as class D sites. The profiles of shear wave velocities corresponding to class D sites are shown in Figures (14).

As discussed previously in site characterization using geotechnical data, the depth of engineering bedrock in the study area varies from 1 m to about 40 m. Site classification considering Vs^{30} included rock velocity, because there was a shallow mass of rock within 30 m, which may lead to a higher site classification than NEHRP. This is why site classifications with an equivalent shear wave velocity for soil overburden (Vs^{ST}) was calculated and mapped. The average *Vs* up to engineering bedrock (overburden soil) was calculated based on the thickness of soil corresponding to its location from the borehole, or the shear wave velocity >700 m/s from the MASW. The average *Vs* in the study area up to engineering bedrock is shown in Figure (16). Based on Figure (16), the study area can be classified as class C and D sites, although a major part of this area falls into the class D site. About 4% of the test location was class C site and 96% was class D. Classifying sites using the shear wave velocity showed that where Vs^{ST} about 40% of the sites tested

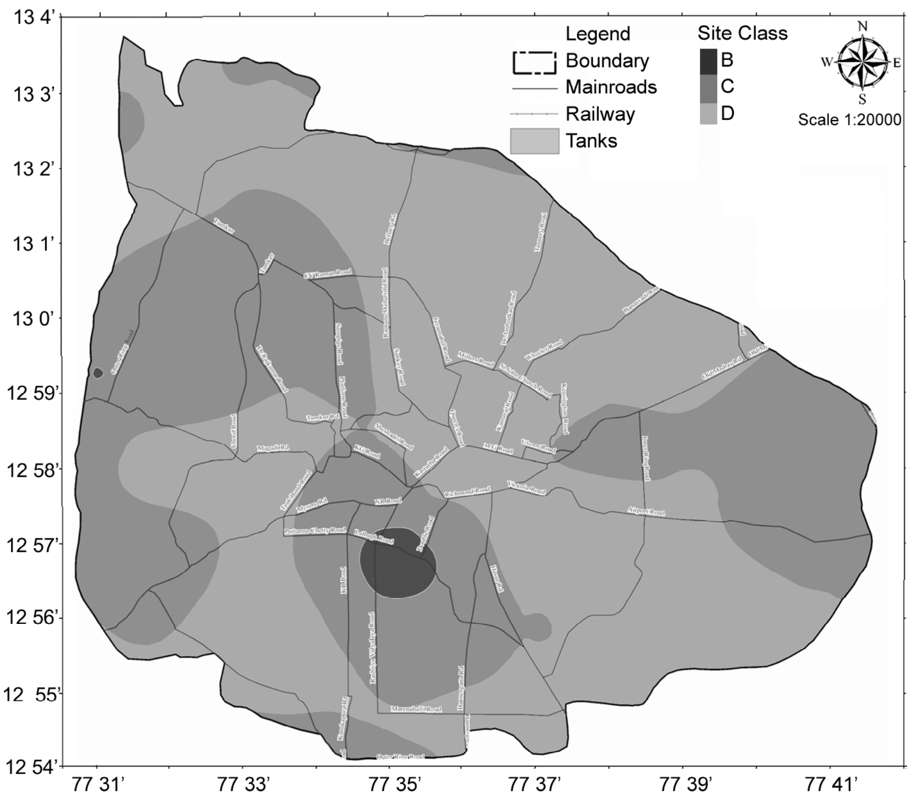

Figure 15. Equivalent shear wave velocity for 30 m depth.

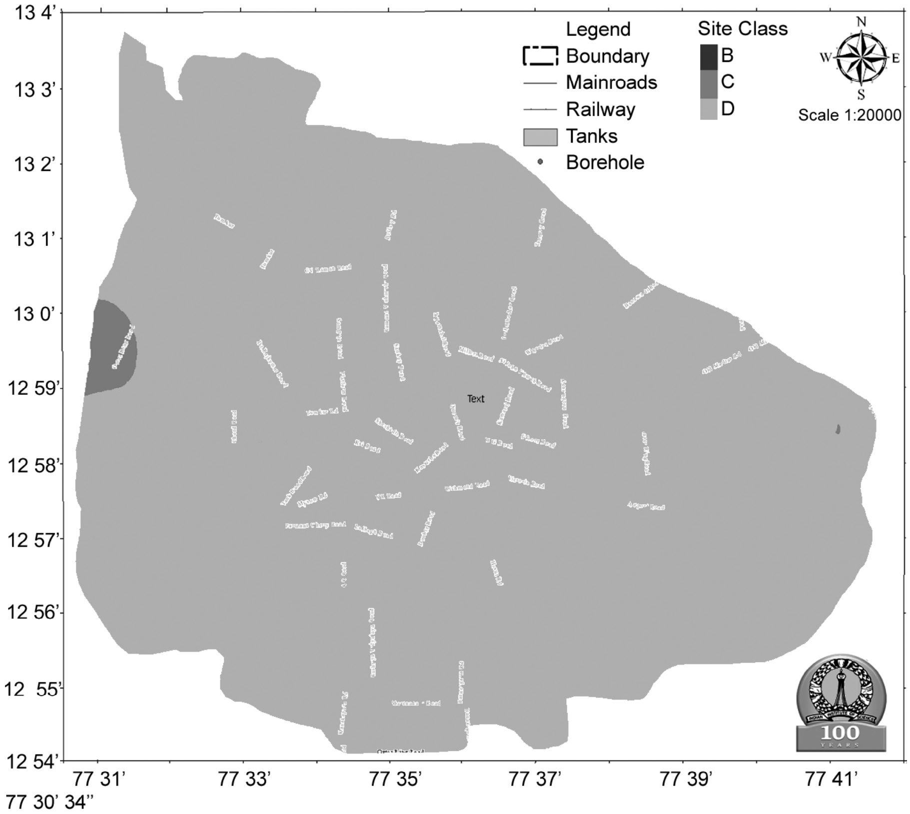

Figure 16. Equivalent shear wave velocity for thickness of soil overburden.

resulted in lower class sites compared to Vs^{30}. Figure (17) shows profile of the average velocity of sites with lower classes using Vs^{ST}. The average shear wave velocities for these sites varied from 270 m/s to 720 m/s, and the soil overburden thickness varied from 1 m to a maximum of about 10 m thick, with an average of about 6.5 m. Site class based on Vs^{30} were higher because the Vs values of the engineering bedrock were added, which also matches with the SPT N value site classification findings.

6. Site Specific Response Study

Site effect studies and amplification correlations with shear wave velocity are available for deep soil sites where the engineering bedrock is not noticed or more than 100 m. In contrast, limited recorded ground motions at rock and surface with shear wave velocity profiles are available for shallow rock sites. The correlations developed for deep soil sites are used directly to represent site classification in seismic codes to account site effects in shallow region [55]. Recently, many seismic microzonation studies are being carried out considering site classification scheme developed for deep soil sites without accounting engineering bedrock depth in the region. These practices are widely followed by many researchers in the world, because it is given in the international standards and well accepted publications from western countries. This study clearly shows that site classification scheme based 30 m average SPT N and shear wave velocity (Vs) gives stiffer site class

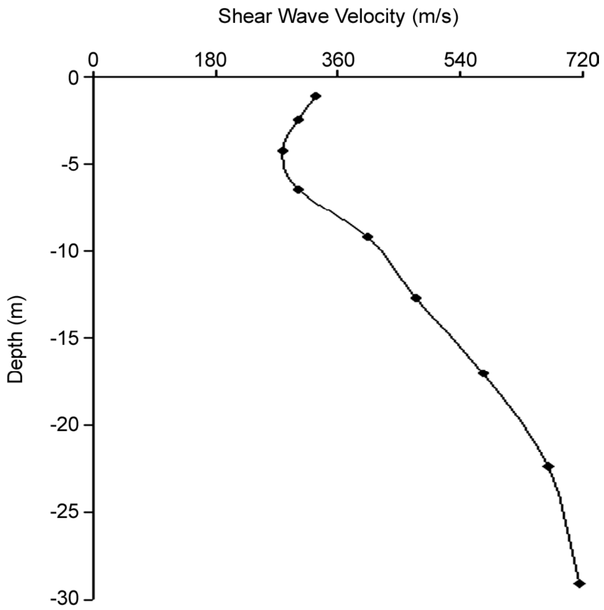

Figure 17. Average shear wave velocity of sites corresponding to the Site class D as per Vs^{ST}.

for shallow bedrock regions when compared to soil average values up to engineering bedrock. In this study, further site specific response study has been carried out by giving input at engineering bedrock and 30 m depth. Few geotechnical and geophysical profiles are selected from the data used for site classification with regional seismic data. Site specific one-dimensional ground response analysis is widely used to predict the ground surface motions at surface for a given input to develop site specific design response spectrum. 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 [56]. 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 that extends to infinite depth were presented in Schnabel et al [57].

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 [58] and Schnabel [59], respectively. In order to understand the site effects due to moderate earthquake, synthetic ground motion generated by Sitharam and Anbazhagan [60] and Anbazhagan and Sitharam [61] has been used in this study. Detailed discussion on site response analysis and input ground motion can be found in Anbazhagan and Sitharam [29, 61]. Figure (18) shows response spectrum of input motion and design spectrum as per NEHRP for site class B, C and D. Site class B is similar to rock site condition or input motion, design spectrum for site class C and D are study area a site classes as per 30 m classification system. Figure 18 also shows Indian code design spectrum for the study area at hard rock condition. Spectral values given in IS1893 are much less than IBC for short period and more than IBC for long period. It can be noted that Indian seismic code of IS 1893 [62] has limited consideration of geotechnical aspects of site and induced effects [63]. Hence, site specific response spectrum developed here have been

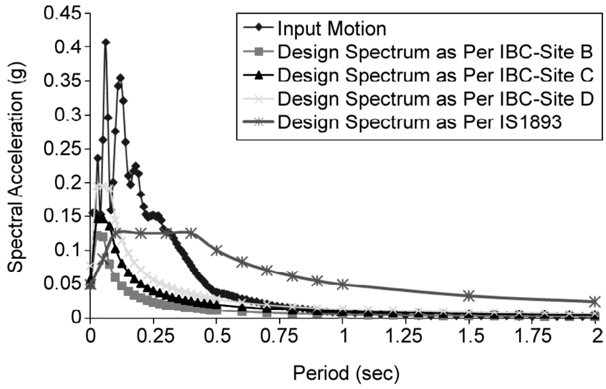

Figure 18. Response spectrum of input motion used for the study along with respective design spectrum as per IBC for site classes B, C and D and design spectrum as per Indian Standard IS1893 (2002).

compared with IBC [34] and NEHRP [37] design spectrum provision. Site response analysis has been carried out by giving input ground motions at engineering bedrock level as per drilled bore hole data or where *Vs* is more than 760±60 m/s and at 30 m depth. For 30 m site response analysis SPT N or *Vs* and density of last layer is extend up to 30 m similar to $\overline{N_{30}}$ and Vs^{30} calculation. Peak ground acceleration (PGA) with depth, response spectrum for rock and surface layers, Fourier spectrum and amplification ratio are arrived. To focus amplification calculation, only PGA and response spectrum will be discussed in the coming sections.

6.1. Response Spectrum from Site Response Study

Anbazhagan and Sitharam [26] studied the site response in this region using SPT N values and gave a synthetic ground motion developed by Sitharam and Anbazhagan [60] as input at the engineering bedrock level. The authors mapped the response parameters, including the predominant frequencies, which were comparable with the predominant frequency obtained from an experimental study of *H*/*V* ratio by Srinagesh et al [64]. However, the authors did not compare site response results by giving input at engineering bed rock and 30 m depth (as per site classification). Hence, in this study, site response analysis has been carried out on selected profiles by giving input at engineering bedrock and 30 m depth. Figure (19) shows selected SPT N profiles used for analysis. SPT N profiles given in Figure (19a) corresponds to Site Class C and Figure (19b) corresponds to site class D as per 30 m classification system. In all 17 locations, input is given at

30 m depth (as per site classification) irrespective of material type and thickness, and response at surface has been estimated. Response spectrum arrived at surface for site class C and D profiles are given in Figure (20). Further response parameters has been calculated by giving input motion at engineering rock level (where SPT N >100 or rebound). Figure (21)

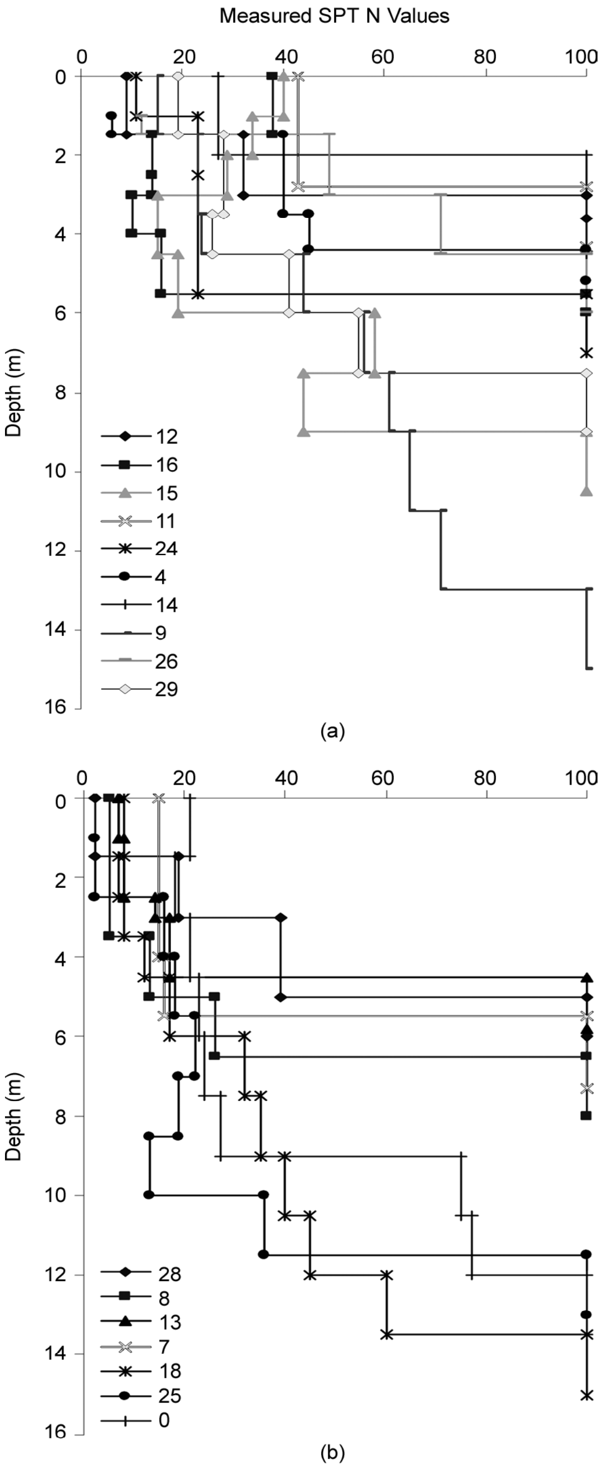

Figure 19. Selected SPT N profiles used for site response analysis (a) profile of site class C and (b) profiles of site D.

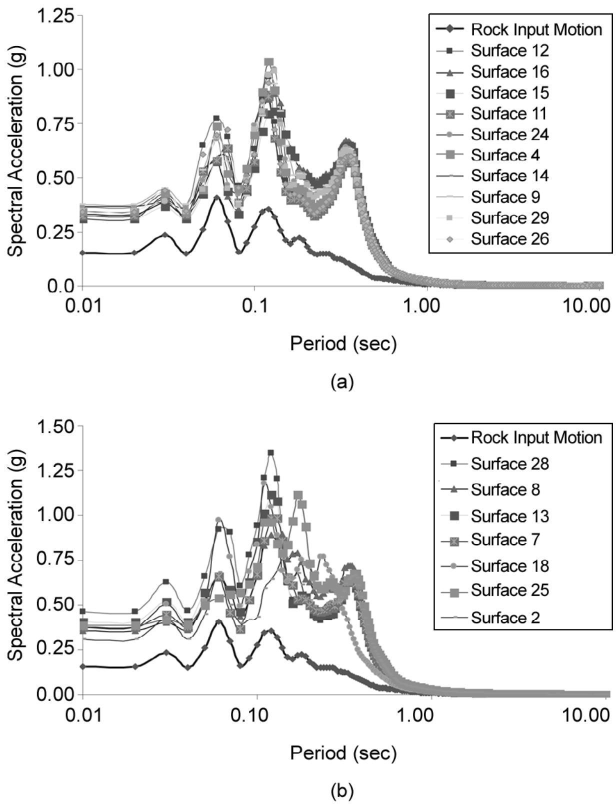

Figure 20. Response spectrum of selected SPT N profiles by giving input at 30 m (a) sites classified as site class C and (b) sites classified as site class D as per IBC (2009).

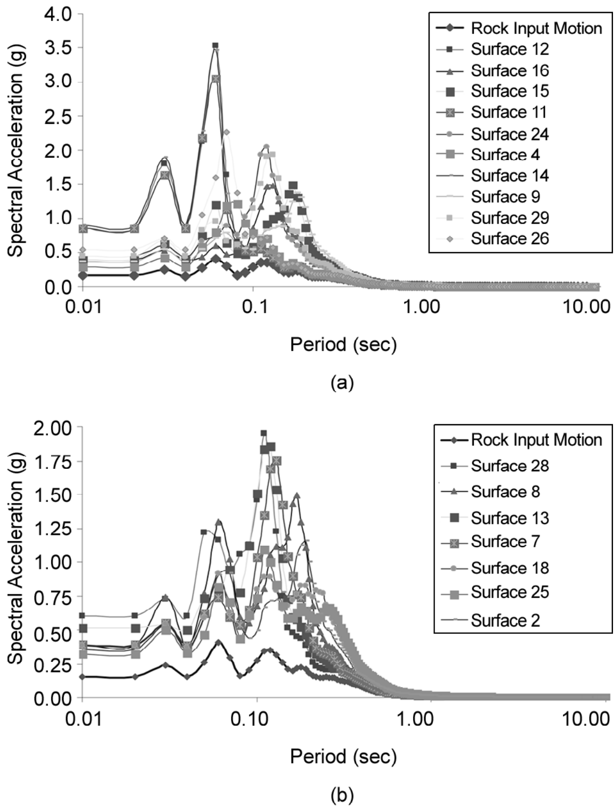

Figure 21. Response spectrum of selected SPT N profiles by giving input at engineering bedrock level (a) sites classified as site class C and (b) sites classified as site class D as per IBC (2009).

shows response spectrum by giving input at engineering bedrock level. Spectral values obtained by giving input at engineering bedrock are much more than spectral values obtained by giving input at 30 m depth.

Soil stiffness in the form of shear wave velocity is a useful parameter and widely used to estimate site specific response parameters for given input of seismic waves and amplifications. Shear wave velocity profiles measured for study has been screened and 13 profiles are selected for site response analysis. In these profiles, weathered to engineering bedrock layer having *Vs* of 400 m/s to 700 m/s are within 30 m. The layers corresponding to *Vs* of 760 ± 60 m/s are considered as base layer for engineering design and are to give input motions for site response analysis. Shear wave velocity from MASW tests are close to SPT boreholes, where soil layers and rock depth are comparable [31]. These profiles are classified as site class B and C as per NEHRP. Site response analysis has been carried out by giving input ground motions at engineering bedrock level where *Vs* is more than 760±60 m/s and at 30 m depth. Peak ground acceleration (PGA) with depth, response spectrum for rock and surface layers, Fourier spectrum and amplification ratio are arrived. To focus amplification calculation, only PGA and response spectrum has been considered here. Figure (22) shows response spectrum for shear wave velocity profiles categorized as site class B and C by giving input at 30 m depth. Site class B (rock) design spectrum is approximately similar to rock level spectrum as per IBC and NEHRP for all periods, but site response study shows that response spectrum of sites classified as B does not match with rock spectrum up to 0.3 sec due to amplification of thin overburden above rock, see Figure (22a). Site specific response study shows that response spectrum of site class C sites are much amplified when compared to rock spectrum, see Figure (22b), when input is given in 30 m and the amplification values are much more than NEHRP values. Similar findings are also observed when input motion is given at engineering bedrock level for the same sites. Figure (23) shows the response spectrum of shear wave velocity profiles categorized as site class B and C by giving input at engineering bedrock.

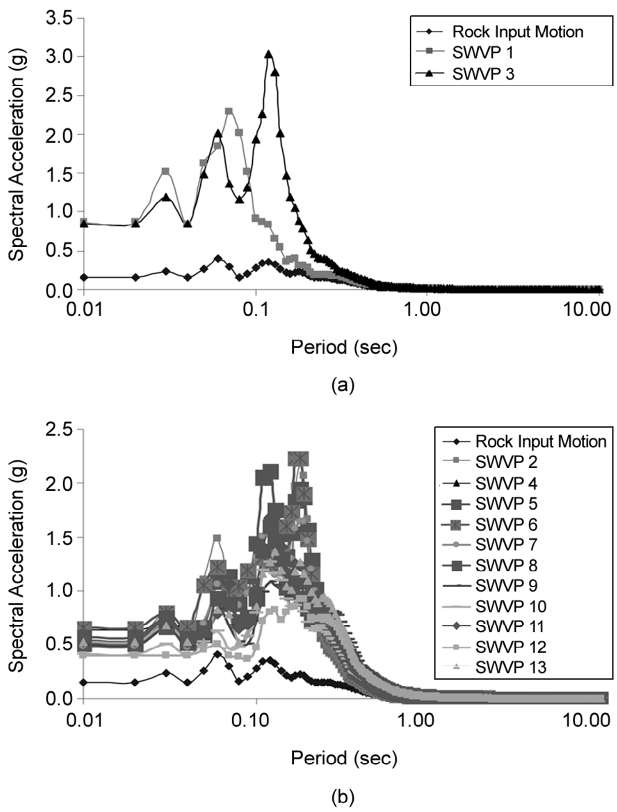

Figure 22. Response spectrum of selected shear wave velocity profiles by giving input at 30 m (a) sites classified as site class B and (b) sites classified as site class C as per IBC (2009).

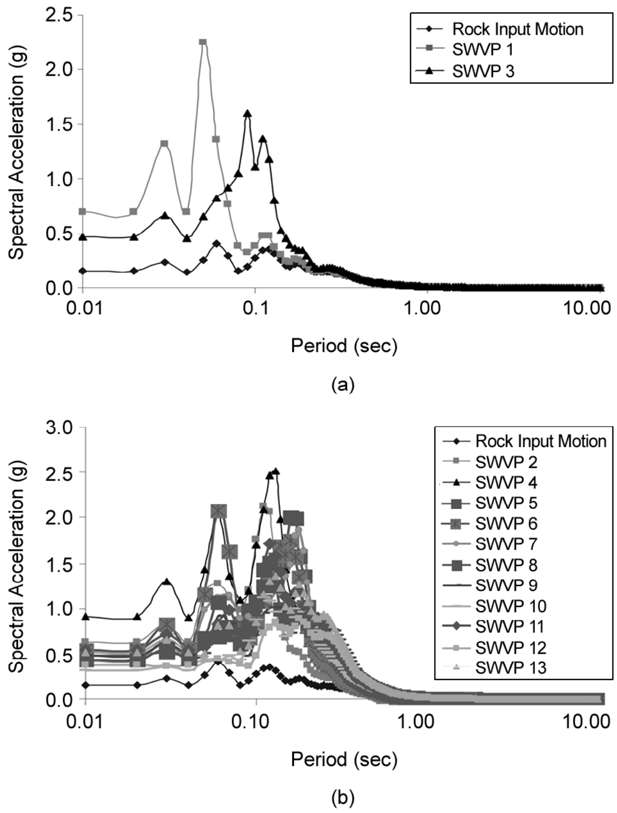

Figure 23. Response spectrum of selected shear wave velocity profiles by giving input at engineering rock depth (a) sites classified as site class B and (b) sites classified as site class C as per IBC (2009).

6.2. Amplification Factors of Spectral Accelerations

Site-specific ground response analyses are carried out to determine the effect of local soil conditions, i.e., amplification of seismic waves. Site effects are a combination of soil and topographical effects, which can modify (amplify and de-amplify) the characteristics (amplitude, frequency content and duration) of the incoming wave field. Empirical correlations to estimate amplification for Grade-2 seismic zonation are widely practiced [65]. Most widely used amplification factors to indicate site effects are relative amplification factor and average horizontal spectral amplification factor. Relative amplification factor is the ratio of surface to rock acceleration/velocity/displacement at particular period or frequency. Among these amplification factors, the factors between peak ground velocity to peak rock velocity are generally used for microzonation. Relative amplification factors are correlated with the ratio of shear wave velocity of hard stratum/foundation to the average of soil shear wave velocity and with average shear wave velocity for 30 m or over a depth of one-quarter wavelength. Average horizontal spectral amplification (AHSA) is the average spectral acceleration between surface and rock for the period range of 0.4-2.0 sec [65-66]. Spectral shape has been divided as different period segment (<0.02, 0.02-0.04, 0.04-0.08, 0.08-0.16, 0.16 -0.4, 0.4-1.0, 1.0 -2.0 and 0.4-2.0 sec) based on input response spectrum. Maximum spectral values in each segment has been identified and used to estimate relative amplification factors between peak spectral values of surface and rock at specified period segment. Table (2) shows amplification factors considering peak spectral values for different period segment for the input at 30 m and at ER depth using SPT data site class C and D profiles. Average horizontal spectral acceleration has been estimated for each period segment for surface and rock spectrum. These values are used to estimate average horizontal spectral amplification values. Table (3) shows average horizontal spectral amplification values for different period segment for the input at 30 m and at ER depth using SPT data site class C and D profiles. Tables (4) and (5) shows amplification

Table 2. Amplification factors considering maximum spectral accelerations in each period segment for site class C and D as per SPT data.

	SPT -12		SPT -16		SPT -15		SPT -11		SPT -24		SPT -4		SPT -14		SPT -9		SPT -26		SPT -29	
Period (sec)	**30 m**	**3.6 m**	**30 m**	**6 m**	**30 m**	**10.5 m**	**30 m**	**4.3 m**	**30 m**	**7 m**	**30 m**	**5.2 m**	**30 m**	**4.5 m**	**30 m**	**15 m**	**30 m**	**6 m**	**30 m**	**9 m**
<0.02	***2.3***	***5.5***	***2.1***	***2.5***	***2.0***	***2.5***	***2.1***	***5.4***	***2.4***	***2.8***	***2.2***	***1.8***	***2.0***	***5.8***	***2.4***	***2.3***	***2.2***	***3.4***	***2.2***	***2.9***
0.02-0.04	1.9	7.6	1.6	2.2	1.6	2.6	1.7	6.9	1.6	2.5	1.8	1.7	1.8	8.0	1.9	2.3	1.9	2.9	1.7	2.8
0.04 - 0.08	1.9	8.7	1.4	1.5	1.4	2.9	1.6	7.5	1.7	2.2	1.8	3.0	1.5	8.5	1.7	1.9	1.8	5.6	1.7	2.3
0.08 - 0.16	2.7	1.7	2.5	4.1	2.3	3.8	2.5	1.6	2.8	5.8	2.9	2.6	2.5	1.7	2.7	3.0	2.6	2.2	2.8	5.4
0.16 - 0.4	2.7	1.4	3.0	3.3	2.9	6.6	2.6	1.3	2.8	3.0	2.7	1.5	2.6	1.4	2.8	6.1	2.7	1.5	2.8	3.6
0.4 - 1.0	5.2	1.1	5.6	1.6	5.6	1.8	5.2	1.1	5.5	1.6	5.3	1.1	5.2	1.1	5.5	2.2	5.2	1.1	5.4	1.7
1 - 2.0	2.6	1.1	2.7	1.2	2.6	1.2	2.6	1.1	2.6	1.5	2.6	1.2	2.6	1.1	2.6	1.4	2.6	1.1	2.6	1.3
0.4-2.0	***5.4***	***1.1***	***5.7***	***1.6***	***5.7***	***1.8***	***5.3***	***1.1***	***5.6***	***1.6***	***5.5***	***1.0***	***5.4***	***1.1***	***5.7***	***2.1***	***5.4***	***1.1***	***5.5***	***1.7***

	SPT -28		SPT -8		SPT -13		SPT -7		SPT -18		SPT -25		SPT -2	
Period (sec)	**30 m**	**6 m**	**30 m**	**8 m**	**30 m**	**5.8 m**	**30 m**	**7.3 m**	**30 m**	**15 m**	**30 m**	**13 m**	**30 m**	**13.5 m**
<0.02	***3.0***	***3.9***	***2.3***	***2.5***	***2.6***	***3.3***	***2.4***	***2.5***	***2.4***	***2.5***	***2.5***	***2.1***	***2.0***	***2.3***
0.02-0.04	2.7	3.1	1.7	3.1	2.2	2.3	1.9	2.3	2.1	2.3	1.8	2.1	1.8	2.3
0.04 - 0.08	2.3	3.0	1.6	3.2	1.6	2.3	1.6	1.8	2.4	2.3	1.4	2.0	1.7	2.2
0.08 - 0.16	3.8	5.5	2.5	4.0	3.1	5.2	2.8	4.9	3.3	2.5	2.7	3.1	2.1	2.5
0.16 - 0.4	2.8	2.0	3.5	6.6	2.9	2.6	2.9	3.4	3.4	3.7	4.9	3.0	3.0	5.1
0.4 - 1.0	5.5	1.3	6.1	1.8	5.6	1.5	5.6	1.6	2.8	2.5	6.9	2.8	5.9	2.1
1 - 2.0	2.7	1.5	2.8	1.2	2.7	1.6	2.7	1.2	1.7	1.5	3.1	1.8	2.7	1.3
0.4 - 2.0	***5.6***	***1.4***	***6.3***	***1.8***	***5.7***	***1.5***	***5.7***	***1.6***	***2.7***	***2.4***	***7.2***	***2.8***	***6.1***	***2.1***

Table 3. Amplification factors considering average spectral accelerations in each period segment for site class C and D as per SPT data.

	SPT -12		SPT -16		SPT -15		SPT -11		SPT -24		SPT -4		SPT -14		SPT -9		SPT -26		SPT -29	
Period (sec)	**30 m**	**3.6 m**	**30 m**	**6 m**	**30 m**	**10.5 m**	**30 m**	**4.3 m**	**30 m**	**7 m**	**30 m**	**5.2 m**	**30 m**	**4.5 m**	**30 m**	**15 m**	**30 m**	**6 m**	**30 m**	**9 m**
<0.02	***2.3***	***5.5***	***2.1***	***2.5***	***2.0***	***2.5***	***2.1***	***5.4***	***2.4***	***2.8***	***2.2***	***1.8***	***2.0***	***5.8***	***2.4***	***2.3***	***2.2***	***3.4***	***2.2***	***2.9***
0.02-0.04	2.1	6.8	1.8	2.3	1.7	2.6	1.9	6.4	1.9	2.6	2.0	1.8	1.9	7.2	2.1	2.3	2.0	3.1	1.9	2.9
0.04 - 0.08	2.3	7.0	1.6	1.8	1.6	2.7	1.9	6.2	1.8	2.7	1.9	3.3	1.9	6.9	1.9	2.3	2.2	5.6	1.7	2.7
0.08 - 0.16	2.4	1.7	2.7	4.0	2.5	3.3	2.2	1.6	2.7	5.0	2.7	2.2	2.2	1.7	2.7	2.9	2.3	2.1	2.7	5.0
0.16 - 0.4	3.3	1.2	4.0	2.2	3.9	3.3	3.2	1.1	3.7	2.0	3.4	1.2	3.2	1.2	3.7	3.9	3.3	1.2	3.6	2.3
0.4 - 1.0	3.8	1.1	4.1	1.4	4.0	1.6	3.8	1.1	3.9	1.5	3.8	1.2	3.8	1.1	4.0	1.9	3.8	1.2	3.8	1.5
1- 2.0	2.6	1.1	2.7	1.2	2.7	1.6	2.6	1.1	2.6	1.5	2.6	1.2	2.6	1.1	2.6	1.7	2.6	1.2	2.6	1.4
0.4-2.0	***3.8***	***1.1***	***4.1***	***1.4***	***4.1***	***1.6***	***3.8***	***1.1***	***3.9***	***1.5***	***3.8***	***1.2***	***3.8***	***1.1***	***4.0***	***1.9***	***3.8***	***1.2***	***3.9***	***1.5***

	SPT -28		SPT -8		SPT -13		SPT -7		SPT -18		SPT -25		SPT -2	
Period (sec)	**30 m**	**6 m**	**30 m**	**8 m**	**30 m**	**5.8 m**	**30 m**	**7.3 m**	**30 m**	**15 m**	**30 m**	**13 m**	**30 m**	**13.5 m**
<0.02	***3.0***	***3.9***	***2.3***	***2.5***	***2.6***	***3.3***	***2.4***	***2.5***	***2.4***	***2.5***	***2.5***	***2.1***	***2.0***	***2.3***
0.02 - 0.04	2.8	3.4	2.0	2.9	2.4	2.7	2.1	2.4	2.3	2.4	2.1	2.1	1.9	2.3
0.04 - 0.08	2.8	3.9	1.9	3.3	2.0	2.8	1.8	2.2	2.5	2.3	1.9	2.2	1.8	2.6
0.08 - 0.16	3.5	4.2	2.9	3.7	3.1	4.7	2.9	4.5	3.1	2.8	3.1	2.8	2.2	2.5
0.16 - 0.4	3.7	1.6	4.5	3.3	3.8	1.9	3.9	2.2	3.9	3.8	4.8	3.6	4.0	3.6
0.4 - 1.0	3.9	1.3	4.4	1.6	3.9	1.4	4.0	1.4	2.4	2.2	4.9	2.5	4.2	1.9
1 - 2.0	2.7	1.5	3.0	1.7	2.7	1.6	2.7	1.3	1.7	1.6	3.3	1.8	2.8	1.6
0.4 - 2.0	***3.9***	***1.4***	***4.4***	***1.6***	***4.0***	***1.4***	***4.0***	***1.4***	***2.4***	***2.2***	***5.0***	***2.5***	***4.3***	***1.9***

Table 4. Amplification factors considering maximum spectral accelerations in each period segment for site class B and C as per shear wave velocity data.

	SWVP 1		SWVP 3	
Period (sec)	**30 m**	**6 m**	**30 m**	**12.85 m**
<0.02	***5.6***	***4.5***	***5.5***	***3.0***
0.02-0.04	6.4	5.6	5.0	2.8
0.04 - 0.08	5.6	5.5	4.9	2.6
0.08 - 0.16	4.3	1.3	8.5	4.5
0.16 - 0.4	1.8	1.2	4.7	1.6
0.4 - 1.0	1.2	1.1	1.9	1.1
1 - 2.0	1.3	1.0	1.7	1.4
0.4 - 2.0	1.1	1.1	1.9	1.3

	SWVP 2		SWVP 4		SWVP 5		SWVP 6		SWVP 7		SWVP 8		SWVP 9		SWVP 10		SWVP 11		SWVP 12		SWVP 13	
Period (sec)	30m	10m	30m	16.5m	30m	19.2 m	30m	19.6m	30m	20.7m	30m	23.7m	30m	25.2m	30m	25.5m	30m	25.7m	30m	26.7m	30m	27.6m
<0.02	***3.5***	***4.1***	***4.1***	***5.8***	***3.3***	***3.1***	***4.2***	***3.5***	***3.1***	***2.8***	***3.7***	***2.8***	***3.2***	***3.1***	***2.6***	***2.0***	***3.5***	***3.5***	***2.5***	***2.4***	***3.4***	***3.4***
0.02-0.04	3.4	3.6	3.0	5.5	2.8	2.2	3.4	3.5	3.0	2.8	3.2	2.4	2.8	2.6	2.1	1.5	3.1	3.0	1.7	1.6	2.9	2.8
0.04 - 0.08	3.7	3.1	2.8	5.0	2.8	2.1	3.0	5.1	2.6	2.8	2.3	2.6	2.1	2.2	1.5	1.2	2.6	2.4	1.2	1.1	2.0	2.0
0.08 - 0.16	4.8	6.0	7.3	7.1	6.0	5.7	4.9	4.9	4.3	4.2	4.5	4.2	3.1	2.8	3.6	3.2	4.8	4.8	2.4	2.4	3.8	3.8
0.16 - 0.4	9.7	2.4	11.4	4.4	8.7	8.8	9.9	7.0	7.3	8.3	4.8	4.2	4.2	4.1	4.0	4.4	5.6	5.3	4.1	3.9	5.7	5.6
0.4 - 1.0	2.5	1.5	2.1	1.8	2.8	2.0	2.4	1.7	2.5	2.2	3.1	2.7	4.0	3.8	2.9	2.4	3.1	3.0	3.7	3.5	3.8	3.7
1 - 2.0	1.9	1.6	1.7	1.6	1.8	1.4	1.8	1.3	1.7	1.6	1.8	1.6	2.4	2.2	1.6	1.5	1.9	1.8	2.3	2.1	2.5	2.4
0.4 2.0	***2.4***	***1.5***	***2.0***	***1.8***	***2.7***	***2.0***	***2.3***	***1.6***	***2.4***	***2.2***	***3.0***	***2.7***	***3.9***	***3.7***	***2.8***	***2.3***	***3.0***	***2.9***	***3.6***	***3.5***	***3.7***	***3.6***

Table 5. Amplification factors considering average spectral accelerations in each period segment for site class B and C as per shear wave velocity data.

	SWVP 1		SWVP 3	
Period (sec)	**30 m**	**6 m**	**30 m**	**12.85 m**
<0.02	***5.6***	***4.5***	***5.5***	***3.0***
0.02-0.04	6.0	5.2	5.3	2.9
0.04 - 0.08	6.9	4.2	5.4	3.1
0.08 - 0.16	2.8	1.3	7.4	3.4
0.16 - 0.4	1.3	1.1	2.7	1.4
0.4 - 1.0	1.3	1.1	1.7	1.3
1 - 2.0	1.3	1.1	1.9	1.4
0.4 - 2.0	1.3	1.1	1.7	1.3

	SWVP 2		SWVP 4		SWVP 5		SWVP 6		SWVP 7		SWVP 8		SWVP 9		SWVP 10		SWVP 11		SWVP 12		SWVP 13	
Period (sec)	30m	10m	30m	16.5m	30m	19.2 m	30m	19.6m	30m	20.7m	30m	23.7m	30m	25.2m	30m	25.5m	30m	25.7m	30m	26.7m	30m	27.6m
<0.02	***3.5***	***4.1***	***4.1***	***5.8***	***3.3***	***3.1***	***4.2***	***3.5***	***3.1***	***2.8***	***3.7***	***2.8***	***3.2***	***3.1***	***2.6***	***2.0***	***3.5***	***3.5***	***2.5***	***2.4***	***3.4***	***3.4***
0.02-0.04	3.4	3.8	3.4	5.7	3.0	2.6	3.8	3.6	3.1	2.8	3.4	2.6	2.9	2.8	2.3	1.7	3.2	3.2	2.0	1.9	3.1	3.1
0.04 - 0.08	4.1	4.1	4.0	5.3	3.3	2.6	3.9	5.0	3.3	3.7	2.8	2.8	2.3	2.5	1.9	1.6	2.8	2.8	1.5	1.5	2.4	2.4
0.08 - 0.16	5.0	4.9	5.9	6.7	6.0	5.2	5.0	4.9	4.7	4.2	4.4	4.1	3.3	3.1	3.7	3.2	4.7	4.7	2.6	2.6	3.9	3.9
0.16 - 0.4	5.4	1.8	4.4	2.7	5.3	3.9	5.1	3.2	4.9	4.5	4.3	3.9	4.9	4.6	3.8	3.6	4.9	4.6	4.5	4.3	5.5	5.4
0.4 - 1.0	2.2	1.4	1.9	1.6	2.5	1.7	2.1	1.6	2.2	2.0	2.8	2.4	3.7	3.4	2.6	2.1	2.9	2.8	3.4	3.2	3.6	3.5
1 - 2.0	2.4	1.6	2.2	1.7	2.2	1.9	2.4	1.7	2.0	2.1	1.9	1.6	2.4	2.3	1.7	1.5	2.2	2.0	2.2	2.1	2.5	2.5
0.4 2.0	***2.2***	***1.4***	***1.9***	***1.6***	***2.5***	***1.8***	***2.2***	***1.6***	***2.2***	***2.0***	***2.8***	***2.3***	***3.6***	***3.4***	***2.6***	***2.0***	***2.8***	***2.7***	***3.3***	***3.2***	***3.6***	***3.5***

factors using shear wave velocity similar to Tables (3) and (4). These amplification values are more than the values given in the IBC and NEHRP values. Well-established correlations are available to estimate amplification of seismic waves using ratio of average shear wave velocity for deep soil sites. However, very limited similar correlations are available for shallow bedrock sites. Comparison of amplification factors arrived from the site specific response analysis using synthetic and recorded data with existing correlations were presented by Anbazhagan et al [55].

6.3. Average Response Spectrum

Average response spectrum of each site class has been arrived separately for SPT N and *Vs* data, which are further used to estimate spectral amplification (ratio of average surface spectrum divided by rock spectrum). Figure (24) shows the average response spectrum for each site class by giving input at 30 m depth and engineering bedrock. Spectral values are amplified up to period of 0.5 second beyond which amplification is negligible. Spectral amplification values are calculated for all the periods for SPT data and *Vs* data separately and shown in Figure (25). Figures clearly show that shallow bedrock profiles are having the tendency to modify seismic waves. Modifications are considerable in short period when compared to long period irrespective of the input depth. Anbazhagan et al [55] highlighted that amplification values from SPT data and *Vs* data in shallow bedrock region is much more than the amplification correlations developed based on ratio of shear wave velocity or average 30 m shear wave velocity by Shima [67], Joyner and Fumal [68], Midorikawa [67] and Kokusho and Sato [70]. First three correlations are the basis for developing design spectrum and widely used for seismic microznation [55]. Mismatching of spectral amplifcation values may be attributed to shallow engineeirng bedrock, site specific seismology and geotehncial paramters. Empirical correlations are developed based deep soil depsoits which are completely different from the soil deposits in the study region. Hence, following the IBC and NEHRP site calssifcation in shallow bedrock region city like Bangalore without cheking its applicability may not be appropriate.

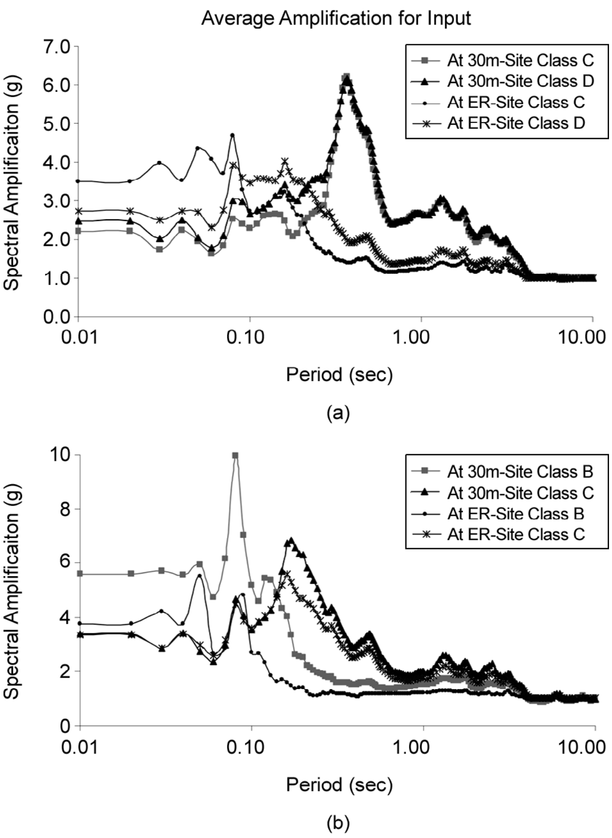

Figure 25. Average spectral amplification for each site class by giving input at 30 m and engineering rock depth (a) using SPT N values and (b) using Vs values.

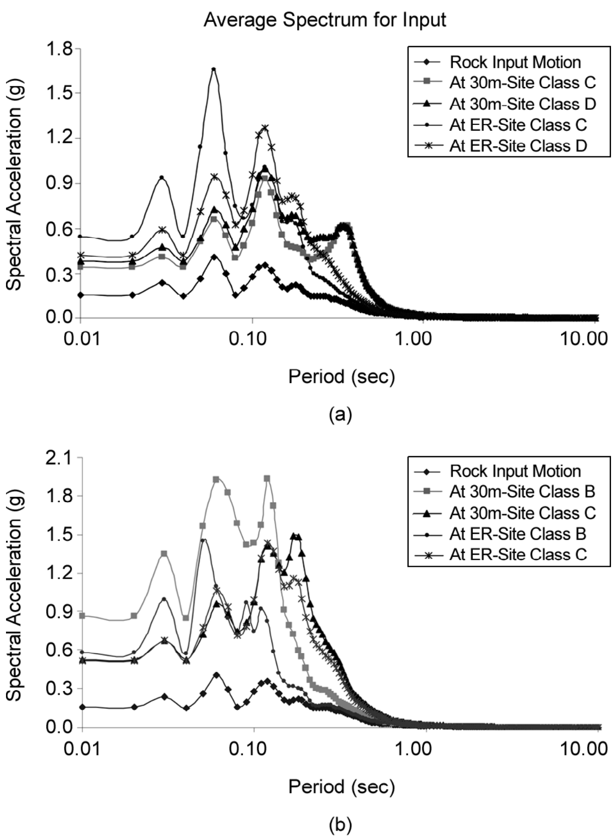

Figure 24. Average response spectrum for each site class by giving input at 30 m and engineering rock depth (a) using SPT N values (b) using Vs values.

7. Results and Discussions

The geotechnical and geophysical results revealed that Bangalore can be classified as stiffer site classes when the 30 m average SPT-N and *Vs* values were used, although a major part of study area are prone to more impedance construed due loose shallow thickness soil over a dense hard rock. Site classifications using N and *Vs* values up to engineering bedrock showed that a major part of the study area was class D. In many locations, soil average SPT N and *Vs* values are much less than 30 m average values which results in lower site class as NEHRP. In general, most of the study area with site classifications using *N* or *Vs* values up to engineering bedrock and thickness of soil could be class D sites. The sites of dense and very dense soil with high SPT N values up to shallow engineering bedrock show a similar site class, irrespective of the depth of the engineering bedrock and *N* values. In contrast, sites of loose and medium soil values up to shallow engineering bedrock show a different site class with respect of depth of the engineering bedrock and *N* values. The SPT N value, which corresponds to loose-to-medium layers of soil, should not be used to classify sites because it may mislead when the engineering bedrock is at a shallow depth. A Vs^{30} is only meaningful if the column of soil is deeper than 30 m. A comparison of $Vs^{30}/(\overline{N_{30}})$ and $Vs^{ST}/\overline{N_{ST}}$ has made it clear that an average 30 m site classification gave a higher average SPT N/shear wave velocity and different site class than average values up to engineering bedrock. These results concurred with Kockar et al. [3] findings where the author used Vs^{30} and the top layer of soil separately for site classification. Stiffer site class may be attributed to adding the engineering bedrock *N* or *Vs* in the 30 m classification. This may be investigated further if the data of measured site effects with bore log or *Vs* are available from the region where the engineering bedrock is shallow.

Site specific response analysis has been carried out by considering selected SPT N and *Vs* profiles and synthetic input motion applicable to the region. Response spectrum and amplification values are estimated and compared with IBC and NEHRP provision and existing correlations. The study shows that spectral values and amplification factors are high and are not comparable with conventional design spectrum and amplifications based on 30 m average shear wave velocity. Applicability of 30 m average for an empirical site response and seismic microzonation studies in shallow engineering bedrock regions like Bangalore need to be investigated. Anbazhagan and Sitharam [26] estimated predominant period by site response analysis using *Vs* and input synthetic ground motion at engineering bedrock level. These predominant frequencies are well compared with the predominant frequency measured using the *H*/*V* noise survey. Therefore, the site with clearly defined shallow engineering bedrock (within 40 m) may be classified based on the average SPT N values up to engineering bedrock, using the same class sites recommended in the NEHRP and IBC. However, detailed separate site classification scheme may be developed for shallow bedrock sites, where impedance contrast is high resulting in considerable modification of seismic waves.

8. Conclusions

The urban centre at Bangalore was characterized using geotechnical and geophysical techniques. A map generated to identify the thickness of the soil overburden and depth of the rock shows that the engineering bedrock depth varies from 1 m to 40 m. An MASW survey at 58 locations was conducted and the shear wave velocity with depth was measured. Equivalent SPT N values and shear wave velocity were calculated by considering the 30 m average and the results show that a major part of study area can be classified as class C and D sites, as per NEHRP and IBC. Due to variations in the depth of the engineering bedrock, an attempt was made in this study to calculate an equivalent SPT-N and Vs values using the depth of the engineering bedrock. An equivalent N/shear wave velocity above the engineering bedrock shows that the study area can be classified as a class D site. A higher class site in the 30 m average was a result of adding rock *N* or *Vs* values in the 30 m average calculation in regions with a shallow overburden. Site specific response analysis has been carried out by considering selected SPT N and *Vs* profiles by giving at 30 m and engineering bedrock. A surface level response spectrum and amplification are higher than 30 m based spectrum and amplification values. This study shows that using 30 m average values for site classifications may not be appropriate for regions where the depth of engineering bedrock is clearly defined within 30 m. A seismic site class may be carried out using average values up to engineering bedrock for sites with engineering bedrock within 30 m. However, separate site classification schemes may be needed and can be developed in future for shallow bedrock regions.

Acknowledgement

The authors would like to thank the Department of Atomic Energy for funding the project " Seismic Site Classification for Indian Shallow Soil Deposits" (Ref No: DAEO/MCV/ANB/0165) and Seismology Division, Ministry of Earth Sciences, Government of India for funding the project entitled "Site Response Studies Using Strong Motion Accelerographs" (Ref no. MoES/P.O. (Seismo)/1 (20)/2008).

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Aberration Nomenclature for the Symbols and Abbreviations

$\overline{N_{30}}$: Equivalent SPT N values for 30 m depth

$\overline{N_{ST}}$: Equivalent SPT N values up to engineering rock depth

AHSA: Average horizontal spectral amplification

ANN: Artificial neural networks

B, C, D: Site classes

BMP: Bangalore Mahanagar Palike

BSSC: The Building Seismic Safety Council

d_i: Thickness of i^{th} layers

GIS: Geographical information system

G_{max}: Shear modulus

HVSR: Horizontal to vertical spectral ratio

IBC: International Building Code

IISc: Indian Institute of Science

IS: Indian Standard

MASW: Multi-channel analysis of the surface wave

MSL: Mean sea level

NEHRP: National Earthquake Hazards Reduction Program

PGA: Peak ground acceleration

SPT -1, 2: Standard penetration test N profiles

SPT N: Standard penetration test N values

S_u^{30} : Undrained shear strength

SWVP 1, 2: Shear wave velocity profiles

TRFI: Torsteel Research Foundation in India

Vs: Shear wave velocity

Vs^{30}: Equivalent 30 m shear wave velocities

Vs^{ST}: Equivalent shear wave velocity for soil over-burden