# Mapping of Average Shear Wave Velocity for Bangalore Region: A Case Study

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## ABSTRACT

Mapping the shear wave velocity profile is an important part in seismic hazard and microzonation studies. The shear wave velocity of soil in the city of Bangalore was mapped using the Multichannel Analysis of Surface Wave (MASW) technique. An empirical relationship was found between the Standard Penetration Test (SPT) corrected N value ($(N_1)_{60cs}$) and measured shear wave velocity (*Vs*). The survey points were selected in such a way that the results represent the entire Bangalore region, covering an area of 220 km$^2$. Fifty-eight 1-D and 20 2-D MASW surveys were performed and their velocity profiles determined. The average shear wave velocity of Bangalore soils was evaluated for depths of 5 m, 10 m, 15 m, 20 m, 25 m and 30 m. The sub-soil classification was made for seismic local site effect evaluation based on average shear wave velocity of 30-m depth ($V_s^{30}$) of sites using the National Earthquake Hazards Reduction Program (NEHRP) and International Building Code (IBC) classification. Mapping clearly indicates that the depth of soil obtained from MASW closely matches with the soil layers identified in SPT bore holes. Estimation of local site effects for an earthquake requires knowledge of the dynamic properties of soil, which is usually expressed in terms of shear wave velocity. Hence, to make use of abundant SPT data available on many geotechnical projects in Bangalore, an attempt was made to develop a relationship between Vs (m/s) and $(N_1)_{60cs}$. The measured shear wave velocity at 38 locations close to SPT boreholes was used to generate the correlation between the corrected N values and shear wave velocity. A power fit model correlation was developed with a regression coefficient ($R^2$) of 0.84. This relationship between shear wave velocity and corrected SPT N values correlates well with the Japan Road Association equations.

## Introduction

Shear wave velocity (*Vs*) is an essential parameter for evaluating the dynamic properties of soil in the shallow subsurface. A number of geophysical methods have been developed for near-surface characterization and measurement of shear wave velocity. These methods use a great variety of testing configurations, processing techniques, and inversion algorithms. Two of the best known techniques are Spectral Analysis of Surface Waves (SASW) and Multichannel Analysis of Surface Waves (MASW). The SASW has been used for site investigation for several decades (*e.g.*, Nazarian *et al.*, 1983; Al-Hunaidi, 1992; Stokoe *et al.*, 1994; Tokimatsu, 1995; Ganji *et al.*, 1997). It utilizes the spectral analysis of surface waves generated by an impulsive source and recorded by a pair of receivers. Evaluating and distinguishing signal from noise with only a pair of receivers is difficult, and therefore the MASW method was developed (Park *et al.*, 1999; Xia *et al.*, 1999; Xu *et al.*, 2006). It is based on multiple channel analysis of surface waves and it is a more efficient method for unraveling the shallow subsurface properties (Park *et al.*, 1999; Xia *et al.*, 1999; Zhang *et al.*, 2004). MASW is a non-invasive seismic method that can be used for geotechnical site characterization (Park *et al.*, 1999; Xia *et al.*, 1999; Miller *et al.*, 1999; Park *et al.*, 2005a; Kanli *et al.*, 2006). In particular, it is used in geotechnical engineering for the measurement of shear wave velocity and dynamic properties, and for identification of subsurface material boundaries. 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 (Ivanov *et. al.*, 2005). 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 (Ivanov *et. al.*, 2005). MASW is also used to generate a two-dimensional (2-D) shear wave velocity profile. The MASW method has been successfully applied to various types of geotechnical and geophysical projects such as mapping 2-D bedrock surface and shear modulus of overburden materials

(Miller *et al.*, 1999), generation of shear-wave velocity profiles (Xia *et al.*, 2000), seismic evaluation of pavements (Ryden *et al.*, 2004), seismic characterization of sea-bottom sediments (Park *et al.*, 2005b), and mapping of a fault zone with higher then expected resolution (Ivanon *et al.*, 2006).

In this paper, the average shear wave velocity is imaged over an area of 220 $km^2$ in Bangalore Municipal corporation limits at depths of 5 m, 10 m, 15 m, 20 m, 25 m and 30 m. In addition, use of a large number of Standard Penetration Test (SPT) borelogs available in the study area allows for the development of a relation between SPT corrected N value and shear wave velocity. The study was carried out for assigning soil classification for seismic local site effect evaluation and also to find a relationship between corrected SPT N value ($(N_1)_{60cs}$) and measured shear wave velocity ($Vs$).

## Study Area

Bangalore city covers an area of over 220 $km^2$ 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, in the southwestern part of India (Fig. 1). It experiences temperate and salubrious climate, and an annual rainfall of around 940 mm. Bangalore city had over 150 tanks (*i.e.*, man made ponds), though most of them are dried up because of erosion and encroachments, leaving only 64 at present in an area of 220 $km^2$. These tanks were once distributed throughout the city for better water supply facilities and are presently in a dried up condition, the residual silt and silty sand forming thick deposits over which structures have been erected. These soil conditions may be susceptible for site amplification during excitation of seismic waves.

The population of Bangalore region is over 6 million. It is situated at a latitude of 12°58′ north and longitude 77°37′ east. Bangalore city is the fastest growing city and fifth biggest city in India. Bangalore possesses many national laboratories, defense establishments, small and large-scale industries and information technology companies. These establishments have made Bangalore a very important and strategic city. Because of density of population, mushrooming of buildings of all kinds from mud buildings to reinforced cement concrete (RCC) framed structures and steel construction, and improper and low quality construction practice, Bangalore is vulnerable even to average earthquakes (Sitharam *et al.*, 2006). The recent studies by Ganesha Raj and Nijagunappa (2004), Sitharam *et al.* (2006), and Sitharam and Anbazhagan (2007) have suggested that Bangalore be upgraded from the present seismic zone II (BIS, 2002) to zone III, based on the regional seismotectonic details and hazard analysis. Hence, sub-soil classification for the Bangalore region is important to evaluate seismic local site effects for an earthquake. From the three-dimensional (3-D) subsurface model of geotechnical borelog data developed by Sitharam *et. al.* (2007), the authors have determined that the overburden thickness of the study area varies from 1 m to about 40 m. Subsurface profile information, such as unit weight, ground water level, and SPT N values (see Fig. 2 for a typical borelog), are obtained from borehole data collected and compiled in the study area for the development of a geotechnical subsurface model. Because of the abundance of data in the study area, these borelogs are considered to be representative for the typical soil profiles. Based on the nature of soils, classification of soils has been done for general identification of soil layers. Layer thickness and type of material are summarized in Table 1 (modified after Sitharam *et al.*, 2007).

## MASW Field Acquisition

MASW is a geophysical method that generates a shear wave velocity ($Vs$) profile (*i.e.*, $Vs$ versus depth) from the analysis of Raleigh-type surface waves on a multichannel record. The equipment used consisted of a Geode seismograph and 24 single component geophones with 4.5-Hz natural frequency. The seismic waves are generated using an impulsive source (ten shots of a 15-lb sledge hammer striking a 300 mm × 300 mm steel plate). The recorded Rayleigh waves were analyzed using SurfSeis software (a software package of the Kansas Geological Survey (KGS)). 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, ii) dispersion-curve analysis, and iii) inversion. The test locations were selected in such a way that they cover the entire city (Fig. 1). In total, 58 one-dimensional (1-D) surveys and 20 2-D surveys were performed. About 38 MASW survey locations are very close to the SPT borehole locations. Most of the survey locations selected are on flat ground and in relevent places like parks, hospitals, schools and temple yards, etc. The optimum field parameters, such as source to first and last receiver, receiver spacing, and spread length of survey lines, were selected in such a way that the required depth of information can be obtained. All tests were carried out with a geophone interval of 1 m. The source was positioned on both sides of the spread and the source-receiver offset was set at 5 m, 10 m and 15 m to avoid near-field and far-field effects. These source distances help ensure good signals in very soft,

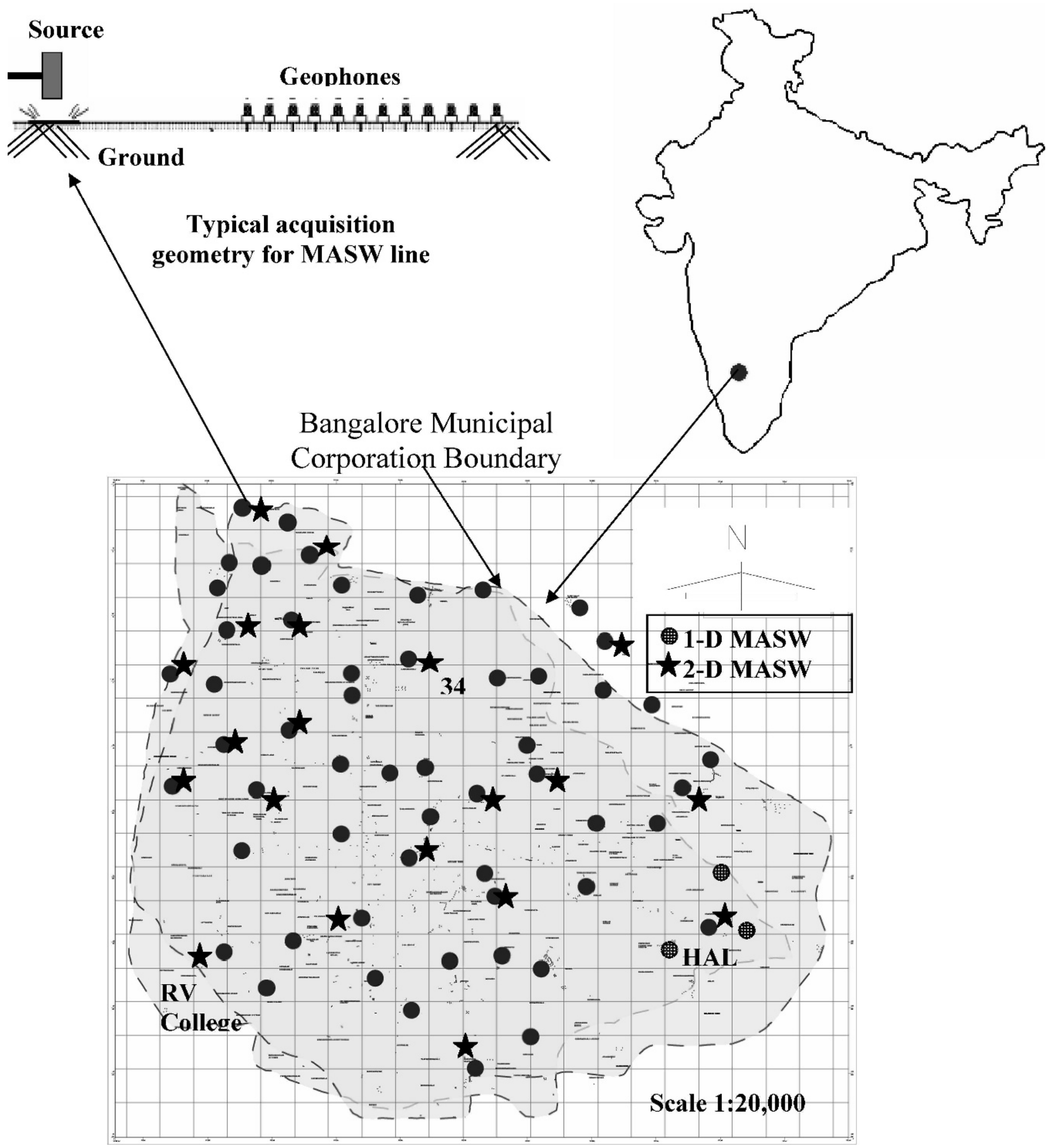


**Figure 1. Study area within India with MASW testing locations.**

soft and hard soils. Xu *et al.* (2006) suggested offset distances for very soft, soft and hard soil of 1 m to 5 m, 5 m to 10 m, and 10 m to 15 m, respectively. Typical recorded surface wave arrivals using a source to first receiver distance of 5 m with recording length of 1,000 ms is shown on Fig. 3.

### MASW Methodology

The generation of a dispersion curve is a critical step in the MASW method. 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

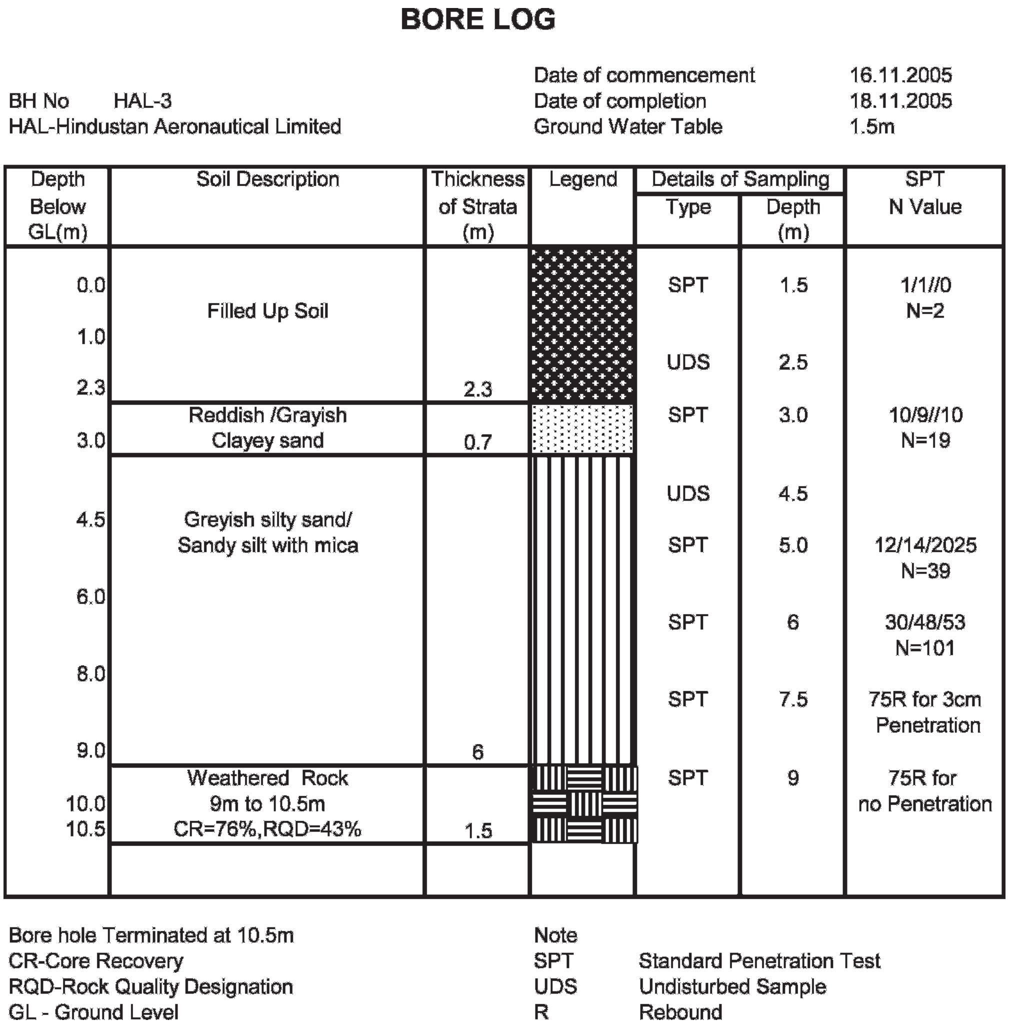


**Figure 2. Standard penetration test data along with typical borelog in the study area.**

record. The lowest analyzable frequency in the dispersion curve is around 4 Hz and the highest frequency considered is 75 Hz. A typical dispersion curve is shown in Fig. 4 with signal-to-noise (S/N) ratio shown by the dotted line. Each dispersion curve obtained for corresponding locations has a very high S/N ratio of about 80% (0.8 on right side axis of Fig. 4) and above. A *Vs* profile has been calculated using an iterative inversion process that uses the dispersion curve developed earlier as an input. A least-squares approach allows automation of

**Table 1. Soil distribution in Bangalore (modified after Sitharam *et al.*, 2007).**

| | Soil description with depth and direction | | | |
|---|---|---|---|---|
| Layer | Southwest | Northwest | Northeast | Southeast |
| First layer | Silty sand with clay 0–3 m | Silty sand with gravel 0–1.7 m | Clayey sand 0–1.5 m | Soil fill 0–1.5 m |
| Second layer | Medium to dense silty sand 3–6 m | Clayey sand 1.7–3.5 m | Clayey sand with gravel 1.5–10 m | Silt sandy with clay 1.5–9 m |
| Third layer | Weathered rock 6–17 m | Weathered rock 3.5–8.5 m | Silty sand with gravel 10–15.5 m | Sandy clay 9–17.5 m |
| Fourth layer | Hard rock below 17 m | Hard rock below 8.5 m | Weathered rock 15.5–27.5 m | Weathered rock 17.5–38.5 m |
| Fifth layer | Hard rock | Hard rock | Hard rock below 27.5 m | Hard rock below 38.5 m |

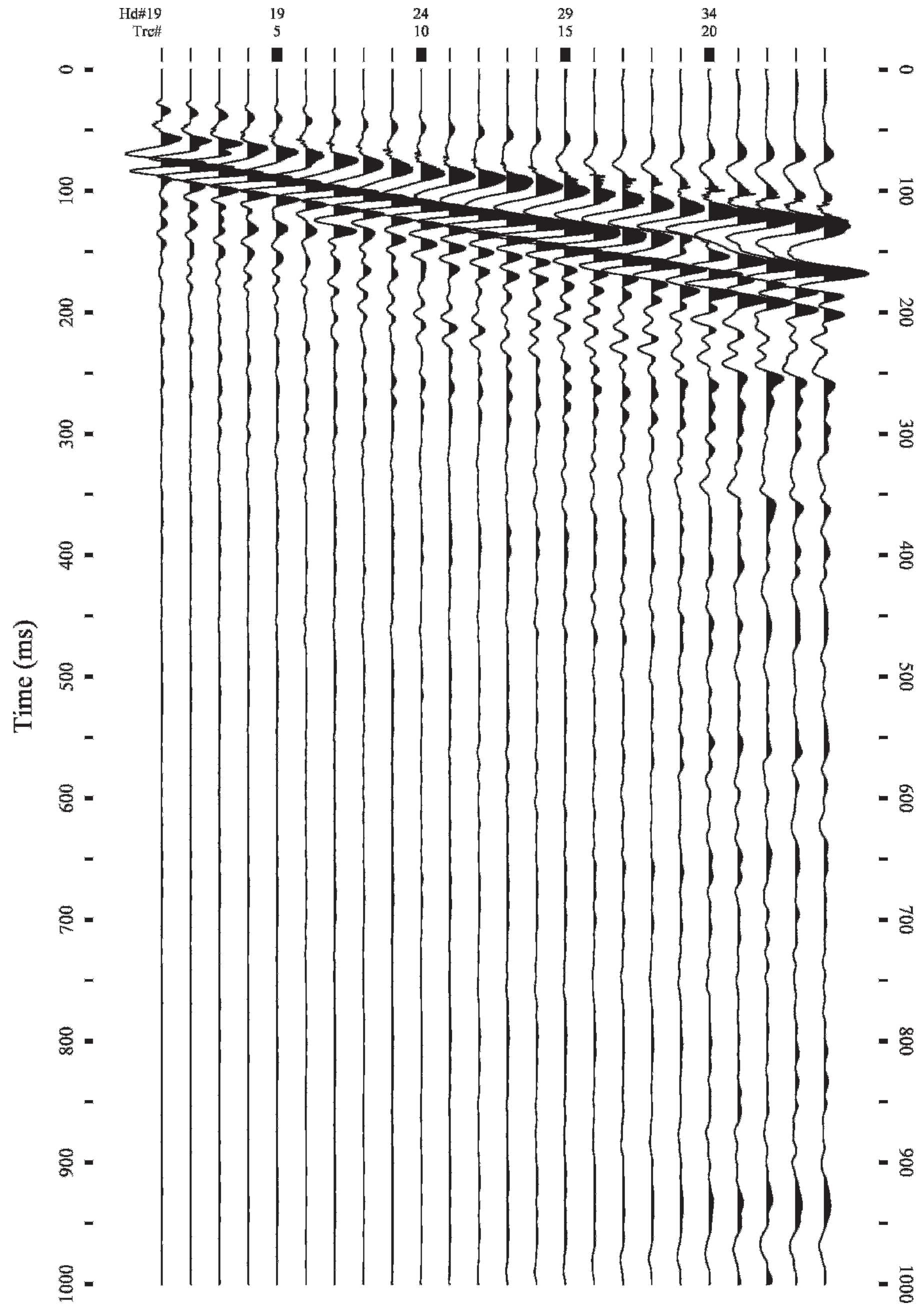


**Figure 3. Typical seismic waves recorded with Geode seismograph.**

the process (Xia *et al.*, 1999). An initial earth model is specified to begin the iterative inversion process. The earth model consists of velocity (P-wave and S-wave), density, and thickness parameters. Shear wave velocity is updated each iteration, while parameters such as Poisson's ratio, density, and thickness of the model remain unchanged. A 1-D *Vs* profile is shown in Fig. 5 for survey location 34 (see Fig. 1). Minimum shear wave velocity found in the region is about 100 m/s, with a maximum *Vs* of about 1,200 m/s. Generally, the trend in the velocity profiles is increasing with depth. This likely represents soil deposits overlying weathered and hard rock in the study area. The range of shear wave velocity values obtained from each survey line for the different layers falls within the recommendations of NEHRP *Vs* site classification (Martin, 1994) and IBC code site classification (IBC-2000).

## MASW Results

Two-dimensional velocity profiles were used to determine layer thickness, subsurface layering informa-

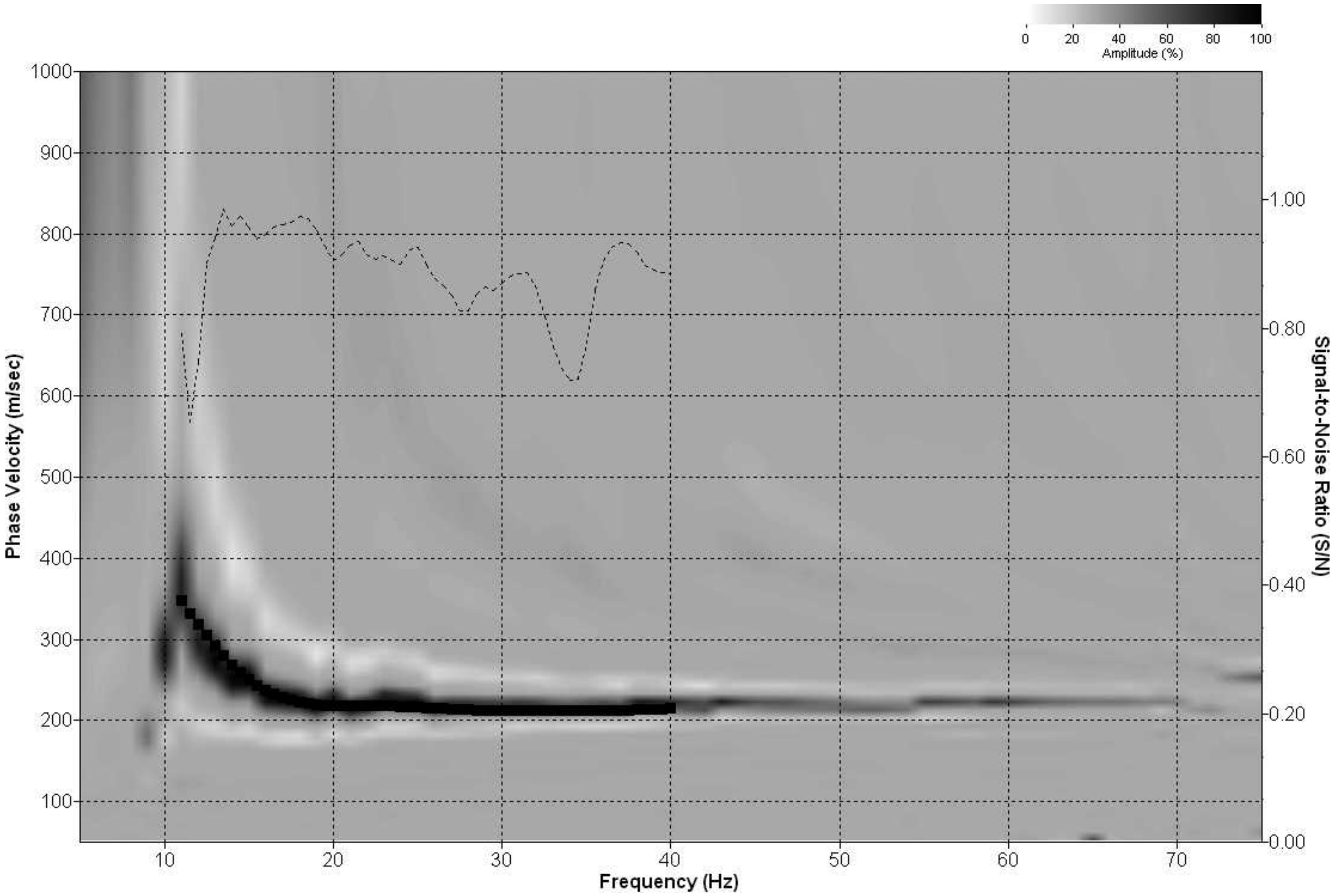


**Figure 4. Typical dispersion curve obtained from MASW survey.**

tion (soft or hard) and rock dipping directions in Bangalore. To obtain the 2-D *Vs*, a number of shot gathers were acquired in a consecutive manner along the survey line by moving both source and receiver spread simultaneously by a fixed amount of distance after each shot. Each shot gather was then analyzed for 1-D *Vs* profile in a manner previously stated. In this way, a number of *Vs* profiles were generated. The *Vs* data are assigned into a 2-D (x–z) grid. Various types of data processing techniques can be applied to get 2-D *Vs*. For mapping, a simple interpolation and data smoothing technique has been used. When the *Vs* data are assigned to the grid, there is ambiguity in the horizontal coordinate (x) because each *Vs* profile was obtained from a shot gather that spanned a distance too large to be considered as a single point. It seems reasonable that the center of the receiver spread be the most appropriate point because the analyzed *Vs* profile represents an average property within the spread length (Park *et al.*, 2005a).

2-D MASW tests were carried out at 20 locations with a minimum receiver length of 12 m. Kriging was used to interpolate each mid point velocity and generate the 2-D *Vs* profile from the midpoint of the first spread line to the midpoint of last spread line. An example of a 2-D velocity profile is shown in Fig. 6. Shallow depth shear wave velocities vary up to 360 m/s. As depth increases, the shear wave velocities also increase. A general observation from the 2-D *Vs* profiles is that material layers with a velocity of 300 m/s and greater are dipping, which may be caused by the undulation and variation in original ground elevation. However, at a few locations soil fill material is found. The fill material is loose and contains larger stones. The lower velocity (<200 m/s) zones seen in the 2-D velocity profiles represent the soil fill material. A typical 2-D velocity profile is shown in Fig. 7, where borehole data are available at the middle of the survey line. The borelog is shown in Fig. 8. The presence of boulders in the soil does not allow penetration of the SPT sampler tube. The 2-D shear wave velocity profile down to about 7 m shows that the *Vs* distribution is irregular, due to layering and heterogeneity. This may be caused by the

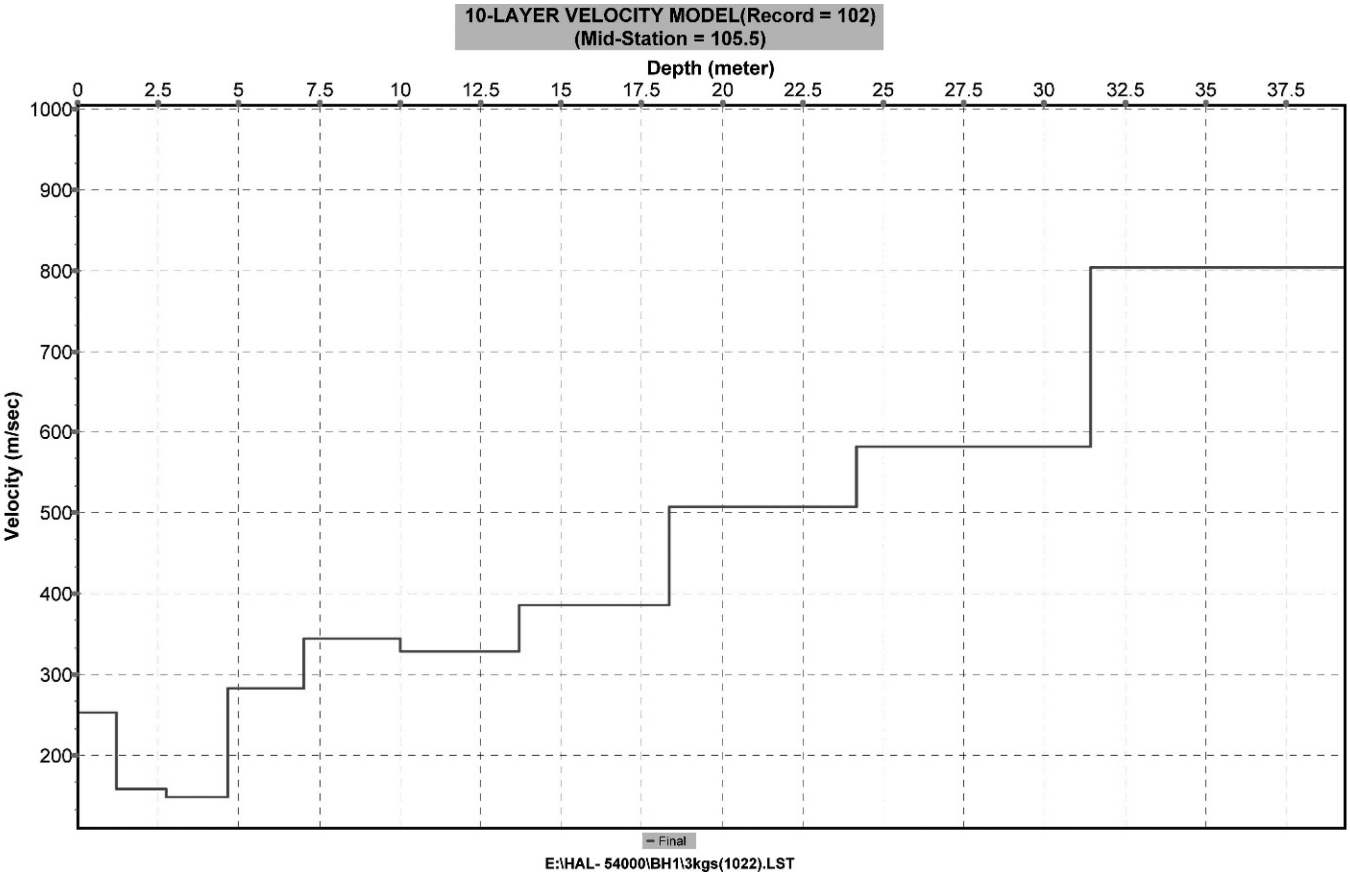


**Figure 5. 1-D shear wave velocity profile for survey location 34.**

presence of the soil fill that contains boulders. For depths of 7 m up to 18 m, the shear wave velocity varies from 300 m/s to 500 m/s, which corresponds to soft weathered rock, as identified in the borehole. For a depth of 18 m to 20 m, *Vs* varies from 500 m/s to 700 m/s; this can be classified as hard weathered rock (also correlates with the borehole data). The borelog (Fig. 8) indicates that hard rock is at 18-m depth. A shear wave velocity of more than 700 m/s corresponds to that depth.

Elastic properties of near-surface materials and their effects on seismic wave propagation are very important in earthquake, civil engineering and environmental earth science studies. 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 to as $V_H$. The average shear wave velocity up to a depth of $H$ ($V_H$) is computed as:

$$V_H = \sum d_i \Big/ \sum (d_i/v_i) \quad \text{(Kanli } et\ al\text{., 2006)} \quad (1)$$

where $H = \Sigma d_i$ is the cumulative depth in m. For 30-m average depth, shear wave velocity is calculated from:

$$Vs^{30} = \frac{30}{\sum_{i=1}^{N} \left( {d_i}/{v_i} \right)} \quad \text{(Kanli } et\ al\text{., 2006)} \quad (2)$$

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 $i^{\text{th}}$ formation or layer, respectively, in a total of N layers, existing in the top 30 m. $Vs^{30}$ is accepted for site classification as per NEHRP classification and also UBC classification (Uniform Building Code in 1997) (Dobry *et al.*, 2000; Kanli *et al.*, 2006). In order to figure out the average shear wave velocity distribution in Bangalore, the average velocity was calculated using Eq. (1) at each location. A simple spread sheet was generated to carry out the calculation, as shown in Table 2. The *Vs* average was calculated at 5 m intervals up to a depth of 30 m. Also, average *Vs* for the soil overburden was calculated. Usually, for amplification and site response studies the 30 m average *Vs* is considered. Because rock is found within a depth of about 30 m in Bangalore at many locations, only near-surface shear wave velocity of soil has been considered to prepare average shear wave velocity of the overburden soil. Otherwise, $Vs^{30}$ obtained would be

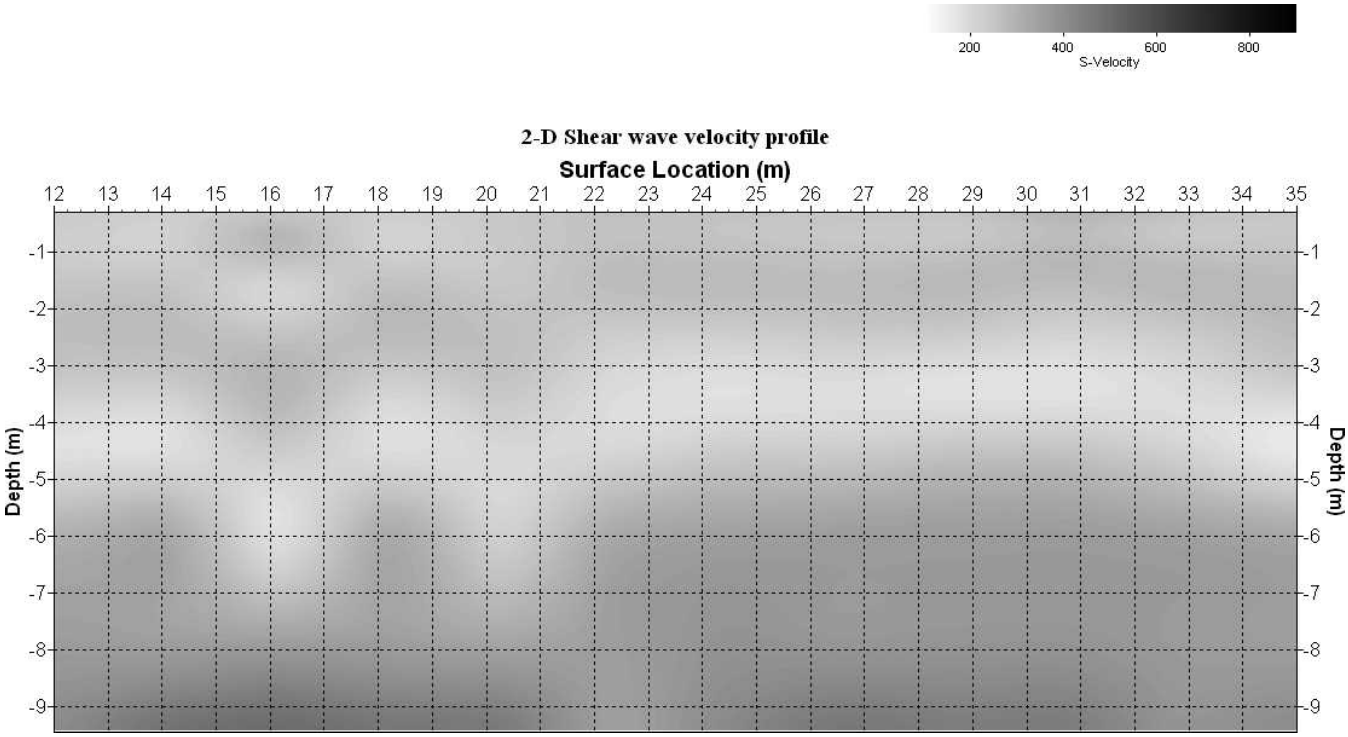


**Figure 6. 2-D spatial variation of shear wave velocity.**

higher because of the velocity of the rock mass. In Bangalore the soil overburden thickness varies from 1 m to about 40 m. Hence, for overburden soil alone, average *Vs* has also been calculated based on the soil thickness corresponding to the location, which is also shown in column 4 of Table 2.

The soil overburden thickness and depth of bedrock were obtained from the Geotechnical Geo-

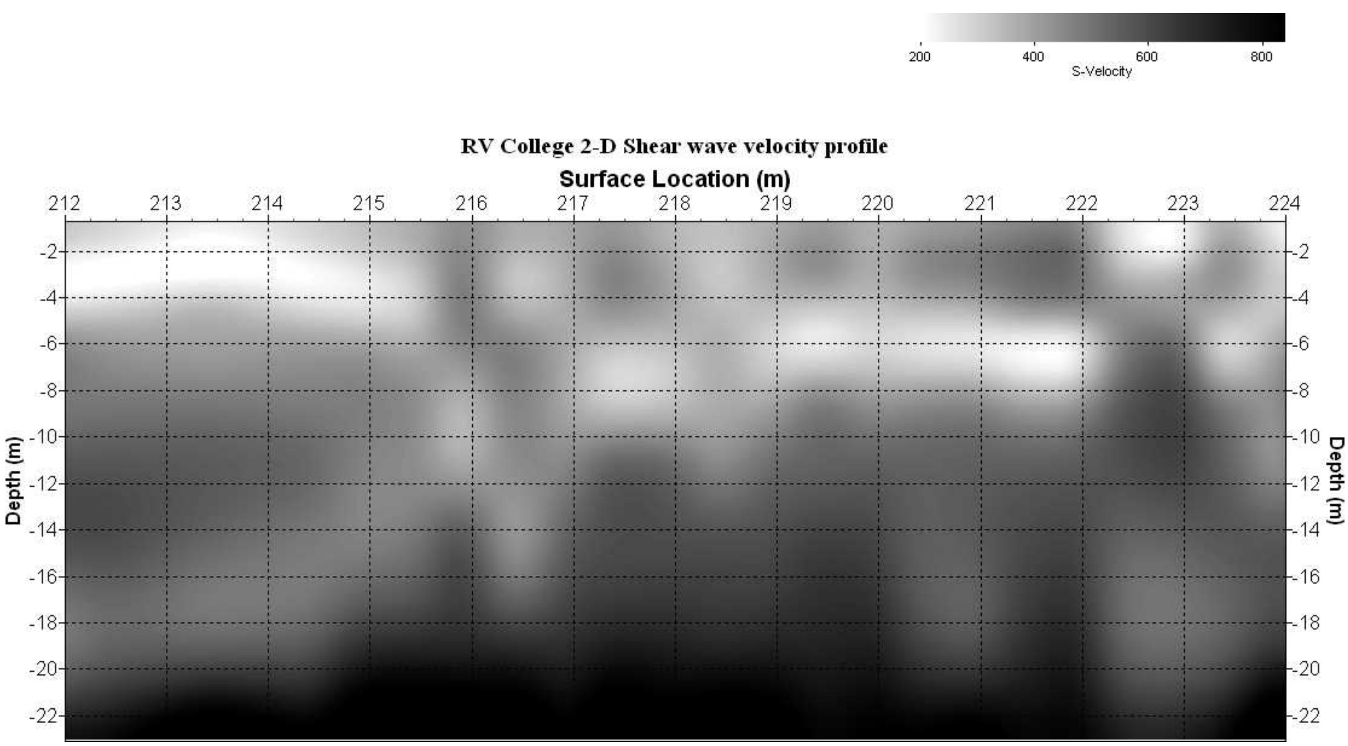


**Figure 7. Ground anomalies observed in the *Vs* profile caused by soil fill.**

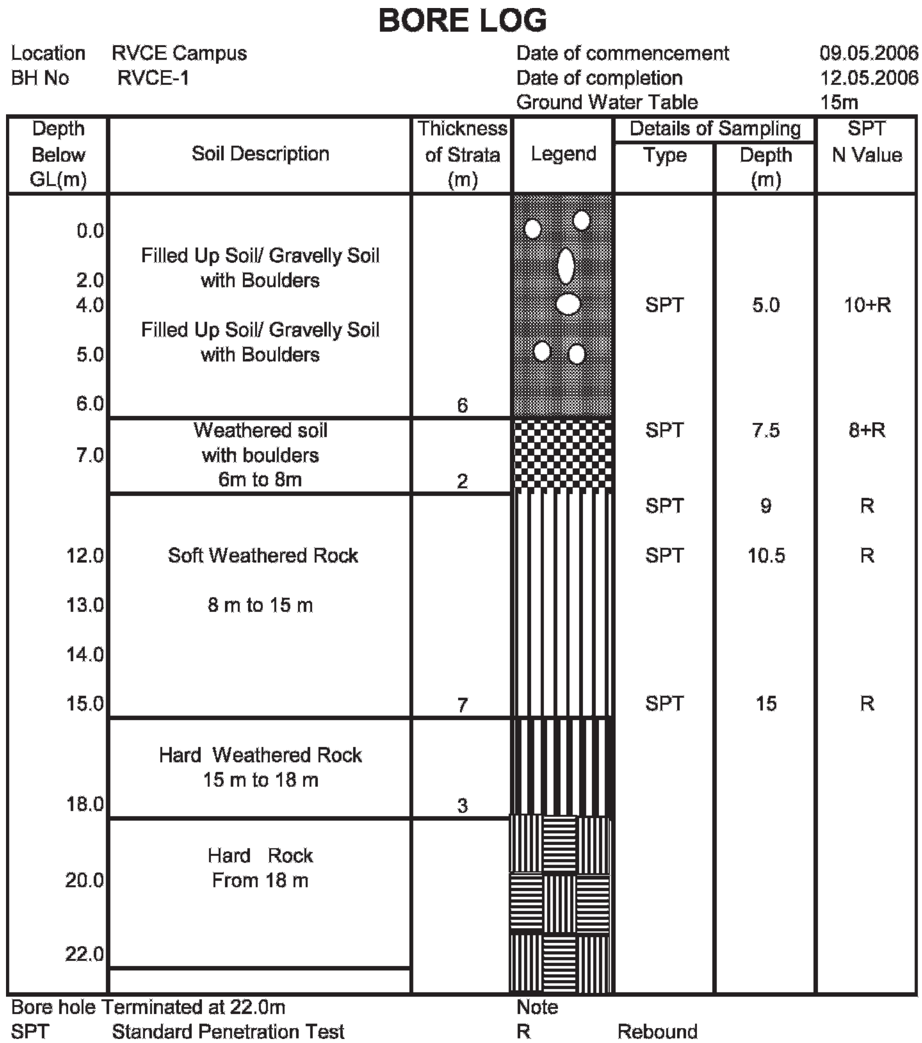


**Figure 8. Borelog corresponding to Fig. 7.**

graphical Information System (GIS) database developed by Sitharam *et al.* (2007) for Bangalore (Table 1). Table 1 shows that the northwestern part has an overburden thickness less than 4 m, whereas the eastern, central, and other areas have an overburden thickness of 4 m to about 40 m (Sitharam *et al.*, 2007). The calculated average shear wave velocities are grouped according to the NEHRP site classes and corresponding

**Table 2. Typical average shear wave velocity calculation.**

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

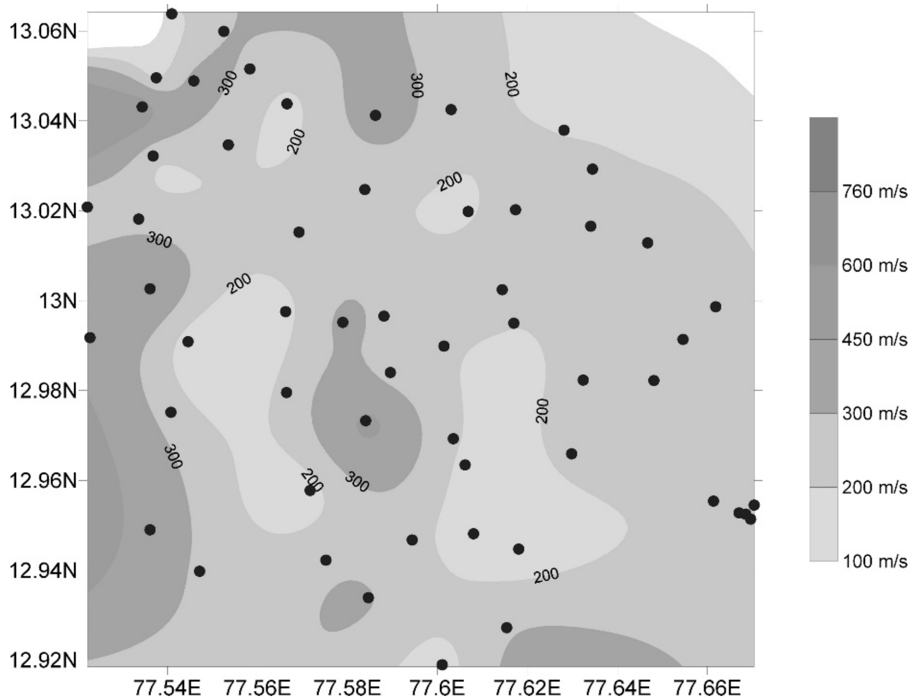


**Figure 9. Average shear wave velocity for 5-m depth with test locations (filled circles).**

maps were generated. The average shear wave velocity calculated for 5-m, 10-m, 15-m, 20-m, 25-m and 30-m depths are mapped and shown in Figs. 9–14, respectively. From Fig. 9, the average velocity to a depth of 5 m ranges from 180 m/s to 360 m/s. A few locations in the southeastern part, and in a smaller portion of northwestern Bangalore, have an average shear wave velocity of less than 180 m/s, which indicates soft soil. The average shear wave velocity for the 10-m depth varies from 180 m/s to 360 m/s (Fig. 10). In the 10-m average

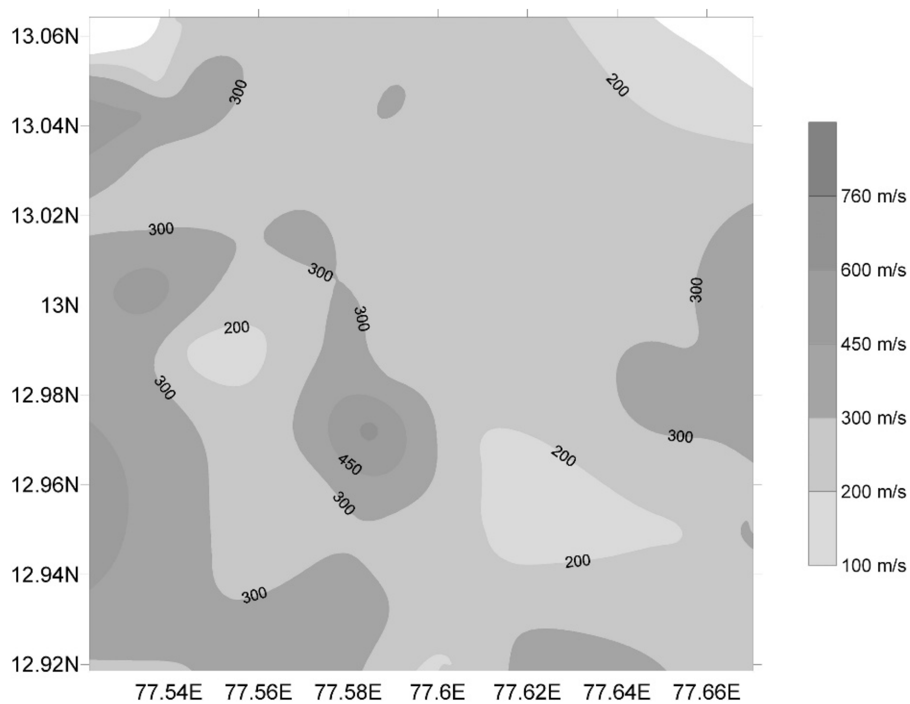


**Figure 10. Average shear wave velocity for 10-m depth.**

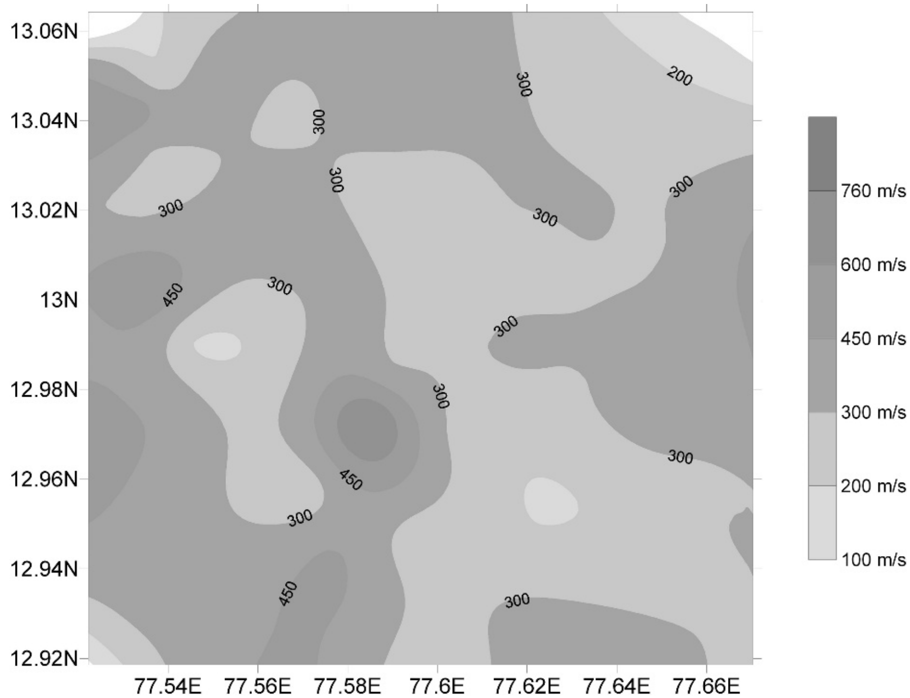


**Figure 11. Average shear wave velocity for 15-m depth.**

map, very dense soil/soft rock with velocity ranging from 360 m/s to 760 m/s is found in the western part of the study area. In this location, the bedrock depth is found within 10 m, as seen in Table 1. The 15- m depth map (Fig. 11) shows a greater coverage of very dense soil/soft rock when compared to Fig. 10 (10-m depth). In this map, the southeastern part has an average velocity of less than 180 m/s, correlating with a larger overburden thickness (Table 1). The average shear wave velocity maps corresponding to depths of 20 m and

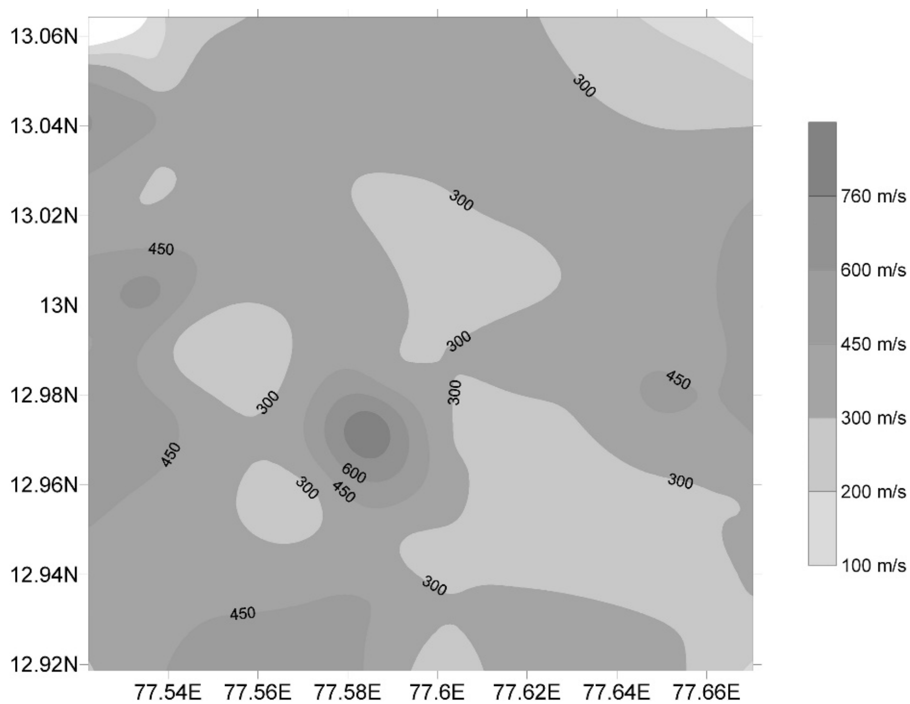


**Figure 12. Average shear wave velocity for 20-m depth.**

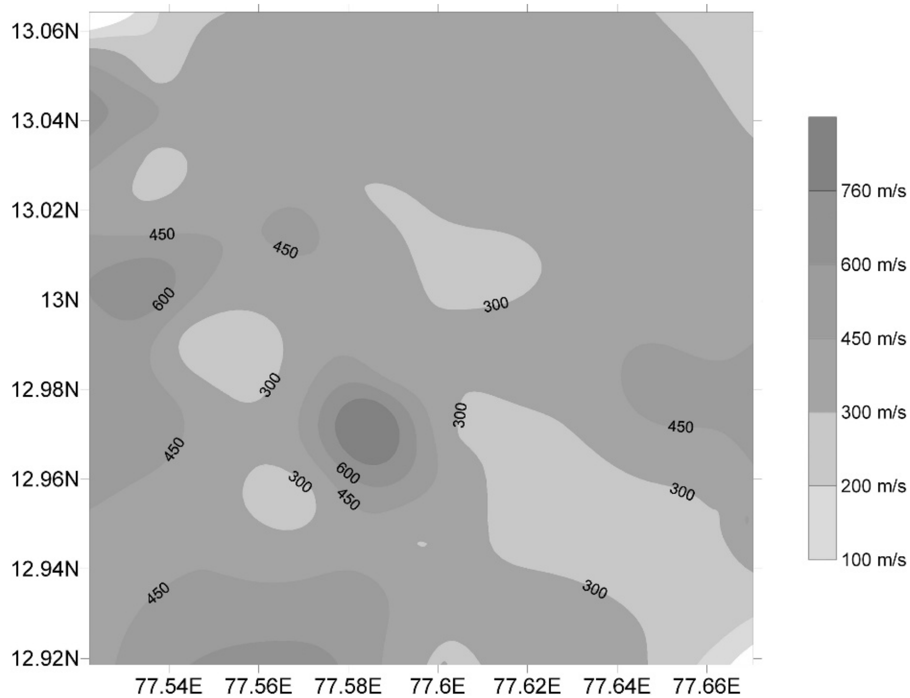


**Figure 13. Average shear wave velocity for 25-m depth.**

25 m (Figs. 12 and 13, respectively) indicate a velocity of 300 m/s and above.

Usually the subsoil classification for seismic local site effect evaluation is carried out by considering the depth of 30-m average shear wave velocity ($V_s^{30}$). Figure 14 shows the map of average shear wave velocity for a depth of 30 m. A prominent high velocity concentration is found at (12.97°N, 77.58°E), caused by the presence of hard rock at shallow depth. Even though the average shear wave velocity is calculated for

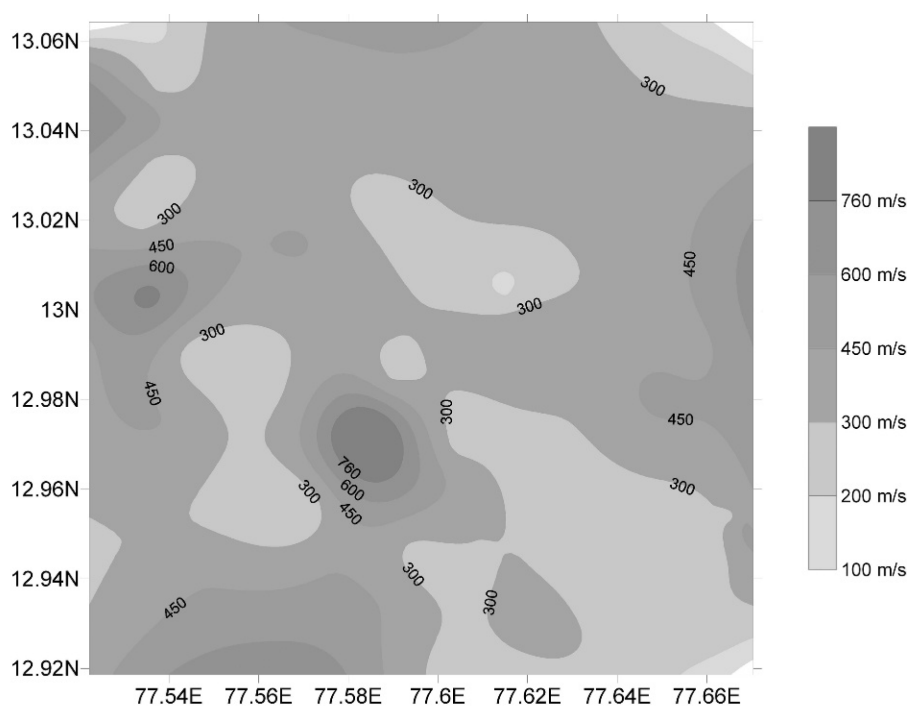


**Figure 14. Average shear wave velocity for 30-m depth.**

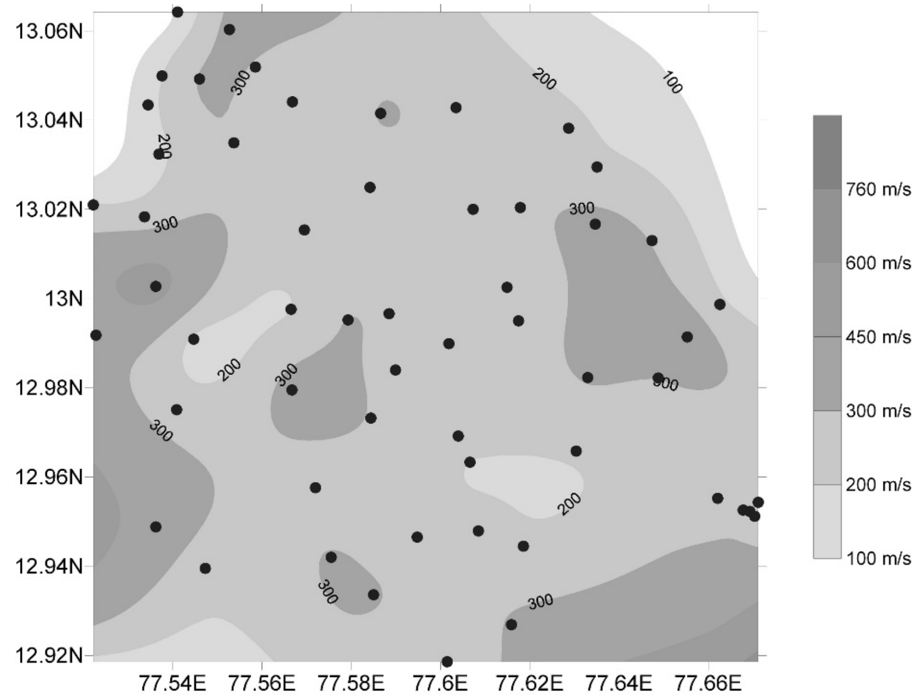


**Figure 15. Average shear wave velocity for overburden soil with test locations (filled circles).**

5-m depth intervals and up to a maximum depth of 30 m, these maps do not show the average shear wave velocity of soil because of the wide variation in the soil overburden. Hence, the average shear wave velocity of soil has been calculated based on the depth of soil obtained from boreholes close to the MASW testing locations. The average shear wave velocity for soil overburden in the study area is shown in Fig. 15. Figure 15 shows that most of the study area has medium to dense soil with a velocity range of 180 m/s to 360 m/s.

## SPT and MASW Data

Among the 58 MASW testing points, 38 MASW locations are close to the SPT borehole locations. These 38 MASW locations, shown in Fig. 16, have been used to generate the relationship between *Vs* and the SPT corrected N values. The SPT is carried out in a borehole by repeated blows of a standard split spoon sampler using a 63.5-kg hammer falling through 750 mm. The boreholes had a diameter of 150 mm and were drilled using rotary hydraulic drilling down to bedrock. The hammer was dropped on the rod head at the top of the borehole, and the rod head was connected to the split spoon by rods. The split spoon was lowered to the bottom of the hole and driven for a depth of 450 mm; the blows are counted normally for each 150 mm of penetration. The penetration resistance (N) is the number of blows required to drive the split spoon for the last 300 mm of penetration. The penetration resistance during the first 150 mm of penetration is ignored. The N values measured in the field using the SPT procedure have been corrected for overburden pressure ($C_N$), hammer energy ($C_E$), borehole diameter ($C_B$), presence or absence of liner ($C_S$), rod length ($C_R$), and fines content ($C_{fines}$) (Seed *et al.*, 1983; Skempton, 1986; Youd *et al.*, 2001; Cetin *et al.*, 2004).

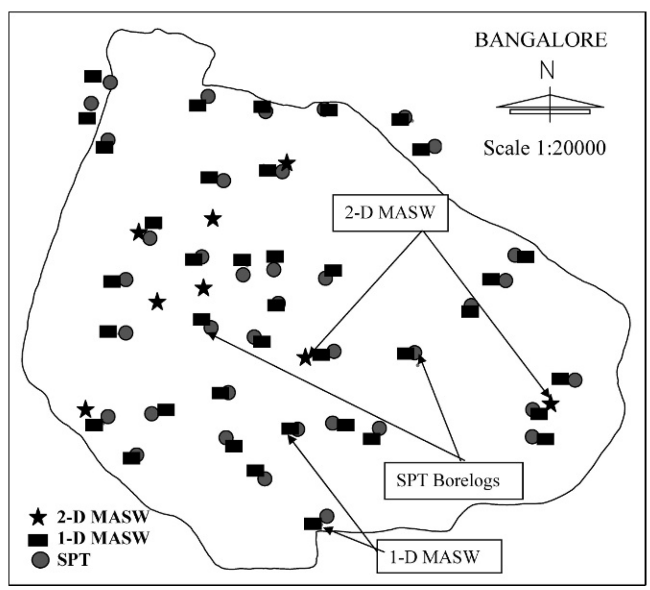


**Figure 16. SPT and MASW locations used for developing the relation between *Vs* and $(N_1)_{60cs}$.**

The SPT corrected N values, *i.e.*, $(N_1)_{60}$, are obtained using the following equation:

$$(N_1)_{60} = N \times (C_N \times C_E \times C_B \times C_S \times C_R). \quad (3)$$

The $(N_1)_{60}$ value is further corrected for fines content based on the revised boundary curves derived by Idriss and Boulanger (2004) for cohesionless soils:

$$(N_1)_{60cs} = (N_1)_{60} + \Delta(N_1)_{60} \quad (4)$$

$$\Delta(N_1)_{60} = \exp\left[1.63 + \frac{9.7}{FC + 0.001} - \left(\frac{15.7}{FC + 0.001}\right)^2\right] \quad (5)$$

where $FC$ = percent fines content (percent dry weight finer than 0.074 mm). A typical N correction calculation table for borehole data is shown in Table 3. In Table 3, columns 4 and 5 show the total stress (T.S.) and effective stress (E.S.) calculated and used to evaluate the overburden pressure ($C_N$) correction factor.

### Correlation Between $(N_1)_{60cs}$ and $V_S$

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

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

where $Vs$ is the shear wave velocity in m/s. Figure 17 shows the actual data along with the fitted equation. Japan Road Association equations (JRA, 1980) relating $Vs$ and $N_{60}$ are:

$$Vs = 100(N_{60})^{1/3} \quad \text{for clayey soil} \quad (7)$$

$$Vs = 80(N_{60})^{1/3} \quad \text{for sandy soil.} \quad (8)$$

A comparison between the JRA equations with the newly developed Eq. (6) is shown in Fig. 18. The coefficients are close to the value for sandy soil. From Fig. 18, it is clear that the fitted equation lies between the JRA equations for sandy and clay equations for a

**Table 3. Typical N correction table for borelog.**

| Borehole 4 | | | | | | Correction factors for | | | | | Water table = 1.4 m/19-11-2005 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Depth m | Field N value | Density kN/m$^3$ | T.S. kN/m$^2$ | E.S. kN/m$^2$ | $C_N$ | Hammer energy | Borehole diameter | Rod length | Sample method | $(N_1)_{60}$ | FC % | $\Delta(N_1)_{60}$ | Corrected N value $(N_1)_{60cs}$ |
| 1.50 | 19 | 20.00 | 30.00 | 30.00 | 1.47 | 0.7 | 1.05 | 0.75 | 1 | 15.36 | 48 | 5.613 | 21 |
| 3.50 | 28 | 20.00 | 70.00 | 50.38 | 1.29 | 0.7 | 1.05 | 0.8 | 1 | 21.26 | 43 | 5.597 | 27 |
| 4.50 | 26 | 20.00 | 90.00 | 60.57 | 1.22 | 0.7 | 1.05 | 0.85 | 1 | 19.79 | 60 | 5.602 | 25 |
| 6.00 | 41 | 20.00 | 120.00 | 75.86 | 1.12 | 0.7 | 1.05 | 0.85 | 1 | 28.77 | 48 | 5.613 | 34 |
| 7.50 | 55 | 20.00 | 150.00 | 91.14 | 1.04 | 0.7 | 1.05 | 0.95 | 1 | 40.02 | 37 | 5.541 | 46 |
| 9.00 | 100 | 20.00 | 180.00 | 106.43 | 0.97 | 0.7 | 1.05 | 0.95 | 1 | 67.84 | 28 | 5.270 | 73 |
| 10.50 | 100 | 20.00 | 210.00 | 121.71 | 0.91 | 0.7 | 1.05 | 1 | 1 | 66.90 | 28 | 5.270 | 72 |
| 12.50 | 100 | 20.00 | 250.00 | 142.09 | 0.84 | 0.7 | 1.05 | 1 | 1 | 61.70 | 28 | 5.270 | 67 |

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

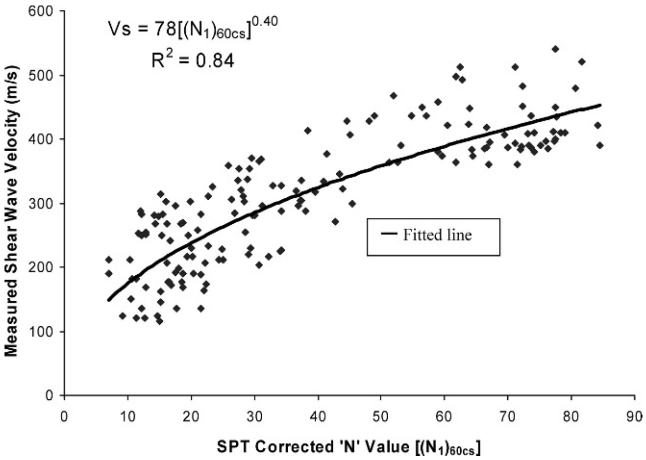


**Figure 17. Shear wave velocity versus corrected SPT N values.**

wide range of $(N_1)_{60cs}$ values. This is because the soil overburden in Bangalore has sand and silt with some percentage of clay content.

## Conclusions

In this MASW study, 1-D surveys at 58 locations and 2-D surveys at 20 locations were carried out covering an area of 220 km$^2$ in Bangalore city. The shear wave velocity profiles, spatial variability of shear wave velocity and ground layer anomalies were presented. The average shear wave velocity of the study area was estimated for depths of 5 m, 10 m, 15 m, 20 m, 25 m and 30 m. Also presented is the average shear wave velocity for the soil depth, which is estimated based on overburden thickness. Site soil classification was carried out by considering the NEHRP and IBC classification. The estimated $V_s^{30}$ for Bangalore soil can be classified as site class D as per NEHRP and IBC classification. Among a total of 58 MASW surveys carried out, 38 locations were very close to the SPT borehole locations and these were used to generate a correlation between *Vs* and SPT corrected N values. A power fit regression equation was developed for 162 pairs of *Vs* and $(N_1)_{60cs}$ with a regression coefficient of 0.84. The empirical relationship obtained in this study is the first in Peninsular India. The shear wave velocity versus SPT corrected N value relation can be effectively used to find the shear modulus for ground shaking response studies at similar soil sites in Peninsular India.

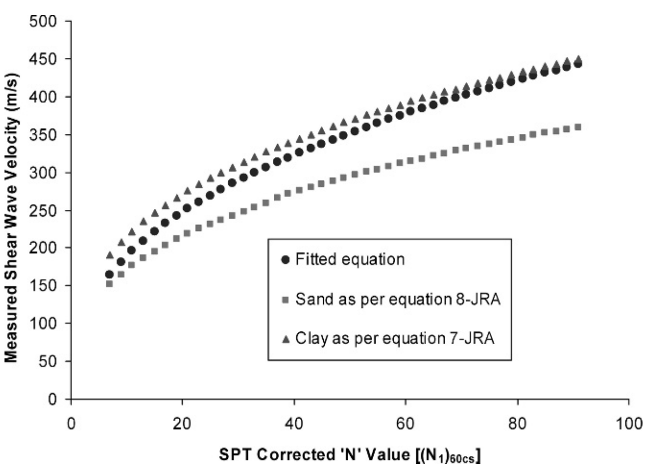


**Figure 18. Comparison of shear wave velocity versus corrected SPT N equations.**


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## References


Al-Hunaidi, M.O., 1992, Difficulties with phase spectrum unwrapping in spectral analysis of surface waves nondestructive testing of pavements: Can. Geotech. J., **29**, 506–511.

BIS, 2002, IS 1893–2002, Indian standard criteria for earthquake resistant design of structures, part 1 - general provisions and buildings: Bureau of Indian Standards, New Delhi.

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

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

Ganesha Raj, K., and Nijagunappa, R., 2004, Major lineaments of Karnataka State and their relation to seismicity: Remote sensing based analysis: J. Geol. Soc. India, **63**, 430–439.

Ganji, V., Gukunski, N., and Maher, A., 1997, Detection of underground obstacles by SASW method—Numerical aspects: J. Geotech. Geoenviron. Eng., **123**(3) ASCE, 212–219.

Idriss, I.M., and Boulanger, R.W., 2004, Semi empirical procedures for evaluating liquefaction potential during earthquakes: *in* Proceedings: 11th International Conference on Soil Dynamics and Earthquake Engineering, and 3rd International Conference on Earthquake Geotechnical Engineering, Doolin, D. et al. (eds.), Stallion Press, **1**, 32–56.

International Building Code, 2000, International code council: Inc. 5th Edition, Falls Church, VA.

Ivanov, J., Park, C.B., Miller, R.D., and Xia, J., 2005, Analyzing and filtering surface-wave energy by muting shot gathers: Journal of Environmental and Engineering Geophysics, **10**(3) 307–321.

Ivanov, J., Miller, R.D., Lacombe, P.J., Johnson, C.D., and Lane, J.W. Jr., 2006, Delineating a shallow fault zone and dipping bedrock strata using Multichannel Analysis of Surface Waves (MASW) seismic method with a land streamer: Geophysics, **71**, A39–A42.

Japan Road Association, 1980, Specification for highway bridges: Part V, Earthquake Resistant Design.

Kanli, A.I., Tildy, P., Pronay, Z., Pinar, A., and Hemann, L., 2006, $Vs^{30}$ mapping and soil classification for seismic site effect evaluation in dinar region, SW Turkey: Geophysics J. Int, **165**, 223–235.

Martin, G.R. (ed.), 1994, *in* Proceedings of the NCEER/SEAOC/BSSC: Workshop on Site Response during Earthquakes and Seismic Code Provisions, University of California at Los Angeles.

Miller, R.D., Xia, J., Park, C.B., and Ivanov, J., 1999, Multichannel analysis of surface waves to map bedrock: The Leading Edge, **18**(12) 1392–1396.

Nazarian, S., Stokoe II, K.H., and Hudson, W.R., 1983, Use of spectral analysis of surface waves method for determination of moduli and thicknesses of pavement systems: Transp. Res. Rec., **930**, 38–45.

Park, C.B., Miller, R.D., and Xia, J., 1999, Multi-channel analysis of surface waves: Geophysics, **64**(3) 800–808.

Park, C.B., Miller, R.D., Xia, J., and Ivanov, J., 2005a, Multichannel seismic surface-wave methods for geotechnical applications: http://www.kgs.ku.edu/Geophysics2/Pubs/Pubs PAR-00-03.pdf.

Park, C.B., Miller, R.D., Xia, J., Ivanov, J., Sonnichsen, G.V., Hunter, J.A., Good, R.L., Burns, R.A., and Christian, H., 2005b, Underwater MASW to evaluate stiffness of water-bottom sediments: Leading Edge, **24**, 724–728.

Ryden, N., Park, C.B., Ulriksen, P., and Miller, R.D., 2004, Multimodal approach to seismic pavement testing: Journal of Geotechnical and Geoenvironmental Engineering, **130**, 636–645.

Seed, H.B., Idriss, I.M., and Arango, I., 1983, Evaluation of liquefaction potential using field performance data: Journal of Geotechnical Engineering, **109**(3) 458–482.

Sitharam, T.G., Anbazhagan, P., and Ganesha Raj, K., 2006, Use of remote sensing and seismotectonic parameters for seismic hazard analysis of Bangalore: Nat. Hazards Earth Syst. Sci., **6**, 927–939.

Sitharam, T.G., and Anbazhagan, P., 2007, Seismic Hazard Analysis for Bangalore Region: Journal of Natural Hazards, **40**, 261–278.

Sitharam, T.G., Anbazhagan, P., and Mahesh, G.U., 2007, 3-D subsurface modelling and preliminary liquefaction hazard Mapping of Bangalore city using SPT data and GIS: Indian Geotechnical Journal, **37**(3) 23–57.

Skempton, A.W., 1986, Standard Penetration Test Procedures: Geotechnique, **36**(3) 425–447.

Stokoe II, K.H., Wright, G.W., James, A.B., and Jose, M.R., 1994, Characterization of geotechnical sites by SASW method: *in* Geophysical characterization of sites: ISSFME Technical Committee #10, Woods, R.D. (ed.), Oxford Publishers, New Delhi.

Tokimatsu, K., 1995, Geotechnical site characterization using surface waves: *in* Proceedings: 1st Int. Conf. on Earth. Geotechn. Eng., IS-Tokyo, 36.

Xia, J., Miller, R.D., and Park, C.B., 1999, Estimation of near-surface shear-wave velocity by inversion of Rayleigh wave: Geophysics, **64**(3) 691–700.

Xia, J., Miller, R.D., Park, C.B., Hunter, J.A., and Harris, J.B., 2000, Comparing shear-wave velocity profiles from MASW with borehole measurements in unconsolidated sediments, Fraser River Delta, B.C., Canada: Journal of Environmental and Engineering Geophysics, **5**(3) 1–13.

Xu, Y., Xia, J., and Miller, R.D., 2006, Quantitative estimation of minimum offset for multichannel surface-wave survey with actively exciting source: Journal of Applied Geophysics, **59**(2) 117–125.

Youd, T.L., Idriss, I.M., Andrus, R.D., Arango, I., Castro, G., Christian, J.T., Dobry, R., Liam Finn, W.D., Harder Jr, L.H., Hynes, M.E., Ishihara, K., Koester, J.P., Liao, S.S.C., Marcuson, W.F., Marting, G.R., Mitchell, J.K., Moriwaki, Y., Power, M.S., Robertson, P.K., Seed, R.B., and Stokoe, K.H., 2001, Liquefaction resistance of soils: Summary from the 1996 NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils: Journal of Geotechnical and Geoenvironmental Engineering, **127**(10) 817–833.

Zhang, S.X., Chan, L.S., and Xia, J., 2004, The selection of field acquisition parameters for dispersion images from multichannel surface wave data: Pure and Applied Geophysics, **161**, 185–201.