Site characterization studies of Bangalore using a geophysical method

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ABSTRACT: A number of geophysical methods have been proposed for near-surface site characterization and measurement of shear wave velocity by using a great variety of testing configurations, processing techniques, and inversion algorithms. In particular, two widely-used techniques are SASW (Spectral Analysis of Surface Waves) and MASW (Multichannel Analysis of Surface Waves). MASW is increasingly being applied to earthquake geotechnical engineering for the local site characterization, microzonation and site response studies. A MASW is a geophysical method, which generates a shear-wave velocity ($V_s$) profile (i.e., $V_s$ versus depth) by analyzing Raleigh-type surface waves on a multichannel record. MASW system consisting of 24 channels Geode seismograph with 24 geophones of 4.5 Hz frequency have been used in this investigation. For the site characterization program, the MASW field experiments consisting of 58 one-dimensional shear wave velocity tests and 20 two-dimensional shear wave tests have been carried out. The survey points have been selected in such a way that the results supposedly represent the whole metropolitan Bangalore having an area of 220 km$^2$. The average shear wave velocity of Bangalore soils have been evaluated for depths of 5 m, 10 m, 15 m, 20 m, 25 m and 30 m. The subsoil site classification has been made for seismic local site effect evaluation based on average shear wave velocity of 30 m depth ($V_s^{30}$) of sites using National Earthquake Hazards Reduction Program (NEHRP) and International Building Code (IBC) classification. Soil average shear wave velocity estimated based on overburden thickness from the borehole information is also presented. Mapping clearly indicates that the depth of soil obtained from MASW is closely matching with the soil layers in bore logs. Among total 55 locations of MASW survey carried out, 34 locations were very close to the SPT borehole locations and these are used to generate correlation between $V_s$ and corrected “N” values. The SPT field “N” values are corrected by applying the NEHRP recommended corrections.

1 INTRODUCTION

To ascertain the manifestation of earthquake shaking on the ground surface, velocity parameters at a shallow level would be of consequence. Shear wave velocity ($V_s$) is an essential parameter for evaluating the dynamic properties of soil in the shallow subsurface. A number of geophysical methods have been proposed for near-surface characterization and measurement of shear wave velocity by using a great variety of testing configurations, processing techniques, and inversion algorithms. The most widely-used techniques are SASW (Spectral Analysis of Surface Waves) and MASW (Multichannel Analysis of Surface Waves). SASW method uses the spectral analysis of a surface wave generated by an impulsive source and recorded by a pair of receivers. Evaluating and distinguishing signal from noise with only a pair of receivers by this method is difficult. Thus to improve inherent difficulties, a new technique incorporating multichannel analysis of surface waves using active sources, named as MASW, was developed (Park et al., 1999; Xia et al., 1999; Xu et al., 2006). The MASW has been found to be a more efficient method for unraveling the shallow subsurface properties (Park et al., 1999; Xia et al., 1999; Zhang et al., 2004). MASW is increasingly being applied to earthquake geotechnical engineering for microzonation and site response studies. In particular, MASW is used in geotechnical engineering for the measurement of shear wave velocity and estimation of dynamic properties, identification of subsurface material boundaries and spatial variations of shear wave velocity. MASW is non-intrusive and less time consuming geophysical method. It is a seismic method that can be used for geotechnical characterization of near surface materials (Park et al., 1999; Xia et al., 1999; Miller et al., 1999; Park et al., 2005a; Kanli et al., 2006). MASW identifies each type of seismic waves on a multichannel record based on the normal pattern recognition technique that has been used in oil exploration for several decades. The identification leads to an optimum field configuration that assures the highest signal-to-noise ratio (S/N). Effectiveness in signal analysis is then further enhanced by diversity
and flexibility in the data processing phase (Ivanov et al., 2005). MASW is also used to generate 2-D shear wave velocity profiles. In this paper the average shear wave velocity for 5 m, 10 m, 15 m, 20 m, 25 m and 30 m ($V_s^{30}$) has been evaluated and mapped for Bangalore covering an area of 220 km$^2$ in Bangalore Municipal corporation limits. The study has been carried out for assigning soil classification for seismic local site effect evaluation.

2 STUDY AREA AND MASW

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 situated on a latitude of 12° 58' North and longitude of 77° 37' East. It is the principal administrative, industrial, commercial, educational and cultural capital of Karnataka state, in the South-Western part of India (Figure 1). There were over 150 lakes, though most of them are dried up due to erosion and encroachments leaving only 64 at present in an area of 220 sq km. These tanks were once distributed throughout the city for better water supply facilities and are presently in a dried up condition, the residual silt and silty sand forming thick deposits over which buildings/structures have been erected. These soil conditions may be susceptible for site amplification during excitation of seismic waves. 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 against average earthquakes (Sitharam et al., 2006).

The recent studies by Ganesha Raj and Nijagunappa (2004), Sitharam et al. (2006) and Sthiram 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 subsoil classification for the Bangalore region is important to evaluate seismic local site effects for an earthquake. From the 3-D subsurface model of geotechnical bore log data developed by Sthiram et al., (2007), authors have identified that the overburden thickness of study area varies from 1 m to about 40 m.

MASW is a geophysical method, which generates a shear wave velocity ($V_s$) profile (i.e., $V_s$ versus depth) by analyzing Raleigh-type surface waves on a multi-channel record. A MASW system consisting of a 24 channels Geode seismograph with 24 geophones of 4.5 Hz frequency were used in this investigation. The seismic waves are created by the impulsive source of 15 pound (sledge hammer) with 300 mm $\times$ 300 mm size hammer plate using ten shots. The recorded Rayleigh wave is further analyzed using SurfSeis software. SurfSeis is designed to generate $V_s$ data (either in 1-D or 2-D format) using a simple three-step procedure: i) preparation of a multichannel record (some times called a shot gather or a field file), ii) dispersion-curve analysis, and iii) inversion. MASW has been effectively used with highest signal-to-noise ratio (S/N) of surface waves. 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 ($V_s$) profiles (Xia et al., 2000), seismic evaluation of pavements (Ryden et al., 2004), and seismic characterization of sea-bottom sediments (Park et al., 2005b).

The test locations are selected in such a way that these supposedly represent the entire city subsurface information (Figure 1). In total 58 one-dimensional (1-D) surveys and 20 two-dimensional (2-D) surveys have been carried out. In about 38 locations MASW survey point are very close to the SPT borehole locations. Most of the survey locations are selected in flat ground and also in important places like parks, hospitals, schools and temple yards etc. The optimum field parameters such as source to first and last receiver, receiver spacing and spread length of survey lines are selected in such a way that required depth of information can be obtained. All tests have been carried out with a geophone interval of 1 m, source has been kept on both sides of the spread and distance from source to the first and last receiver were also varied from 5 m, 10 m and 15 m to avoid the effects of near-field and far-field. These source distances were helped to record good signals in very soft, soft and hard soils. The exploration services section at the Kansas Geological Survey (KGS) has suggested an offset distance...
for very soft, soft and hard soil as 1 m to 5 m, 5 m to 10 m and 10 m to 15 m respectively (Xu et al., 2006).

3 DATA ANALYSIS AND RESULTS

The generation of a dispersion curve is a critical step in 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 record. The lowest analyzable frequency in this dispersion curve is around 4 Hz and a highest frequency of 75 Hz has been considered. Each dispersion curve obtained for corresponding locations has a very high signal to noise ratio of about 80 and above. A Vs profile has been calculated using an iterative inversion process that requires the dispersion curve developed earlier as input. A least-squares approach allows automation of the process (Xia et al., 1999) which is inbuilt in SurfSeis. Typical 1-D Vs profile is shown in Figure 2. Borelog close to Vs profile shown in Figure 3, the both results are matches well. Minimum shear wave velocity found in the region is about 100 m/s and maximum is about 1200 m/s. Generally the trend in the velocity profiles is increasing with depth, accordingly to the soil deposits followed by 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).

4 AVERAGE SHEAR WAVE VELOCITY

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

$$V_H = \frac{\sum d_i / \sum (d_i/v_i)}{H}$$

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

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

$$V_s^{30} = \frac{30}{\sum_{i=1}^{N} (\%)}$$

where $d_i$ and $v_i$ denote the thickness (in meters) and shear-wave velocity in m/s (at a shear strain level of $10^{-5}$ or less) of the ith formation or layer respectively, in a total of N layers, existing in the top 30 m. $V_s^{30}$ is

![Figure 2. Typical 1-D shear wave velocity profile.](image)

![Figure 3. Borelog close to Vs profile in figure 2.](image)
Table 1. Typical average shear wave velocity calculation.

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>( V_s ) (m/s)</th>
<th>Soil-72 m</th>
<th>5 m</th>
<th>10 m</th>
<th>15 m</th>
<th>20 m</th>
<th>25 m</th>
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</table>

accepted for site classification as per NEHRP classification and also UBC classification (Uniform Building Code in 1997) (Dobry et al., 2000; Kanli et al., 2006). In order to figure out the average shear wave velocity distribution in Bangalore, the average velocity has been calculated using the equation (1) for each location. A simple spreadsheet has been generated to carry out the calculation, as shown in Table 1. The \( V_s \) average has been calculated for every 5 m depth interval up to a depth of 30 m and also average \( V_s \) for the soil overburden has been calculated. Usually, for amplification and site response study the 30 m average \( V_s \) is considered. However, if the rock is found within a depth of about 30 m, nearer surface shear wave velocity of soil has to be considered. Otherwise, \( V_s^{30} \) obtained will be higher due to 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 \( V_s \) has also been calculated based on the soil thickness corresponding to the location, which is also shown in column 3 of Table 1.

5 SHEAR WAVE VELOCITY DISTRIBUTION IN BANGALORE

The soil overburden thickness and depth of rock level information are obtained from the Geotechnical Geographical information system (GIS) data base developed by Sitharam et al. (2007) for Bangalore. The north western part has lesser overburden thickness. However, eastern part, central and other areas have the overburden thickness of 4 m to about 40 m. The calculated average shear wave velocities are grouped according to the NEHRP site classes and the related maps has been generated. For the mapping of shear wave velocity the Surfer plotting software has been used. For the interpolation of data gridding method of minimum curvature has been used. 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 Figures 4, 5, 6, 7, 8 and 9 respectively. From Figure 4, the average velocity up to a depth of 5 m covering most of the study area has a velocity range of 180 m/s to 360 m/s. Few locations in south eastern part and in smaller portion of northwestern part of Bangalore have the velocity less than 180 m/s indicating soft soil. The depth may also extend beyond 5 m, matching with the rock level shown in Table 1. The average shear wave velocity for 10 m depth varies from 180 m/s to 360 m/s (Figure 5). In the 10 m average map, very dense soil/soft rock velocity range of 360 m/s to 760 m/s is found in western part of the study area. In this location, the rock depth is found within 10 m as seen in Table 1. Figure 6 show that the area covered has a very dense soil/soft rock, which is increased when compared to Figure 6. In this map south eastern part having an average velocity less than
Figure 6. Average shear wave velocity for 15 m depth.

Figure 7. Average shear wave velocity for 20 m depth.

Figure 8. Average shear wave velocity for 25 m depth.

Figure 9. Average shear wave velocity for 30 m depth.

Figure 10. Average shear wave velocity for only soil overburden.

180 m/s, matching with the larger overburden thickness. Similar increased area of higher velocity is found in average depths of 20 m and 25 m shear wave velocity profiles (Figures 7 and 8). Figure 9 shows the map of average shear wave velocity for a depth of 30 m. Even though the average shear wave velocity is calculated for every 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/rock level. Hence, the average shear wave velocity of soil has been calculated based on the overburden thickness obtained from bore holes close to the MASW testing locations. The average shear wave velocity for soil overburden in the study area is shown in Figure 10. Figure 10 shows that most of the study area has medium to dense soil with a velocity range of 180 m/s to 360 m/s. Based on the 30 m average shear wave velocity and average soil overburden velocity maps, major part of Bangalore BMP (Bangalore Mahanagara Palike) has the shear
wave velocity of 180 m/s to 360 m/s. Hence BMP area can be classified as “Site class D” as per NEHRP and IBC recommendation.

6 CONCLUSIONS

In this study MASW one-dimensional survey at 58 locations and two-dimensional surveys at 20 locations have been carried out in an area of 220 km² in Bangalore city. The shear wave velocity profiles ($V_s$ versus depth), spatial variability of shear wave velocity ($V_s$ versus depth and length) and ground layer anomalies have been presented. The average shear wave velocity of study area has been estimated for 5 m, 10 m, 15 m, 20 m, 25 m and 30 m depth and presented in this paper. Also average shear wave velocity for the soil depth, which is estimated based on overburden thickness, is presented. Site soil classification has been carried out by considering the NEHRP and IBC classification system. Based on the estimated $V_{30}$ BMP area can be classified as “site class D” as per NEHRP and IBC classification chart.

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