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SHEAR WAVE VELOCITY MAPPING OF DHAKA CITY FOR SEISMIC HAZARD ASSESSMENT

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ABSTRACT: Average shear wave velocities of the subsurface geological materials of Dhaka City up to a depth of 30 m (AVS30) have been estimated using in-situ site investigation techniques such as, Downhole Seismic, Multichannel Analysis of Surface Wave (MASW), Small Scale Microtremor Measurement (SSMM) and Standard Penetration Test (SPT) blow counts (N-values). Then shear wave velocity map of the city is prepared using AVS30 of different locations. The AVS30 of the subsurface geological materials of the city varies from 127 m/sec to 295 m/sec. The central part, from north to south and the middle western part of the city exhibit high shear wave velocities from 200 m/sec to 295 m/sec whereas the eastern and western parts of the city show low shear wave velocities from 127 m/sec to 240 m/sec. The geological materials of the city are classified as site classes D (stiff soils) and E (soft soils) based on AVS30 according to NEHRP (National Earthquake Hazards Reduction Program, USA). The AVS30 map is generally used to determine the amplification factors for site-specific seismic hazard analysis.

1. Introduction

Dhaka, the capital city of Bangladesh, is one of the highest risk cities in the world for earthquake vulnerability. The city is located close to the seismically active plate boundary between the Eurasian Plate and the Indian Plate. Most of the old buildings and a large number of new buildings in the city are non-engineered. A recent study predicted that in Dhaka City about 270,604 buildings (83% of the total buildings) will be moderately damaged and about 238,164 buildings (73% of the total buildings) will be damaged beyond repair for a worst case scenario earthquake (CDMP, 2009).

Dhaka City is also one of the world's most densely populated and fast growing cities having a population of more than 14 million. About 10% of Bangladesh's population, that contributes 36% of country's GDP lives in Dhaka metropolitan area (Muzzini and Aparicio, 2013). The destructive and deadly hazard of an earthquake may create a real and serious threat to life, property damage, economic growth and development of a country. In the past, several large earthquakes occurred in Bangladesh and Northeastern India (Ambraseys and Douglas, 2004).Recent research indicates that damaging earthquakes may occur in Bangladesh and Northeast India (Bilham and England, 2001; Ambraseys and Bilham, 2003; Bilham and Wallace, 2005). If an earthquake of large magnitude occurs close to a densely populated city of a developing country, millions of causalities may happen (Bilham, 2009). Earthquakes also cause lots of destruction of buildings, bridges, industrial and port facilities, etc. Therefore, a proper understanding on the distribution and level seismic hazard is necessary for Dhaka City.

Seismic site characterization is one of the important components of earthquake hazard assessment. The dynamic properties of the subsurface soils can be expressed in terms of shear wave velocity that is an essential parameter for seismic site characterization (Borcherdt, 1994; Martin and Dobry, 1994; Anderson et al., 1996; UBC, 1997; Park and Elrick, 1998; BSSC, 1998). Borcherdt (1994), Dobry et al. (2000) and others suggested that structures should be designed based on site dependent amplification factors that are estimated using average shear wave velocity of the near surface materials up to a depth of 30 m (AVS30). Therefore, AVS30 is incorporated in the building codes of many countries for site class characterization to calculate the seismic design parameters of structures. However, it was not included in the Bangladesh National Building Codes (BNBC, 1993). The BNBC is now updating to incorporate AVS30 for site class characterization.

The AVS30 estimation methods have not been developed yet in Bangladesh. There is very little literature on AVS30 estimation and mapping in Bangladesh (CDMP, 2009). In the current paper, shear wave velocity map of Dhaka City is prepared using average shear wave velocity of the near surface materials up to a depth of 30 m (AVS30).

2. Geology and Seismotectonics

A geological map is an important component to estimate shear wave velocity of an area. The locations of the shear wave velocity estimation were selected based on the surface geological units of Dhaka City (Fig. 1). The central part of the city from north to south is covered by the Pleistocene reddish brown, stiff to very stiff clayey silt and medium dense silty fine sand up to the depth of about 9 m to more than 30 m from ground surface. These layers are underlain by yellowish brown, dense to very dense sand layers of the Plio-Pleistocene. The eastern and western parts of the city are covered by the Holocene floodplains consisting of sand, silt and clay (Rahman et al., 2015). The elevations of the city vary from 2 m to 14 m above main sea level (MSL) with an average of 6.5 m.

The northward collision of the Indian Plate with the Eurasian Plate has created the Himalayan Ranges between the Indian Plate and Eurasian Plate and the Bengal Basin in the eastern part of the Indian Plate (Curray et al., 1982). The Bengal Basin covers the northeastern part of the Indian Plate, which includes Bangladesh and parts of West Bengal, Tripura and Assam of Indian states. The Bengal Basin is one of the largest sedimentary basins in the world, which has a maximum thickness of sedimentary deposits of more than 22 km (Alam et al., 2003). As the plate boundaries and active faults are considered the main sources of earthquake, the major part of the Bengal Basin is seismically active (Morino et al., 2014).

3. Shear Wave Velocity Estimation Methods

In-situ site investigation techniques have been used to estimate the average shear wave velocity of the geological materials of Dhaka City up to a depth of 30 m (AVS30). The techniques include Downhole Seismic (DS), Multichannel Analysis of Surface Wave (MASW) using active source, Small Scale Microtremor Measurement (SSMM) using passive source and Standard Penetration Test (SPT) blow counts (N-values).

3.1. Downhole Seismic (DS) Method

Downhole Seismic (DS) has been used for deep investigation for many years, such as, oil and gas exploration. It has been used for the last several decades to estimate shear wave velocity (Vs) of the shallow subsurface for seismic site characterization. The Vs estimation using a direct method, such as Downhole Seismic, is more reliable and accurate than surface wave method (Boore and Brown, 1998).

Downhole Seismic investigation has been carried out at 7 sites in Dhaka City. The Crosshole Seismic and Downhole Seismic system of Olson Instruments was used for the investigation. One borehole casing with PVC pipe is required to be used for the geophone receiver. Polarized seismic waves were generated by hitting a wooden plank horizontally on the right and left sides and vertically on the top using a sledgehammer. A pair of three-component geophones that were spaced 1.5 m apart was lowered within the borehole to sense the seismic wave energy. Three different tests were performed at each depth for the 3 different wave polarizations. The tests were performed at each 1 m interval starting from the deepest depth to 1 m depth from the ground surface. Then shear wave velocity versus depth profile has been generated using shear wave velocity at each 1 m interval (Fig. 2).

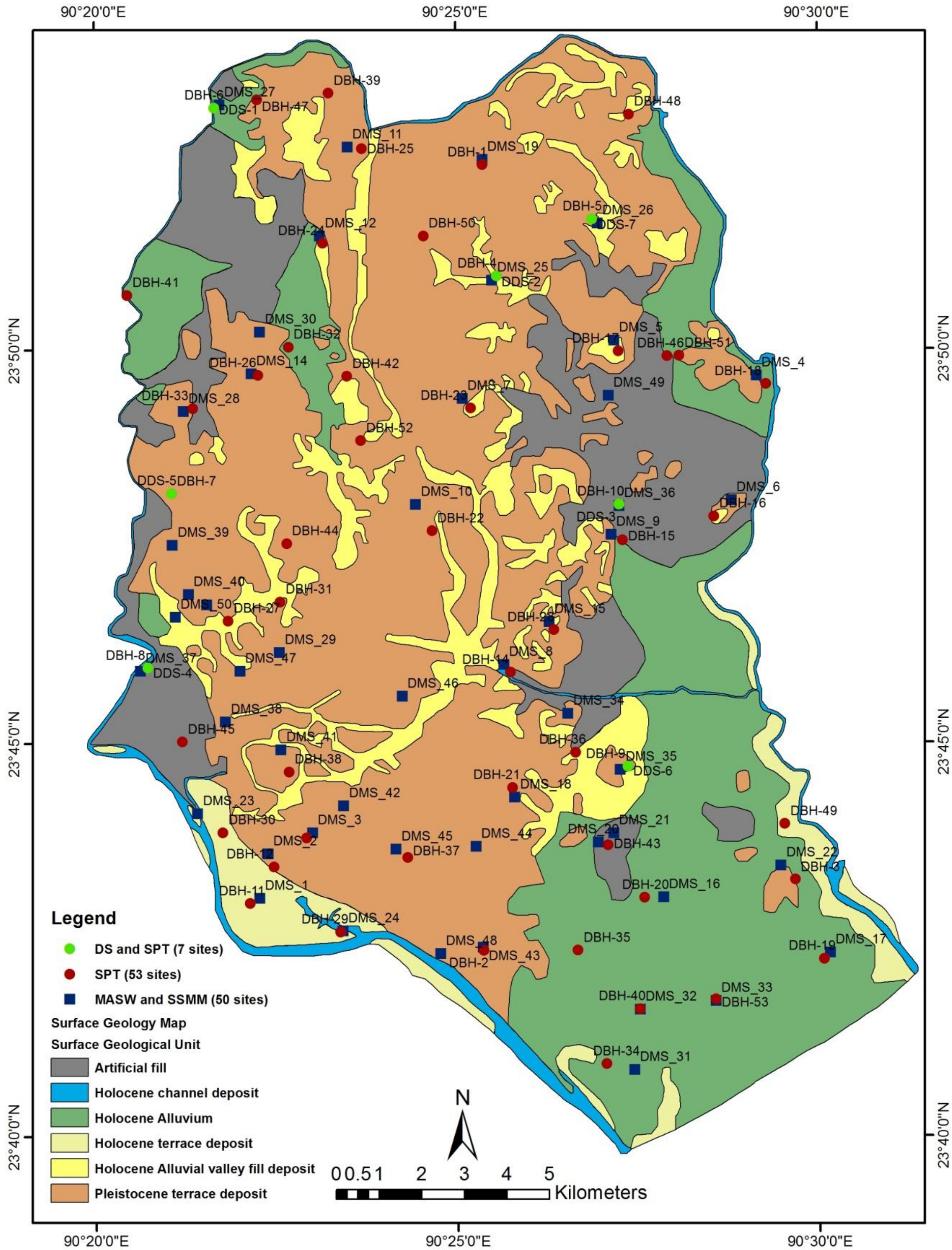

Fig. 1 - Surface geological map of Dhaka City (Rahman et al., 2015) showing locations of shear wave velocity measurement

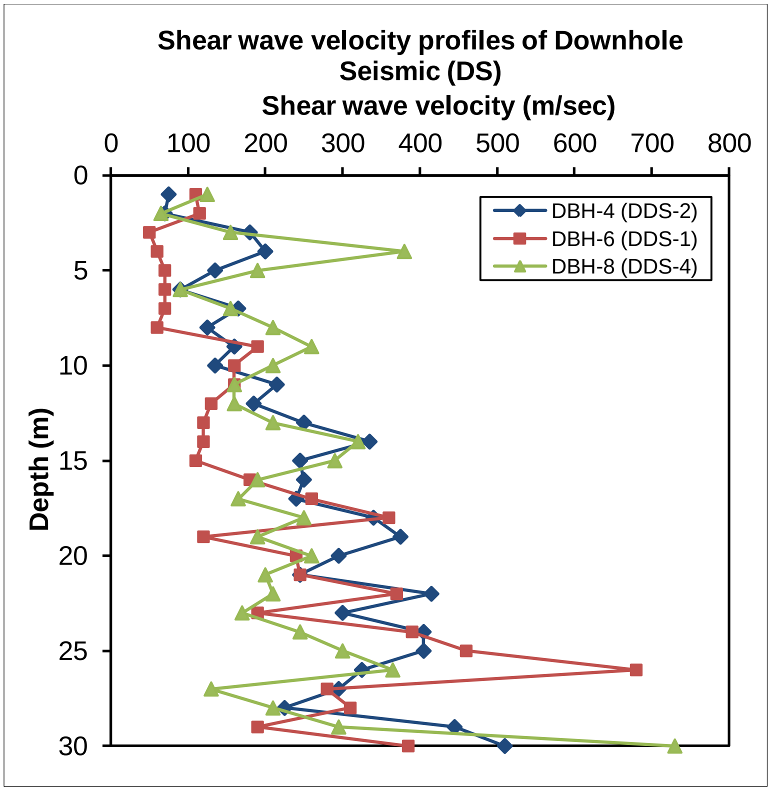

Fig. 2 - Shear wave velocity (V_s) profiles of Downhole Seismic (DS) at boreholes DBH-4, DBH-6 and DBH-8

3.2. Multichannel Analysis of Surface Wave (MASW) Method

Multichannel Analysis of Surface Wave (MASW) is being increasingly used to estimate the near surface shear wave velocity (Vs) for earthquake engineering site characterization. The seismic site investigation using MASW survey is a robust, non-invasive, user friendly and low cost in-situ method (Tian et al., 2003; Xia, 2014). The Vs of the near surface materials using MASW method has been estimated from the dispersion of surface waves (Park et al., 1999; Xia et al., 1999; Tian et al., 2003; Xu et al., 2006; Xia, 2014).

The MASW survey using active source was carried out at 50 sites in Dhaka City to estimate Vs structures for shallower depth. In this study, 12 channel geophones were placed along a 22 m long line with geophones spaced 2 m apart. The natural frequency of the geophones was 10 Hz. An acrylic board was placed at half interval (1m) between two adjacent geophones. Impact energy was generated by hitting on an acrylic board using a sledgehammer to create seismic waves. Seismic waves of different frequencies were generated due to impact on the acrylic board by a sledgehammer. When the surface waves, such as Rayleigh wave, propagate from ground surface to deeper layers of the earth, the phase velocity increases with decreasing frequencies. As the phase velocity changes with depth, the Rayleigh wave is dispersive (Xia et al., 1999). The investigation depth of this method was about 15 m, because the target frequency, geophone spacing and survey line length were not sufficient for 30 m depth of penetration. Therefore, the purpose of this method was to estimate shear wave velocity at shallower depth. This method has the benefit of controlling the seismic waves due to artificial sources. The noise and signal can be separated easily in this method.

The dispersion curve of this survey is in the frequency range between 5 and 30 Hz (Fig. 3). A one-dimensional inversion using a non-linear least square method has been applied to the phase velocity curves (Fig. 4).

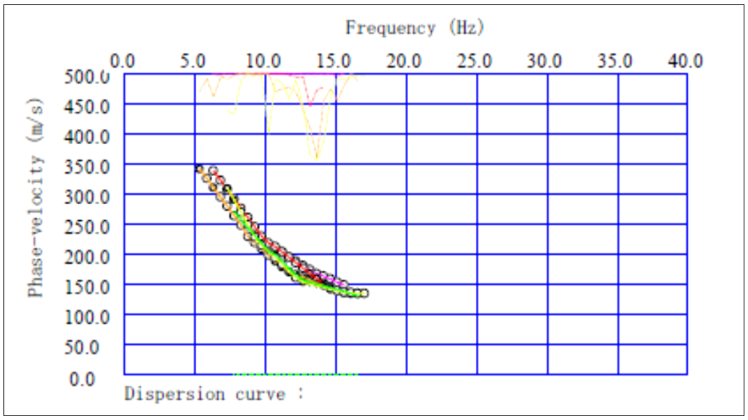

Fig. 3 - Dispersion curve of Multichannel Analysis of Surface Wave (MASW) data

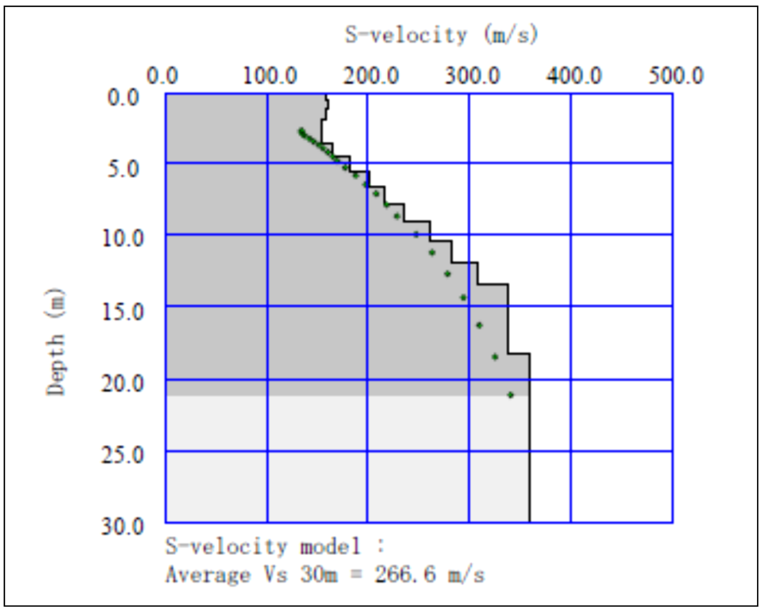

Fig. 4 - One dimensional shear wave velocity structure of MASW data

3.3. Small Scale Microtremor Measurement (SSMM) Method

Small Scale Microtremor Measurement (SSMM) is different from MASW method for the source and frequency range, etc. In case of SSMM, the source is natural (microtremor) and the frequency range is between 2 and 10 Hz due to the scale of measurement. As the shear wave velocity up to a depth 30 m could not be estimated using MASW, the Small Scale Microtremor Measurement (SSMM) was performed at the same sites of the MASW to estimate shear wave velocity structure up to a depth of 30 m. The combined sets of images from active and passive surveys can be a highly effective approach to understand the overall modal nature in extended frequencies and phase velocity ranges (Park et al., 2005). In this method, an L-shaped array of 60 m with geophones (10Hz) spaced 6 m apart was used for Vs estimation. Because of the L-shape array, the resultant one-dimensional structures can be interpolated into a three-dimensional structure. The dispersion curve in terms of phase velocity and frequency is shown in Fig. 5. A one-dimensional inversion using a non-linear least square method has been applied to the phase velocity curves and one-dimensional shear wave velocity structure down to a depth of 30 m has been obtained (Fig. 6).

The result of the one-dimensional shear wave velocity structure from SSMM was finalized combining shallow portion from the result of MASW. Then, AVS30 has been calculated by both SSMM and MASW results as follows:

$$T30 = \sum \frac{Hi}{Vi} \quad (1)$$

$$AVS\ 30 = \frac{30}{T30} \quad (2)$$

Where, Hi: Thickness of i th layer and 30 = $\sum Hi$

Vi: Shear wave velocity of i th layer.

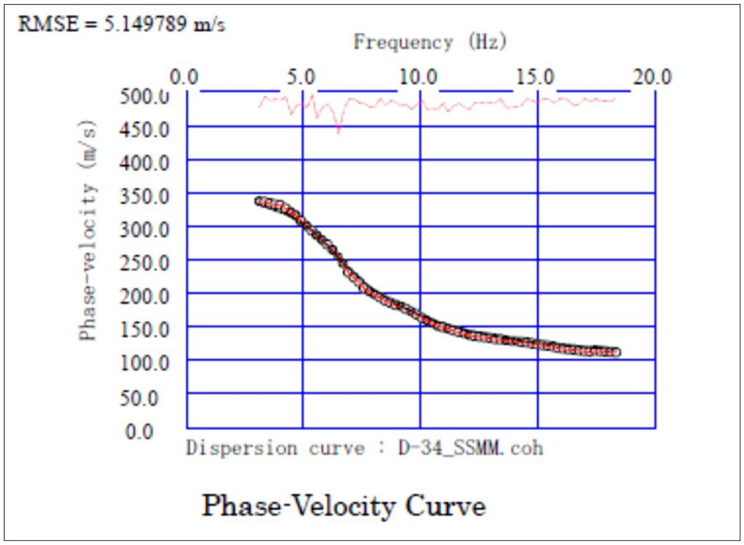

Fig. 5 - Dispersion curve of Small Scale Microtremor Measurement (SSMM) data

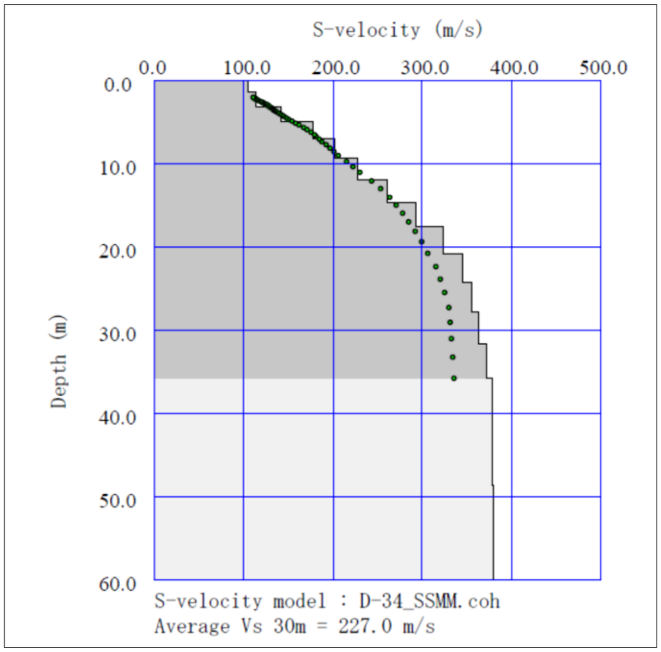

Fig. 6 - One dimension shear wave velocity structure of SSMM data

3.4. Shear Wave Velocity Estimation from SPT N-Values

Geotechnical investigation borings with Standard Penetration Test (SPT) at each 1.5 m interval up to a depth 30 m were conducted in order to know vertical geological conditions and groundwater level, to collect samples for geotechnical laboratory tests and to carry out Downhole Seismic investigation in 7 selected boreholes. The SPT boreholes were located at 53 sites of different surface geological units in the city. The locations of the boreholes were selected close to the MASW and SSMM survey sites. Site-specific formula have developed from the correlations between the shear wave velocity and SPT blow counts (Anbazhagan and Sitharam, 2008; Akin et al., 2011). Therefore, the SPT blow counts (N-values) of different geological units were correlated with the shear wave velocity (V_s) of Downhole Seismic to calculate V_s from the SPT N-values of a site. The relationship between V_s and N-value for each geological unit provides a good correlation and their correlating equations in each geotechnical unit are derived from the relation (Table 1). Using the distribution of geological units in each borehole and the correlating equations, AVS30 were calculated by the following equation:

$$\mathrm{AVS30} = \frac{30}{\sum_i \left(\frac{H_i}{Vs_i}\right)} \quad (3)$$

Where, H_i = Thickness of layer i (m)

Vs_i = Shear wave velocity of layer i (msec)

Table 1 – Correlating equations between shear wave velocity and SPT-N values (CDMP, 2009).

Subsurface geological Unit	Correlating equation
Filling soils	$Vs = 93.11N^{0.13}$ (m/sec)
Holocene clayey soils	$Vs = 115.97\ N^{0.21}$ (m/sec)
Holocene sandy soils	$Vs = 135.31\ N^{0.15}$ (m/sec)
Pleistocene clayey soils	$Vs = 157.34\ N^{0.20}$ (m/sec)
Plio-Pleistocene sandy soils	$Vs = 200.48\ N^{0.13}$ (m/sec)

4. Average Shear Wave Velocity Map of Dhaka City

Shear wave velocity map is an essential component in seismic hazard and microzonation studies. The average shear wave velocity of the near surface materials up to a depth of 30 m (AVS30) is directly related to the amplification of seismic waves at the site during an earthquake. Matsuoka et al. (2006) have prepared an AVS30 map of Japan from an engineering geomorphic map. Kanlı et al. (2006) and Anbazhagan and Sitharam (2008) have prepared average shear wave velocity maps for seismic hazard assessment. The shear wave velocities of the maps were estimated using Multichannel Analysis of Surface Wave (MASW). Then the subsurface soils are categorized based on National Earthquake Hazards Reduction Program (NEHRP) and International Building Codes (IBC) classification systems. The soil classes characterized using AVS30 is well correlated with soil classes that are characterized using Standard Penetration Test (SPT) data. Therefore, a relationship between V_s and SPT N-values has been developed to estimation shear wave velocity using available SPT data (Anbazhagan and Sitharam, 2008). The shear wave velocity map has a good correlation with damage distribution of earthquake (Kanlı et al., 2006).

As Dhaka city is located close to one of the most seismically active zones in the world, average shear velocity map is an important component for seismic hazard assessment of the city. Therefore, a shear wave velocity map has been prepared for Dhaka City using AVS30 estimated by Downhole Seismic (DS), Multichannel Analysis of Surface Wave (MASW), Small Scale Micro-tremor Measurement (SSMM) and Standard Penetration Test (SPT) blow counts (N-values) methods (Fig. 7). The AVS30 of the subsurface geological materials of the city varies from 127 m/sec to 295 m/sec. The central part, from north to south and the middle western part of the city exhibit high shear wave velocities from 200 m/sec to 295 m/sec, whereas the eastern and western parts of the city show low shear wave velocities from 127 m/sec to 240 m/sec. The geological materials of the city are classified as site classes D (stiff soils) and E (soft soils) based on AVS30 according to NEHRP (National Earthquake Hazards Reduction Program, USA).

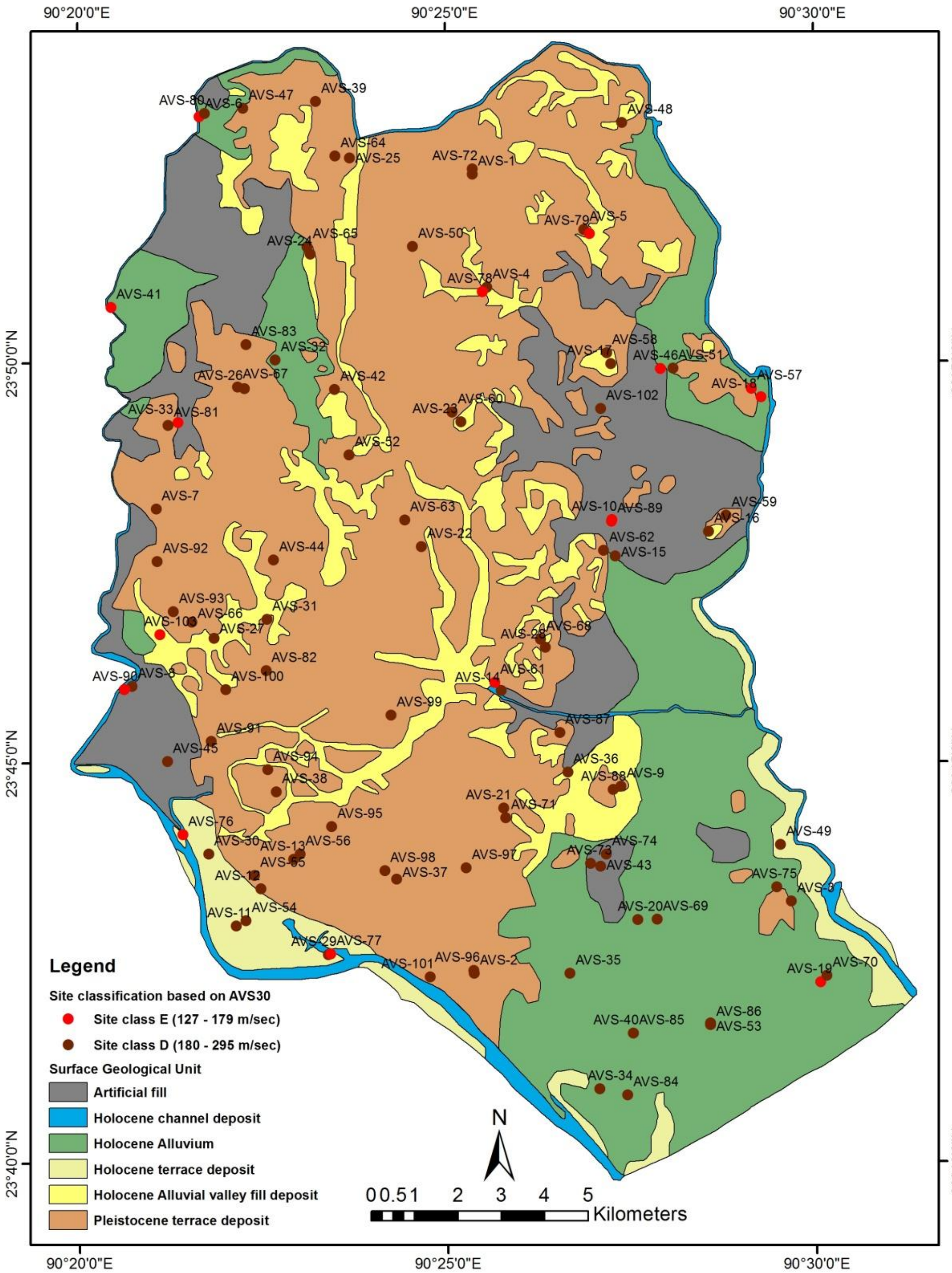

Fig. 7 - Average shear wave velocity up to the depth 30 m (AVS30) map of Dhaka City

5. Conclusions

Seismic site characterization is an important component of the seismic hazard assessment. Average shear wave velocity of the near surface materials up to a depth of 30 m (AVS30) is an essential parameter for seismic site characterization, as the dynamic properties of soils can be expressed in terms of shear wave velocity.

Shear wave velocity estimation using Downhole Seismic is more reliable and accurate. However, it is more expensive than surface wave method. It is also difficult to carry out in densely urban built areas. On the other hand, shear wave velocity estimation using the dispersion characteristics of the surface waves is a robust, non-invasive, fast and low cost technique. The technique has evolved over the last few decades. The shear wave velocity calculated from surface wave analysis is now more accurate and precise than earlier. Therefore, shear wave velocity estimation by Multichannel Analysis of Surface Wave (MASW) and Small Scale Microtremor Measurement (SSMM) methods is a promising option compared to the Downhole and Crosshole Seismic methods that are invasive and costly techniques. The AVS30 can also be estimated from Standard Penetration Test (SPT) blow counts (N-values) using the relationship between the shear wave velocity and SPT N-values.

The AVS30 map of Dhaka City has been prepared using shear wave velocities estimated by Downhole Seismic (DS), Multichannel Analysis of Surface Wave (MASW), Small Scale Microtremor Measurement (SSMM) methods and SPT N-values. The AVS30 map of Dhaka City can be used for the seismic hazard assessment of the city.

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