Shear Wave Velocity Estimation Using Multichannel Analysis of Surface Wave and Small Scale Microtremor Measurement for Seismic Site Characterization

Challenges from North to South
Des défis du Nord au Sud

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ABSTRACT
Average shear wave velocity of the near surface materials up to a depth of 30 m (AVS30) has been estimated using Multichannel Analysis of Surface Wave (MASW) and Small Scale Microtremor Measurement (SSMM) methods. MASW and SSMM are non-invasive and the most economic techniques to accurately estimate AVS30. MASW and SSMM have been carried out at 39 points in Chittagong City, Bangladesh. The results of MASW and SSMM data have been combined to estimate AVS30. The AVS30 of the soils of the city varies from 123 to 420 m/sec. According to the National Earthquake Hazards Reduction Program (NEHRP), the soils of the city are classified as site classes C, D, E and F. The amplification factor of the seismic waves within the soils of the city can be estimated from site classes. Therefore AVS30 estimation by MASW and SSMM methods is a promising option for seismic site characterization.

RÉSUMÉ
La vitesse moyenne des ondes de cisaillement proches de la surface des matériaux jusqu'à une profondeur de 30 m (AVS30) a été estimée, à petite échelle, à l'aide d'une analyse multicanal des ondes de surface (MASW) en utilisant les méthodes de mesure Microtremor (SSMM). MASW et SSMM sont non-invasives et sont les techniques les plus économiques pour estimer avec précision AVS30. MASW et SSMM ont été effectuées à 39 points à la ville de Chittagong, Bangladesh. Les résultats des données MASW et SSMM ont été combinées pour estimer AVS30. L'AVS30 des sols de la ville varie de 123 à 420 m / sec. Selon le Programme national de réduction des risques sismiques (NEHRP), les sols de la ville sont identifiés comme ayant des classes C, D, E et F. Le facteur d'amplification des ondes sismiques dans les sols de la ville peut être estimé à partir des classes de site. Par conséquent, l'estimation d'AVS30 par les méthodes MASW et SSMM est une option prometteuse pour la caractérisation sismique du site.

1 INTRODUCTION

Average shear wave velocity up to a depth of 30 m (AVS30) is considered as an important parameter for site class characterization to determine the amplification factor of seismic waves during an earthquake (Borcherdt, 1994; Anderson et al. 1996; BSSC 1998; Park and Elrick 1998). The elastic properties of the subsurface soils can be estimated by the shear wave velocity and density of the soils. Therefore, the dynamic properties of the near surface materials are expressed in terms of shear wave velocity.

Shear wave velocity of the near surface materials can be estimated using various seismic methods, such as, Down-hole Seismic (DS), Cross-hole Seismic (CS), Multichannel Analysis of Surface Wave (MASW), etc. The DS and CS methods are more reliable and accurate than surface wave methods (Boore and Brown, 1998). But, DS and CS methods are invasive and costly techniques. It is also not economically feasible to use DS and CS techniques to estimate shear wave velocity in case of low cost projects. On the other hand, MASW method is a robust, non-invasive, low cost and suitable technique to measure the shear wave velocity of the near surface materials (Tian et al., 2003). MASW method has been evolved over last few decades. This method is being increasingly used to estimate shear wave velocity of the near surface materials for seismic site characterization. Xia (2014), Tian et al. (2003) and others have examined that the shear wave velocity of the near surface materials can be estimated accurately using MASW method. Therefore, MASW method is accepted as a new technique among the geotechnical earthquake engineering researchers and professionals to estimate shear wave velocity of the near surface materials for seismic site characterization.

In MASW method, shear wave velocity is estimated from the inversion of the dispersion curves of surface wave, such as, Rayleigh waves (Park et al., 1999; Xia et al., 1999). When the surface waves, such as Rayleigh wave propagate from the ground surface to the deeper layers of the earth, the phase velocity increases with decreasing frequencies of the waves. As the phase velocity increases with depth, the Rayleigh wave is dispersive. The shear wave velocity has great influence on the dispersion curve of the Rayleigh waves of the subsurface layered materials (Xia et al., 1999). Park et al. (1999) indicate that the accuracy of shear wave velocity estimated from the dispersion of the surface wave is controlled by the interference of consistent source-generated noises, such as, body waves, scattered and non source-generated surface waves, and higher-mode surface waves. The extent of interference of dispersion curves by these noises depends on the frequency of the waveforms and distance from the source. The noises can be distinguished and separated efficiently from multichannel records according to the coherency in arrival time and amplitude (Park et al., 1999 and Xia et al., 1999).

Tian et al. (2003) have developed a method using a large number of closely spaced geophones to collect MASW data concurrently and automatically. High frequency surface wave data obtained by conventionally setting geophones have been compared with the data obtained by automatically setting geophones to observe the performance of the proposed method. The results indicate that the method can be used efficiently to accurately estimate the shear wave velocity of the near surface materials to reduce time and cost incurred for data acquisition. Xu et al. (2006) have proposed a formula to determine the minimum distance between the source and first receiver (geophone) to carry out MASW using a source, such as, sledgehammer. The minimum offset is an important parameter in a MASW survey to achieve the proper resolution of the dispersion image of the high frequency surface wave for accurate estimation of the shear wave velocity. The results of MASW reveal that the formula derived to determine the minimum off-set, is accurate for near surface shear wave velocity estimation. Xia (2014) has also estimated the shear wave velocity of the near surface materials from the dispersions of high frequency Rayleigh wave and Love wave. It is observed that Multichannel Analysis of Love Wave (MALW) has some fascinating advantages over MASW. The dispersion curves of the Love waves are simpler having higher signal and noise ratio, less dependent on the initial model and more stable than that of the Rayleigh wave.

Artificial energy sources, such as sledgehammer, are used to generate seismic waves in a MASW survey. When MASW survey is carried out using any artificial energy sources, it is called the active MASW method. MASW survey can be performed without artificial energy sources. This method of MASW survey is called passive MASW. In passive MASW survey, the seismic waves are generated from the ambient vibration of the earth due to ocean waves, cultural noises, such as traffic movement, industrial activities, etc. Shear wave velocity is estimated from the dispersion curves of the Rayleigh waves generated by the ocean waves and cultural noises. Shear wave velocity can also be estimated by the combined use of active and passive MASW methods. The modal nature of the passive and active curves should be assessed with extended frequency ranges to an increased depth of investigation. Park et al. (2005) observed that the active and passive MASW with frequencies greater than 30 Hz and frequencies less than 30 Hz, respectively, were recognized as fundamental modes in their earlier survey. But in the later survey it was confidently re-identified as the first higher mode. 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.

In passive surface wave method, a two-dimensional receiver array is necessary for accurate results. But, in an urban area with densely populated buildings, it is difficult to find a spacious area to carry out such a two-dimensional survey. Park and Miller (2008) proposed a passive MASW method along a road side to overcome the problem for the two-dimensional receiver array in densely populated urban areas. Therefore, MASW method is a promising technique to estimate shear wave velocity of near surface materials for seismic site characterization.

As a low cost technique, MASW can be used in developing countries, like Bangladesh to estimate shear wave velocity of the near surface materials for seismic site characterization. But, there is little literature on the shear wave velocity estimation in Bangladesh (CDMP, 2009). A very few educational instructions and government organizations have necessary instrument and expertise knowledge to carry out MASW survey. Although Bangladesh is located close to one of the seismically active zones of the earth, the shear wave velocity of the near surface materials has not been used yet in Bangladesh to estimate the amplification factor of seismic waves and design values of structures. Three big cities of Bangladesh, such as, Dhaka, Chittagong and Sylhet are the highest risk cities for seismic vulnerability. Therefore it is essential to carry out seismic risk assessment of the seismically vulnerable cities of Bangladesh. Borcherdt (1994), Martin and Dobry (1994), Dobry et al. (2000) and others suggested that structures need to be designed based on the site dependent amplification factors which are estimated using average shear wave velocity of the near surface materials up to a depth of 30 m (AVS30). A precise definition of site-class and accurate estimation of site-specific amplification factors in terms of average shear wave velocity of the near surface materials was documented by Borcherdt (1994). Therefore, AVS30 has been incorporated in the building codes of many countries for site characterization to calculate the amplification factor of the site and seismic design parameters of structures.

Seismic site characterization is an important component of seismic risk assessment. Seismic site characterization can be carried out in terms of the average shear wave velocity of the near surface materials up to a depth of 30 m (AVS30). Therefore in the present study, an attempt has been made to estimate the average shear wave velocity of the near surface materials of Chittagong City, Bangladesh using Multichannel Analysis of Surface Wave (MASW) and Small Scale Microtremor Measurement (SSMM) for seismic site characterization. The Small Scale Microtremor Measurement (SSMM) method used in this study is the passive Multichannel Analysis of Surface Wave (MASW).

2 STUDY AREA

Chittagong is the largest seaport and second largest city in Bangladesh. The city covers an area of 168 square kilometers. The city having a population of more than 4.5 million is one of the fast growing cities in the country. Chittagong City is situated at the mouth of the Karnaphuli River in the southeastern part of Bangladesh (Figure 1).

The ground of the city is formed of the Tertiary hills and surrounding alluvial and coastal plains of the Holocene age. The hills are composed of soft sandstone, siltstone, and shale which are overlain by weathered and degraded sandstones, shale dissected by narrow valleys with sand and silt fill. The fine-grained sediments eroded from the hills are deposited in the coastal plains as thick fluviatile, delta plain and floodplain sediments (sand, silt, clay).

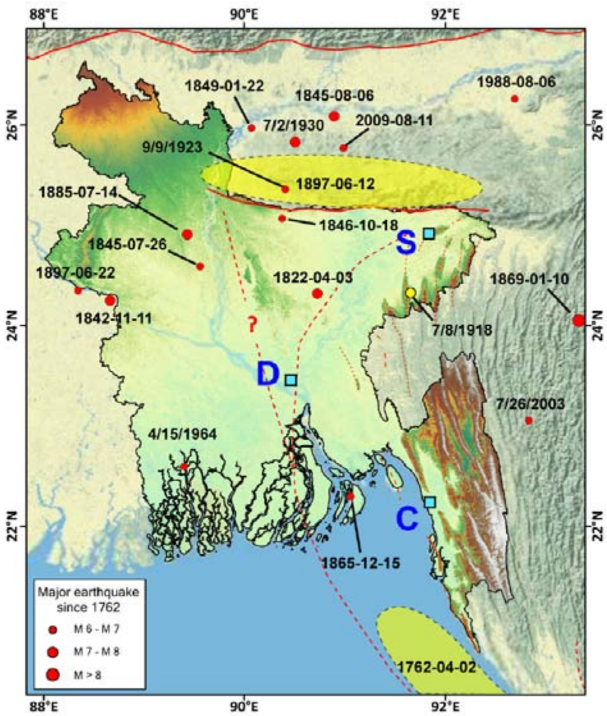

Figure 1. Based on the catalogue of Szeliga et al. (2010), the historical epicenters of earthquakes with a magnitude of more than 6 that occurred during the last 250 years (Yu and Sieh, 2013). D, C and S in the map stand for Dhaka, Chittagong and Sylhet Cities. The east-west red lines are the Himalayan Frontal Thrust (north) and Dauki Fault (south). The dotted red lines are Arakan Megathrust.

3 SEISMOTECTONICS

Bangladesh located in South Asia is an earthquake prone country. Several historical earthquakes occurred in Northeast India and Bangladesh in the last 253 years (Figure 1). Among them, the 1762 Bengal-Arakan, 1885 Bengal, 1918 Srimangal and Great Indian Earthquakes were prominent. The magnitudes of these earthquakes were 7.5, 7.0, 7.6 and 8.7, respectively. The Bengal-Arakan Earthquake which was located near Chittagong City caused considerable damage in the city. Numbers of earthquakes having magnitudes from 4.0 to 6.0 have occurred near Chittagong City in recent years. These earthquakes also caused some damages, such as crakes in the walls of buildings, tilting of buildings, etc. in the city.

Bangladesh constitutes a major portion of the Bengal Basin, which is located at the head of the Bay of Bengal. The Bengal Basin covers an extensive area of the northeastern part of the Indian Plate, which includes Bangladesh and part of adjacent Indian states of West Bengal, Tripura and Assam. Bangladesh covers about three fourths of the Bengal Basin, which is bounded on the west by the Indian Platform, on the north by the Precambrian Shilling Massif, on the east by the Arakan Yoma Folded Belt System and on the south it plunges down to the Bay of Bengal (Reimann, 1993; Alam et al., 2003). The study area is located in the western part of the Eastern Folded Belt of Bangladesh (Figure 1).

4 METHODOLOGY

The shear wave velocity of the near surface materials of Chittagong City were estimated using Multichannel Analysis of Surface Wave (MASW) and Small Scale Microtremor Measurement (SSMM). MASW and SSMM surveys were carried out at 39 points of Chittagong City. The survey points were selected based on the surface geological units of the city. The applied MASW and SSMM methods are described in the subsequent sections.

4.1 Multichannel Analysis of Surface Wave (MASW)

In Multichannel Analysis of Surface Wave (MASW), 12 channel geophones (seismic receivers) along a line of 22 m with geophone spaced 2 m from each other were used to record seismic waves. The natural frequency of the geophones was 10 Hz. An acrylic board was placed at the midpoint of 2 m space (1 m apart from each geophone). Impact energy was created by hilling on an acrylic board using a sledgehammer to generate seismic waves. Seismic waves of different frequencies were generated due to hitting on the acrylic board. In MASW survey, the depth of investigation was 15 m, because the target frequency, geophone spacing and survey length were not sufficient for the depth of 30 m. Therefore the purpose of the MASW survey was to estimate shear wave velocity up to a depth of 15 m. The MASW survey has the advantage to control the seismic waves due to artificial sources. Therefore, the signal and noise can be separated easily.

The collected surface waves (Rayleigh waves) of time domain have been transformed into frequency domain to determine the phase velocity. As the Rayleigh wave is dispersive, the phase velocity increases with decreasing frequency of the waves and with increasing depth. Then the shear wave velocity structure has been generated from the inversion of the dispersion curve (Figure 2).

4.2 Small Scale Microtremor Measurement (SSMM)

In Small Scale Microtremor Measurement (SSMM), 11 channel geophones with a spacing of 6 m were installed along an L-shaped line of 60 m having each arm of L is 30 m. No artificial energy source was required for this survey. In this survey, the source is natural (microtremor) and the frequencies of seismic waves were 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, SSMM survey was carried out at the same sites of MASW to estimate shear wave velocity structure up to a depth of 30 m. The collected surface waves (Rayleigh waves) of time domain have been analyzed using the same technique that was used to analyze MASW data. Then the results of MASW and SSMM were combined to generate shear wave velocity structure up to a depth 30 m. The AVS30 has been estimated from the velocity structure (Figure 3).

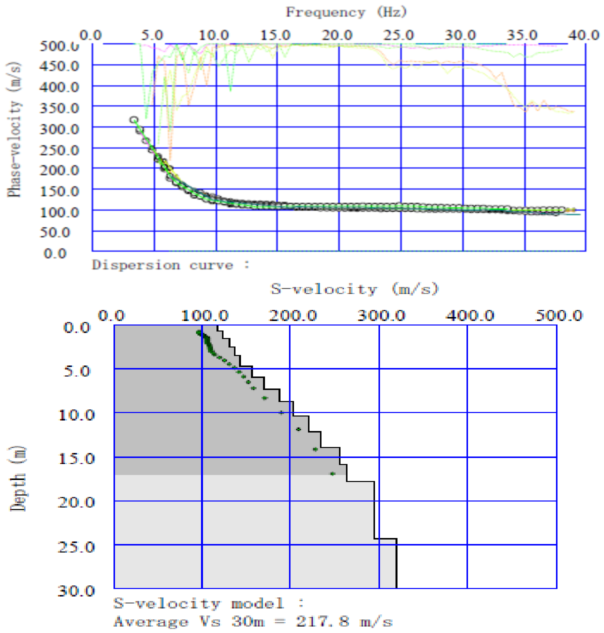

Figure 2. Dispersion curve (top) and shear wave velocity structure (bottom) of MASW survey

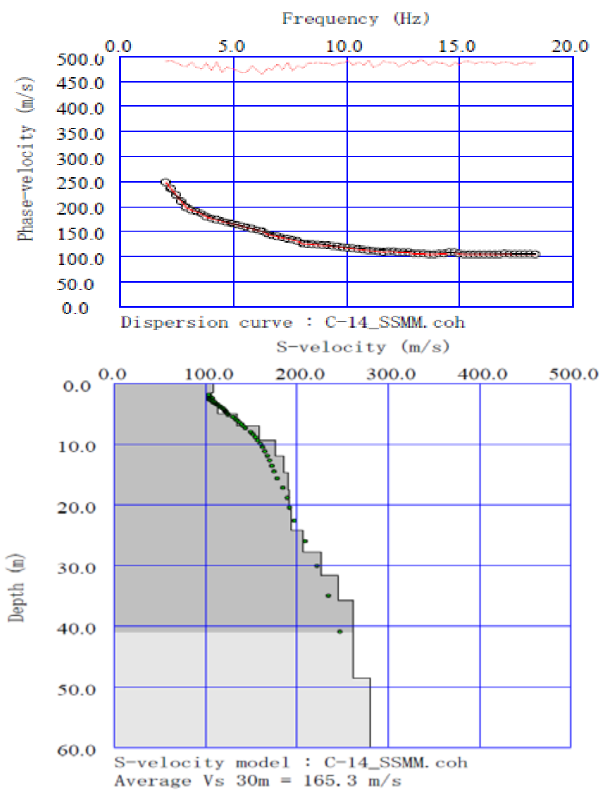

Figure 3. Dispersion curve (top) and shear wave velocity structure (bottom) of SSMM survey

5 RESULTS AND DISCUSSION

The average shear wave velocity of the near surface materials up to a depth of 30 m (AVS30) has been estimated at 39 points in Chittagong City. The calculated AVS30 of each point is given in Table 1. The AVS30 of the soils of the city varies from 123 m/sec to 420 m/sec.

Table 1. Average shear wave velocity up to a depth of 30 m (AVS30) at 39 points in Chittagong City

No	Lat.	Long.	AVS30 (m/s)	No	Lat.	Long.	AVS30 (m/s)
1	22.38	91.86	130	22	22.34	91.86	159
2	22.38	91.83	160	23	22.38	91.82	420
3	22.37	91.82	171	24	22.36	91.80	190
4	22.34	91.84	256	25	22.39	91.76	195
5	22.35	91.79	246	26	22.35	91.85	160
6	22.33	91.80	170	27	22.33	91.83	247
8	22.37	91.84	123	29	22.35	91.77	164
9	22.40	91.83	150	30	22.32	91.79	182
10	22.26	91.82	199	31	22.34	91.80	224
11	22.24	91.80	156	32	22.37	91.78	384
12	22.35	91.77	182	33	22.37	91.76	180
13	22.34	91.78	184	34	22.37	91.83	226
14	22.34	91.78	165	35	22.27	91.86	205
15	22.33	91.78	183	36	22.42	91.86	125
16	22.35	91.82	252	37	22.33	91.85	160
17	22.34	91.82	240	38	22.28	91.77	169
18	22.35	91.84	199	39	22.31	91.77	174
19	22.32	91.81	163	40	22.30	91.86	162
20	22.39	91.87	175	41	22.31	91.85	166
21	22.40	91.85	132				

The AVS30 of different surface geological units is shown as point map on the surface geological map of Chittagong City (Figure 4). It is observed that the Alluvium, Holocene terrace deposit, Holocene alluvial fan deposit, Holocene alluvial valley fill deposit and Holocene tidal flat deposit have low average shear wave velocity, whereas, the Holocene piedmont plain deposit and Tertiary folded sedimentary rock have high average shear wave velocity.

According to the National Earthquake Hazards Reduction Program (NEHRP), the near surface materials of Chittagong City have been classified as site classes C, D, E and F. The average shear wave velocities are for site class C (very dense soils and soft rocks) from 360 m/sec to 760 m/sec, site class D (stiff soils) from 180 m/sec to 360 m/sec, site class E (soft soils) below 180 m/sec. Site specific evaluations are required for site class F which includes liquefiable soils, quick and highly sensitive collapsible clays, more than 3 m thick peat or highly organic clays, more than 8 m very high plasticity clays and more than 36 m thick very soft to medium stiff clays.

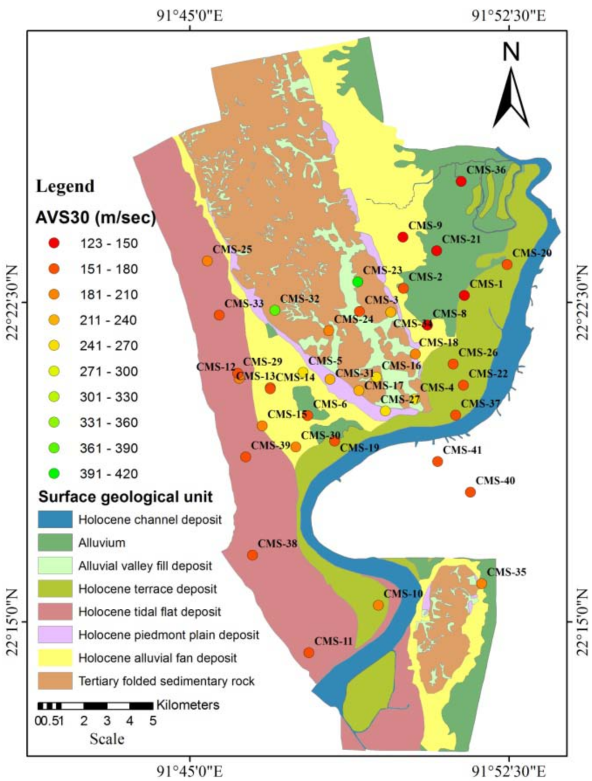

Figure 4. AVS30 at the surface geological units of Chittagong City

The average shear wave velocity up to a depth of 30 m (AVS30) varies from 123 to 175 m/sec in Alluvium, from 171 to 256 m/sec in alluvial valley fill, from 159 to 199 m/sec in terrace, from 156 to 183 m/sec in tidal flat, from 150 to 246 m/sec in alluvial fan, from 224 to 247 in piedmont plain, and from 384 to 420 m/sec in folded sedimentary rock. The soils of the Alluvium is classified as site class E. The soils of the alluvial valley fill, tidal flat, alluvial fan are categorized as site class D and E. The soils of the piedmont plain and Tertiary folded sedimentary rocks are classified as site classes D and C, respectively.

The Standard Penetration Test blow counts (SPT-N) were executed in the same units where shear wave velocities were estimated using Multichannel Analysis of Surface Wave (MASW) and Small Scale Microtremor Measurement (SSMM). From SPT-N values of different surface geological units, it has been observed that in some areas of the Alluvium, Holocene terrace deposit have more than 30 m thick liquefiable soils, peat or highly organic clays and very soft to medium stiff clays. In some areas of the Holocene tidal flat deposit more than 10 m thick liquefiable soils and very soft to medium stiff clays are present. In places of the Holocene alluvial valley fill deposit and alluvial fan deposit, more than 15 m thick very soft to medium stiff clayey soils and very loose to loose sandy soils are encountered. Therefore, the Alluvium, terrace, flat pain, alluvial valley fill and alluvial plain deposits have some soils of site class F.

CONCLUSIONS

Seismic site characterization is an important component of the seismic risk assessment. As the dynamic properties of soils can be expressed in terms of shear wave velocity, 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

Shear wave velocity estimation using downhole seismic is more reliable and accurate. But it is more expensive than surface wave method. On the other hand, shear wave velocity estimation using the dispersion curves 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 seismic and crosshole seismic methods which are invasive and costly techniques.

The shear wave velocity of the near surface materials of Chittagong City, Bangladesh has been estimated using MASW and SSMM techniques. MASW and SSMM surveys have been carried out at 39 points in different surface geological units of Chittagong City. The AVS30 of the units varies from 123 to 420 m/sec. According to National Earthquake Hazards Reduction Program (NEHRP), the soils of the city are categorized as site class C, D, E and F. The amplification factor of the seismic waves within the soils of Chittagong City can be estimated from the site class of the city.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Comprehensive Disaster Management Programme (CDMP), Bangladesh, Asian Disaster Preparedness Center (ADPC), Thailand and OYO International Corporation, Japan for their all types of supports to collect and analyse shear wave velocity data.

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