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Shear wave velocity estimation of the near-surface materials of Chittagong City, Bangladesh for seismic site characterization

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ABSTRACT

The average shear wave velocity of the near-surface materials down to a depth of 30 m (V_s^{30}) is essential for seismic site characterization to estimate the local amplification factor of the seismic waves during an earthquake. Chittagong City is one of the highest risk cities of Bangladesh for its seismic vulnerability. In the present study, the V_s^{30} is estimated for Chittagong City using the multichannel analysis of surface waves (MASW), small scale microtremor measurement (SSMM), downhole seismic (DS), and correlation between the shear wave velocity (V_s) and standard penetration test blow count (SPT-N). The V_s^{30} of the near-surface materials of the city varies from 123 m/s to 420 m/s. A V_s^{30} map is prepared from the V_s^{30} of each 30 m grid using the relationship between the Holocene soil thickness and the V_s^{30}. Based on the V_s^{30}, the near-surface materials of Chittagong City are classified as site classes C, D, and E according to the National Earthquake Hazards Reduction Program (NEHRP), USA and as site classes B, C, and D according to the Eurocode 8. The V_s^{30} map can be used for seismic microzonation, future planning, and development of the city to improve the earthquake resiliency of the city.

1. Introduction

The state of the art practice in seismic hazard analysis is to perform site response analysis for the estimation of the ground motion parameters at the ground surface of a site using the properties of the soil profiles and the ground motion parameters of the baserock at the base of the soil profiles (Bazzurro and Cornell, 2004a, 2004b; Cramer, 2003; Kaklamanos et al., 2015; McGuire and Toro, 2008). Although seismic ground motion at the ground surface can accurately be estimated using site response analysis, as a simplified approach, a common practice for site specific seismic ground motion estimation is simply multiplying the baserock ground motion parameters by the amplification factors which are generally determined using the average shear wave velocity of the near-surface materials down to a depth of 30 m (V_s^{30}). Therefore, the V_s^{30} is considered as an important parameter for site class characterization to estimate the amplification factors of seismic waves during an earthquake (Anderson et al., 1996; Borcherdt, 1994; Park and Elrick, 1998). The National Earthquake Hazards Reduction Program (NEHRP), USA and Eurocode 8 (EC8) use the V_s^{30} for site class characterization to determine the amplification factors. The V_s^{30} was not used to characterize the soils in Bangladesh National Building Code (BNBC)-1993. The BNBC is now updating to incorporate the V_s^{30} for site characterization to estimate the amplification factors. Therefore, in the present study, the near-surface materials are characterized based on the V_s^{30} according to the provisions of the NEHRP and EC8 (Table 1).

The shear wave velocity (V_s) of the near-surface materials can be estimated using various seismic methods, such as crosshole seismic (CS), downhole seismic (DS), and surface wave methods. In the CS test, the source and receiver are placed at the same depths within two adjacent boreholes and the velocities of the compressional waves (P-waves) and shear waves (S-waves) are estimated using the distance between the source and receiver, and the travel times of the P- and S-waves. In the DS test, seismic waves are generated on the ground surface and the travel times of the P- and S-waves are measured placing the receiver at different depths within a borehole and then the velocities of the P- and S-waves are estimated using the distance between the source and receiver, and the travel times of the P- and S-waves. The CS and DS methods are more reliable and accurate than the surface wave methods (Boore and Brown, 1998; Foti et al., 2014; Xia et al., 2002). But, the CS and DS methods are invasive and costly. It is also not economically feasible to use the CS and DS methods to estimate the V_s in the case of low cost projects. On the other hand, the surface wave methods are robust, non-invasive, low cost, and suitable techniques to estimate the V_s of the near-surface materials (Bard et al., 2010; Foti et al., 2014; Foti et al., 2011; Socco et al., 2010; Tian et al., 2003). The surface wave methods continue to evolve since the last several decades (Aki, 1957; Crampin and Bath, 1965; Foti et al., 2014; Horike, 1985; Mcmechan and Yedlin, 1981; Nazarian et al., 1983; Okada, 2003; Park et al.,

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Table 1
Site classes of subsoils according to the National Earthquake Hazards Reduction Program (NEHRP), USA and Eurocode 8 (modified from Dobry et al., 2000; Kanli et al., 2006).

NEHRP, USA			Eurocode 8		
Site class or soil profile type	Description	Average shear wave velocity of top 30 m (m/s)	Subsoil class	Description of stratigraphic profile	Average shear wave velocity of top 30 m (m/s)
A	Hard rock	>1500		–	–
B	Rock	760–1500	A	Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface	>800
C	Very dense soil/soft rock	360–760	B	Deposits of very dense sand, gravel or very stiff clay, at least several tens of m in thickness, characterized by a gradual increase of mechanical properties with depth	360–800
D	Stiff soil	180–360	C	Deep deposits of dense or medium-dense sand, gravel or stiff clay with thickness from several tens to many hundreds of m	180–360
E	Soft soil	<180	D	Deposits of loose-to-medium cohesionless soil (with or without some soft cohesive layers), or of cohesive soil predominantly soft-to-firm	<180
F	Special soils requiring site-specific evaluation (1. Soils vulnerable to potential failure or collapse under seismic loading, e.g., liquefiable soils, quick and highly sensitive clays, collapsible weakly cemented soils; 2. peats and/or highly organic clays (3 m or thicker layer); 3. very highly plasticity clays (8 m or thicker layer with plasticity index >75); 4. very thick soft/medium stiff clays (36 m or thicker layer))		E	A soil profile consisting of a surface alluvium layer with V_s^{30} values of class C or D and thickness varying between about 5 m and 20 m, underlain by stiffer material with $V_s^{30} > 800$ m/s	–
			S_1	Deposits consisting - or containing a layer at least 10 m thick - of soft clays/silts with high plasticity index (PI > 40) and high water content	<100
			S_2	Deposits of liquefiable soils, of sensitive clays, or any other soil profile not included in classes A–E or S1	–

1999). This method is increasingly used to estimate the V_s of the near-surface materials for seismic site characterization (Foti et al., 2011; Park and Miller, 2008; Park et al., 2005; Socco et al., 2010). Bard et al. (2010), Tian et al. (2003) and Xia (2014) observed that the V_s of the near-surface materials can be estimated accurately using the surface wave methods. Therefore, surface wave methods are accepted as new methods among geotechnical earthquake engineers, geophysicists, and geologists to estimate the V_s of the near-surface materials for seismic site characterization.

In surface wave methods, the dispersion properties of the surface waves, generally the Rayleigh waves are used to estimate the V_s of the near-surface materials (Foti et al., 2011; Park and Elrick, 1998). When the surface waves, such as the Rayleigh waves 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 decreasing frequency, the Rayleigh waves are dispersive (Foti et al., 2014; Xia et al., 1999). The surface waves can be recorded using active and passive sources. When the surface waves are recorded using any artificial energy sources, such as sledgehammer, it is called the active surface wave method. The surface waves are also recorded without artificial energy sources. In this case, the ambient vibration of the earth is used as an energy source. The earth is vibrating continuously due to ocean waves and cultural noises, such as traffic movement and industrial activities. When the shear wave velocity (V_s) is estimated using the dispersion curves of the Rayleigh waves that are generated from the ambient vibration of the earth, it is called the passive surface wave method. The active and passive multichannel analyses of surface waves (MASW) methods are widely used to estimate the V_s of the near-surface materials (Foti et al., 2011; Hayashi and Suzuki, 2004; Hayashi et al., 2005; Okada, 2003; Park et al., 1999, 2005; Park and Miller, 2008).

In multichannel analysis of surface waves (MASW) method, the V_s is estimated from the inversion of the dispersion curves of the surface waves, such as the Rayleigh waves (Foti et al., 2011; Park et al., 1999; Xia et al., 1999). The shear wave velocity (V_s) has great influence on the dispersion curve of the Rayleigh waves of the subsurface layered materials (Xia et al., 1999). Park et al. (1999) indicated that the accuracy of the V_s estimated from the dispersion of the surface waves is controlled by the interference of the consistent source-generated noises, such as body waves, scattered and non-source-generated surface waves, and higher-mode surface waves. The extent of the interference of the dispersion curves by these noises depends on the frequency of the waveforms and the distance from the source. The noises can be distinguished and separated efficiently from the multichannel records according to the coherency in the arrival time and amplitude (Park et al., 1999; Xia et al., 1999).

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

The procedures described above are the active MASW surveys using seismic sources acting on the ground surface. In the passive MASW surveys, microtremors that are generated by natural events or human activities are used to estimate the V_s at a greater depth using low frequency surface waves (Hayashi et al., 2005; Socco et al., 2010). Several techniques are developed to extract the dispersion curves of the passive surface wave data. The most widely used techniques are the spatial autocorrelation (Aki, 1957), frequency domain beam forming (Lacoss,