Conversion Shear Wave Velocity to Standard Penetration Resistance

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Abstract. Multichannel Analysis Surface Wave (MASW) measurement is one of the geophysics exploration techniques to determine the soil profile based on shear wave velocity. Meanwhile, borehole intrusive technique identifies the changes of soil layer based on soil penetration resistance, i.e. standard penetration test-number of blows (SPT-N). Researchers across the world introduced many empirical conversions of standard penetration test blow number of borehole data to shear wave velocity or vice versa. This is because geophysics test is a non-destructive and relatively fast assessment, and thus should be promoted to compliment the site investigation work. These empirical conversions of shear wave velocity to SPT-N blow can be utilised, and thus suitable geotechnical parameters for design purposes can be achieved. This study has demonstrated the conversion between MASW and SPT-N value. The study was conducted at the university campus and Sejagung Sri Medan. The MASW seismic profiles at the University campus test site and Sejagung were at a depth of 21 m and 13 m, respectively. The shear wave velocities were also calculated empirically using SPT-N value, and thus both calculated and measured shear wave velocities were compared. It is essential to note that the MASW test and empirical conversion always underestimate the actual shear wave velocity of hard layer or rock due to the effect of soil properties on the upper layer.

Keywords: Soft soil, Multichannel Analysis Surface Wave (MASW), SPT-N blow, stiffness profile.

1. Introduction

Seismic wave techniques, which depend on the modulus and density of the materials can be converted to very useful parameters for engineering purposes, such as elastic modulus, shear modulus and Poisson’s ratio. The seismic method based results are empirically derived geotechnical properties such as maximum shear modulus, bulk modulus (B), Young’s modulus (E), and Poisson’s ratio [1,2]. In addition, seismic velocity can also correlate empirically to the standard penetration test number of blows (SPT-N) obtained from the penetration tests [3,4,5]. The seismic-based techniques have proved particularly useful in determining the shear modulus profile from site investigation [6,7]. There are two methods of obtaining seismic wave data that can potentially be used for site investigation (1) borehole methods and (2) surface methods [8]. The surface wave data collection uses the surface method, which is more versatile than other methods because it is not constrained by any ground models and considered more economical in terms of field operation [9].

Traditionally, the measurement of stiffness profile was carried out by using a combination of laboratory and in situ, invasive field tests. However, geophysical methods, such as seismic surface
wave, offer a non-intrusive and non-destructive approach to carry out these measurements. Moreover, geophysical approaches such as this provide a cost effective way to assess site conditions while overcoming a key limitation of traditional investigative approaches. A comparison between geophysical seismic-based techniques and conventional geotechnical load-testing methods for the measurement of the ground stiffness profile were presented by Matthews et al. [10] and Clayton [11], drawing the conclusion that geophysical testing can deliver results of significant quality. However, care is needed not to overestimate what geophysics can achieve, by understanding geophysical techniques, in particular their limitations [12]. Thus, geophysical assessment of any site investigation must be carried out with physical soundings to ensure proper calibration and validation.

In situ field testing enables larger volumes of soil to be tested and therefore tends to be more representative of the soil mass compared to laboratory testing. In situ field tests have an advantage as samples do not need to be retrieved. Some field tests are considered as destructive tests as they involve preliminary work such as drilling or inserting instruments into the ground. The dynamic Standard Penetration Test (SPT) is used world-wide to measure the force that is needed for an open sampler to penetrate the soil. The SPT is, essentially, a simple test involving the dropping of a standard hammer of known weight from a specific height. The SPT is the most common in situ test method used and is usually accompanied by other complementary measurements, field or laboratory based, for the purpose of making comparisons and establishing the relevant correlations. There were many convincing empirical correlations between N-values and shear wave velocity which are accepted worldwide. However, these empirical correlations were developed based on a local scale in various countries, which are unique to geological conditions and yet to support firm theoretical formulation [13]. In this study, three empirical correlations were referred to are Uma Maheswari et al. [3], Tsiambaos and Sabatakakis [4] and Anbazhagan et al. [5].

Multichannel Analysis of Surface Wave (MASW) method adopted in this study has significant advantages over other surface wave techniques as all seismic wave energy, consisting of both body and surface waves, is recorded by multichannel receivers. Seismic waves propagate in the form of body waves and surface waves. The difference between the two is that body waves are usually non-dispersive. In a solid and homogeneous medium, the velocity of surface waves does not fluctuate significantly as a function of distance propagates. However, when the properties of the medium vary with depth, surface waves become dispersive such that the velocity of propagation varies with respect to wavelength or frequency. Multichannel Analysis of Surface Wave (MASW) method has an investigation depth shallower than 30 m whereas the passive method (source like traffic and tidal motion) can reach a few hundred meters. Sampling redundancy due to multi receivers provides flexibility in the signal processing approach to extract the dispersion curve. Many advantages have been stated above, and thus, the evaluation of this technique for site investigation is conducted to promote this technique. This study aims to investigate the conversion of shear wave velocity obtained from SPT-N value and shear wave velocity from MASW technique or vice versa. The location of this study is shown in Figure 1, on the campus of Universiti Tun Hussein Onn Malaysia and Sejagung Sri Medan. The campus of Universiti Tun Hussein Onn Malaysia possesses marine clay and silt deposits of Quaternary age. Meanwhile, Sejagung Sri Medan is located at the geological boundary between marine deposit and volcanic rock.
2. Methodology
Multichannel Analysis of Surface Wave (MASW) method uses similar equipment in the seismic refraction method, but uses low frequency geophones. A 7 kg sledgehammer is used as source that impacts the metal plate. A 24-unit 4.5 Hz vertical geophone was used as a detector which was connected to a 24-channel cable and ABEM Terraloc MK-8 seismograph as a recorder. The seismograph setting for MASW test required longer record time, i.e. about 2 second to measure seismic data. The sampling interval is between 250 and 500 µs and the number of samples is between 4096 and 8192. Hammering the ground about 5 times produces active waves. The length of array and distance of seismic source to the first geophone are at 69 m and 15 m, respectively. MASW tests were conducted close to the borehole location.

3. Results and Discussions
Figure 2 shows the borehole data at two study areas, i.e. UTHM campus and Sejagung Sri Medan. At the UTHM campus, the soil layer consists of very soft layers (SPT-N < 2) up to 10.5 m followed by soft layers (SPT-N 2-4) up to 19.5 m depth. Meanwhile, borehole data at Sejagung, Sri Medan indicated that the subsurface can be categorized as loose soil (SPT N 4-10) up to 6 m in depth, followed by very dense soil (SPT-N > 50) until 9 m in depth. The borehole continued to drill the rock core for 6 m and was terminated at 15 m. The conversion of the empirical shear wave velocity using SPT-N value via three equations suggested by Anbazhagan et al. [5] using $V_s = 68.96N^{0.51}$; Tsiambaos and Sabatakakis [4] $V_s = 105.7N^{0.327}$; and Uma Maheswari et al. [3] $V_s = 95.64N^{0.301}$ were presented in Figure 3 and Figure 4.
The MASW test to obtain shear wave profiles at the university campus and the Sejagung Sri Medan site was conducted and analysed using SeisImager software. The dispersive phase velocities then produced 1-dimensional shear wave velocity versus depth. The shear wave velocities for very soft soil was below 180 m/s and soft soil was between 180 m/s and 270 m/s at the university campus site as shown in Figure 3. Meanwhile, at Sejagung Sri Medan indicated the shear wave velocities for loose soil was between 220 m/s and 450 m/s, very dense soil was between 450 m/s and 630 m/s and rock was between 630 m/s and 680 m/s as presented in Figure 4. The shear wave velocities using MASW technique indicated good agreement with the converting shear wave velocities using empirical conversion for both cases, i.e. the university campus and Sejagung Sri Medan site. However, at a deeper layer, the differences between measured and empirical conversion shear velocities became significant. This is because the MASW technique measured across its array length of 69 m (geophone 1 to 24) and the frequencies were dispersed according to its depth. As a result, the shear wave velocities were the outcome of an averaged velocity at specified depth across the area. In contrast, the calculated shear wave velocities using an empirical conversion and borehole SPT-N data are specifically at a certain depth.

The surface wave technique utilized Rayleigh wave velocity which is not only dependent on the depth, but also on the horizontal spans of the soil properties. Hence, the depth and horizontal spans can be used to identify the sampling volume. The sampling volume is based on the elliptical particle movement suggested by Madun et al. [14,15]. The relationship between the shear wave velocity and the effective region for each depth and wavelength is important for analysing and interpreting the measured result. Figure 5 illustrates the MASW measurement at Sejagung Sri Medan, where almost 100 % of the elliptical effective regions sit within the first layer of loose soil at a depth of 6 m. This effective region grows and the effective region presents the largest change in averaged shear wave velocity at the stage where the elliptical begins to encroach into the second and third layer of very hard and bedrock, respectively. Thus, this can explain the upward trend in shear wave velocities with further increase in depth. This in turn is a function of its wavelength. All the elliptical-shaped sampling volumes shown in Figure 5 are likely to explain the measured shear wave velocity is lower than actual velocity. For example, at Sejagung, after 9 m to 13 m depth, the shear wave velocity is between 630 m/s and 680 m/s, indicating the rock layer via borehole data. It is worth noting that the shear wave velocity of rock is above 1500 m/s [16]. In practical applications for the understanding of the relationship between the wavelength and the effective region of measurement (the sampling volume) it is important to plot a graphical representation of the dispersion curve, which delineates the variation and defines the soil boundaries. Therefore, understanding the geophysical limitations is
important to avoid overestimating what geophysics can achieve. It is essential to note that the MASW test and three empirical conversions suggested by Anbazhagan et al (2012), Tsiambaos and Sabatakakis (2011), and Maheswari et al (2010) always underestimate the actual shear wave velocity of hard layer or rocks due to the effect of soil properties on the upper layer.

**Figure 3.** The shear wave velocities measured using MASW and empirical conversion for data at university campus

**Figure 4.** The shear wave velocities measured using MASW and empirical conversion for data at Sejagung, Sri Medan
Figure 5. Illustration of volume measurement in elliptical shape to demonstrate that the shear wave velocity is lower than actual values.

4. Conclusion
The MASW seismic profiles at the university campus test site and Sejagung were at 21 m and 13 m in depth, respectively. The shear wave velocities were also calculated empirically using SPT-N value, and thus both calculated and measured shear wave velocities were compared. The shear wave velocity obtained using MASW technique represents the average velocity at specified depth across the lateral length of the array. Thus, it is expected that the velocity was empirically converted using the SPT-N value slightly deviated to the variability of soil horizontally and vertically. Therefore, understanding the geophysical limitations is important to avoid overestimating what geophysics can achieve. It is essential to note that the MASW test and empirical conversion usually underestimates the actual shear wave velocity of hard layers or rock due to the effect of soil properties on the upper layer.

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