Compressive and Shear Wave Velocity Profiles using Seismic Refraction Technique

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Abstract. Seismic refraction measurement is one of the geophysics exploration techniques to determine soil profile. Meanwhile, the borehole technique is an established way to identify the changes of soil layer based on number of blows penetrating the soil. Both techniques are commonly adopted for subsurface investigation. The seismic refraction test is a non-destructive and relatively fast assessment compared to borehole technique. The soil velocities of compressive wave and shear wave derived from the seismic refraction measurements can be directly utilised to calculate soil parameters such as soil modulus and Poisson’s ratio. This study investigates the seismic refraction techniques to obtain compressive and shear wave velocity profile. Using the vertical and horizontal geophones as well as vertical and horizontal strike directions of the transient seismic source, the propagation of compressive wave and shear wave can be examined, respectively. The study was conducted at Sejagung Sri Medan. The seismic velocity profile was obtained at a depth of 20 m. The velocity of the shear wave is about half of the velocity of the compression wave. The soil profiles of compressive and shear wave velocities were verified using the borehole data and showed good agreement with the borehole data.

1. Introduction

Soil velocity profile is often used as subsurface characterization by using seismic-based techniques [1,2,3,4]. Seismic-based techniques are the most sensitive to the physical properties of geo-materials and relatively insensitive to the chemistry of geo-materials and their fluids [5]. The seismic-based techniques shake the ground and produces very small strains. Thus, the soil velocities derived from the seismic-based measurements are related to soil modulus. Therefore, the seismic-based techniques can be used to directly derive the geotechnical properties related to the strain including maximum shear modulus, bulk modulus (B), Young’s modulus (E), and Poisson’s ratio (ν) [5,6,7,8,9].

There are four types of elastic seismic waves, produced by impulses and all of which travel at different velocities. The four are: compression wave, called the P-wave, shear wave called the S-wave, Rayleigh wave and Love wave. P and S waves are known as body waves; Rayleigh and Love waves are surface waves as shown in Figure 1 [10]. A seismic wave transmits energy by the vibration...
of soil particles in different directions. For P-waves, the soil particles vibrate in the direction of the wave propagation and S-waves vibrate in the direction perpendicular to the direction of wave propagation. Both waves are propagated along a hemispherical wave front; thus wave amplitude is attenuated in proportion to $1/r^2$ where r is the distance from seismic source.

The P-wave has the greatest velocity of the elastic seismic waves. The P-wave travels through all media: liquids, gases and solids. On the other hand, the S-wave travels slightly slower than the P-wave in solids and does not propagate through liquids and gases, as these media have no shear strength. Table 1 [6] shows the typical values of P- and S-wave for different earth materials which illustrate key differences. The P-wave causes volumetric strains and the velocity depends on bulk density, bulk modulus and any deformation which are considered to be undrained. Meanwhile, S-waves induce shear distortion in the soil without volumetric changes. The velocity of a P-wave in water is 1450 m/s. Therefore, the undrained bulk modulus of the ground is usually a combination of stiffness in both the soil and the water. In contrast, S-wave velocity in water is 0 m/s. Thus, the measured modulus is represented by the soil only. The use of S-waves is preferred when studying saturated soils because these are independent of water content [11,12].

![Schematic elastic wave propagation in the ground](image)

**Figure 1.** Schematic elastic wave propagation in the ground [10].

**Table 1.** P- and S-wave typical values for different earth materials [6].

| Material            | P-wave velocity, m/s | S-wave velocity, m/s |
|---------------------|-----------------------|-----------------------|
| Air                 | 330                   | 0                     |
| Water               | 1450                  | 0                     |
| Sands and clays     | 300-1900              | 100-500               |
| Glacial till        | 1500-2700             | 600-1300              |
| Chalk               | 1700-3000             | 600-1500              |
| Strong limestone    | 3000-6500             | 1500-3500             |
| Weathered granite   | 100-3000              | 500-1500              |
| Fresh granite       | 3000-6000             | 1500-3000             |
| Slate               | 5000-7000             | 2500-3800             |
There are two common types of seismic survey using body waves: refraction and reflection (see Figure 2). The seismic refraction is fundamentally based on Snell’s Law which states that at the critical incident angle, a wave is refracted along the soil layer boundary before it returns to the surface. Snell’s Law is:

\[ \sin i_c = \frac{V_1}{V_2} \]  

where \( i_c \) is the critical incident angle (degree), \( V_1 \) is the velocity of the upper layer (m/s) and \( V_2 \) is the velocity of the lower layer (m/s).

The seismic refraction method requires the soil layers to increase in density with depth. The reflection method requires density contrast to reflect waves back to surface [13]. The seismic refraction method involves recording the travelling time of either the P-wave or S-wave energy. Thus, interpretation of the data provides layer thicknesses and seismic velocities [6]. Figure 2 shows the difference between refraction and reflection.

\[ G_{\text{max}} = \rho v^2 \]  

\[ B = M_{\text{max}} = \rho v_p^2 = \frac{E}{3(1-2\nu)} \]  

Figure 2. The path of refracted and reflected seismic rays in a two-layer system [6].
\[ E = 2 \rho v_p^2 (1 + \nu) = \frac{\rho v_p^2 (1 - 2\nu)(1 + \nu)}{(1 - \nu)} \] (4)

\[ \nu = \frac{\left( \frac{v_s}{v_p} \right)^2 - 2}{2 \left( \frac{v_s}{v_p} \right)^2 - 1} \] (5)

Where \( \rho \) is the bulk density of the soil (kg/m\(^3\)), \( v_p \) is the P-wave velocity (m/s) and \( v_s \) is the S-wave velocity (m/s) [15,16,17]. \( G_{\text{max}} \) can be obtained from measurements of \( v_s \) and bulk density using equation 2 [17]. Geo-materials have values of Poisson’s ratio in the range of 0.05 for very hard rocks and nearly 0.5 for saturated unconsolidated clays [18]. According to the theory of elasticity, Young’s modulus, \( E \), and constrained modulus, \( M_{\text{max}} \), are related to shear modulus, \( G_{\text{max}} \), by:

\[ G_{\text{max}} = \frac{E}{2(1 + \nu)} \] (6)

\[ G_{\text{max}} = \frac{M_{\text{max}} (1 - 2\nu)}{(1 - \nu)} \] (7)

Where \( \nu \) is the Poisson’s ratio, \( E \) is the Young’s modulus (N/m\(^2\)) and \( M_{\text{max}} \) is the constrained modulus (N/m\(^2\)).

Seismic refraction measuring the travel times of the seismic body waves, the nature and depth of the surface can be computed and later reveal the velocity of soil layers. The velocity of seismic wave that travels through the subsurface varies with material composition and stiffness [19,20]. The layers of soil in p and s wave velocities are determined using intercept-time formula or crossover distance formula as shown in Equation 8 and 9 respectively [18].

\[ Z = \frac{t_i}{2} \frac{v_1 \cdot v_1}{\sqrt{v_2^2 - v_1^2}} \] (8)

\[ Z = \frac{x_c}{2} \frac{v_2 - v_1}{v_2 + v_1} \] (9)

Where \( t_i \) is the intercept time (s), \( Z \) is the depth to refractor two (m), \( x_c \) is the crossover distance (m), \( v_1 \) is the seismic velocity in layer 1 (m/s) and \( v_2 \) is the seismic velocity in layer 2 (m/s).

The aim of this paper is to investigate the P-wave and S-wave velocities obtained from the seismic refraction technique. The location of this study is shown in Figure 3, at Sejagung Sri Medan which is located at the geological boundary between quaternary marine deposit and volcanic rock.
2. Seismic Refraction Method

In this study, the seismic refraction equipment consists of source, detector and recorder. The source of this seismic survey is a sledge hammer weighing 7 kg that is used to strike on an impact plate. The hammer strikes should be in the vertical direction of the steel plate to produce the compressive wave as shown in Figure 4. Meanwhile, the hammer strikes in the horizontal direction to the side of the steel plate to produce horizontal shear wave energy. For detectors, a 24-unit 10 Hz vertical geophone and a 24-unit 14 Hz horizontal geophone were used to detect the compressive wave and the shear wave, respectively. The ABEM Terraloc MK-8 seismograph was used as the recorder for the seismic raw data. For data acquisition, firstly, the compressive wave refraction was recorded followed by shear wave refraction. There were two reels of geophone cables and each reel consisted of 12 geophone connector points. The geophone spacing was set at 3 m and 20 m offset from the first and last geophones. For seismograph settings, the record length used 1 second recording length where the sampling interval was 1000 µs and the number of samples was 1024. Seven shot points were taken at offset and intervals of 1st and 2nd, 6th and 7th, 12th and 13th, 18th and 19th, and 23rd and 24th geophones as shown in Figure 4.

3. Results and Discussions

All result was presented at section 3.1 – 3.3 while the discussion of the results was discussed in section 3.4.
3.1. P-Wave Velocity Soil Profile Result
The first arrival of P wave was selected from the raw seismic data using SeisOptPicker software. Then the data were processed using SeisOpt@2D software to generate a tomography plot along the spread line. The soil profile was divided into several layers depending on the color contrast which showed the difference of its soil velocity. Figure 5 shows that the P-wave velocity soil profile was divided into 4 layers. The layer 1 boundary varied between 5 m and 10 m while the P-wave velocities were in the range of 400 m/s to 1100 m/s. Layer 2 had a boundary between 7 m and 17 m and the velocities were between 1600 m/s and 2200 m/s. Layer 3 boundary was between 11 m and 19 m and the velocities were between 2200 m/s and 3700 m/s. The final layer indicated a velocity higher than 3700 m/s.

![Figure 5. P-wave velocity profile.](image)

3.2. S-Wave Velocity Soil Profile Result
The first arrival of S-wave was selected from the raw seismic data using SeisOptPicker software. Then the data were processed using SeisOpt@2D software. Figure 6 shows the shear wave velocity in horizontal direction (SH-wave) tomography image across the spreadline. The shear wave velocity profile was divided into 4 layers based on its velocity. The layer 1 boundary varied between 4 m and 14 m and the SH-wave velocities were between 190 m/s and 650 m/s. Layer 2 had a boundary between 7 and 20 m and the velocities were between 750 m/s and 1300 m/s. Layer 3 boundary was between 9 m and 19 m and the velocities were between 1500 m/s and 1700 m/s. The final layer indicated a velocity higher than 1700 m/s.

![Figure 6. S-wave velocity profile.](image)

3.3. Borehole Result
The seismic refraction test investigation was conducted at the borehole location in Sejagong, Sri Medan. The borehole indicated that the soil layer consists of silt, sand and gravelly sand and shallow bedrock at 9 m deep. Soil was categorized based on SPT N-value, where the first layer was classified as loose layer up to 6 m deep, followed by a dense layer up to 9 m and a rock core up to 15 m. Figure 7 shows the plot of SPT-N value with depth.
3.4. Discussion

The velocity of shear wave is about half the velocity of compression wave. At a depth of 9 m where the rock head was found, the P- and S-wave velocities were above 3000 m/s and 1500 m/s respectively. The seismic velocities show good agreement with the borehole data. In addition, the velocity of igneous rock reported in Table 1 shows good agreement with the obtained P- and S-wave velocities. Furthermore, the seismic velocity profile was able to provide a visual representation of the rock head across the seismic test spread line. By referring to the geological map in Figure 3, it can be seen that Sejagung is located at the boundary of volcanic formation and quaternary marine clay. Thus, it was expected that the rock head is uneven and drastically changed. The shear modulus, Young’s modulus and Poisson's ratio for each layer can be calculated when the P- and S-wave velocities are obtained. For example, the Poisson's ratios were calculated using the velocity of P- and S-wave in equation 5. The Poisson's ratio of the first layer was between 0.33 and 0.35, between 0.32 to 0.33 for the second layer and between 0.33 to 0.34 for the third layer and final layer. On the other hand, the bulk density of material is required to obtain the shear modulus and Young’s modulus.

4. Conclusion

The soil velocity profiles of P- and S-wave velocities at Sejagung Sri Medan were obtained using Seismic Refraction. The velocity of shear wave is about half the velocity of compression wave. The soil profiles of compressive and shear wave velocities were verified using the borehole data and showed good agreement with the borehole data.

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