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Mean refracted ray path method for reliable downhole seismic data interpretations

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ABSTRACT

The downhole seismic method is one of the most widely used field seismic methods because it is cost-effective and simple to operate compared to other borehole methods. For the interpretation of the data, the direct method is generally used, but this method determines the V_S profile roughly and requires an interpreter's subjective interpretation. To evaluate the V_S profile in detail, the refracted ray path method is used. However, the V_S profiles evaluated by these methods often show meaningless repetitive fluctuations with depth and it is because the estimated travel time data is somewhat inaccurate. In this paper, the mean refracted ray path method (MRM), which combines the advantages of both the direct method and the refracted ray path method, is proposed. It provides the V_S profile more reliably and automatically. The travel time data is corrected based on the refracted ray path and the R^2 value of the regression curve is employed for automation. To verify the proposed method, the synthetic travel time data were generated by forward modeling based on Snell's law with some amount of random error added. As the amount of random error increased, the meaningless repetitive fluctuations in the V_S profile determined by the conventional methods also increased. On the other hand, the V_S profiles determined by the MRM matched the model well and the superiority of the proposed method was thus noted. Finally, the proposed method was applied for the data reduction of several instances of field data. The determined V_S profiles were compared with the drilling logs, the SPT-N values, and/or the CPT result, and the reliability and applicability of the MRM was thus verified.

1. Introduction

Many field seismic methods, such as the crosshole, uphole, downhole seismic methods, suspension PS logging (or full waveform sonic logging) as borehole seismic methods and the Spectral Analysis of Surface Waves (SASW), Multichannel Analysis of Surface Waves (MASW), Harmonic Wavelet Analysis of Waves (HWAW), FK array method, Refraction Microtremor (ReMi) and Spatial Autocorrelation Method (SPAC) as surface wave methods are now generally used to evaluate V_S profiles [1–10]. It is generally known that borehole seismic methods provide better results than surface wave methods, as surface wave methods do not use the shear wave directly and requires an inversion process, thus introducing some uncertainty when seeking a reliable V_S profile. Among borehole seismic methods, the downhole seismic method is very useful for evaluating the in-situ shear wave velocity profile for several reasons. This method requires only one borehole and a simple surface source to perform the test: thus, it is easy to operate in field testing and is relatively cost-effective. The travel times are measured for body waves from the source on the surface to receivers at a series of testing depths in a single borehole. The V_S profile can be obtained directly using a simple interpretation procedure based on a speed equation. The downhole seismic test can be combined with the CPT (cone penetration test) or the DMT (flat dilatometer test) in what are known as the seismic CPT (SCPT) and the seismic DMT (SDMT), respectively [11,12].

For the interpretation, the interval method (IM), the modified interval method (MIM) and the refracted ray path method (RRM) have been used [13–16]. The RRM provides the most reliable V_S profile because the generated wave on the ground surface travels through multi-layered profiles and because the ray path is refracted based on the stiffness difference between the layers [14–16]. However, the V_S profile determined by RRM occasionally shows meaningless repetitive fluctuations. Estimating the arrival point of the shear wave on signal traces is very difficult, and the

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typical soil sites are not ideal stratified systems. Therefore, the obtained travel time data are sometimes inaccurate and result in an erroneous V_S profile. The direct method (DM) has been widely used to determine the V_S profile for the simply structured site and is efficient when the travel time information is erroneous [17,18]. The direct method provides a mean V_S value of each divided layer, whereas other methods determine the V_S value at every testing interval. This method can overcome error related to the travel time measurements, but it determines the V_S profile roughly and requires an interpreter's subjective interpretation.

In this study, the mean refracted ray path method (MRM), which combines the advantages of both the direct method and the refracted ray path method, is proposed. It is similar to the inversion analysis introduced by Mok [19] and Gibbs et al. [20], but the proposed method can provide more detailed V_S profile automatically considering the amount of travel time measurement error. The reliability of the proposed method was verified using synthetic travel time data with forward modeling and numerical simulation involving a downhole seismic test. The V_S profile determined by the proposed method was compared with the results of other conventional methods and the model values. Finally, several field case studies were performed and the applicability and reliability were assessed by comparing the estimated V_S profile with the SPT-N values, the CPT profile, and the drilling logs.

2. Conventional downhole data interpretation methods

Currently, there are two types of downhole data interpretation methods. The first involves determining the general V_S profile by obtaining the mean V_S value of each divided soil layer in a constructed soil model by means of a direct method and an inversion method. The second relies on determining the V_S profile in detail at every testing interval, as in the interval method, modified interval method and refracted ray path method. These methods are briefly reviewed.

2.1. Direct and inversion methods

The direct method is the most widely used downhole seismic interpretation method by site investigation companies in Korea. The first arrival time of an elastic wave from the source to a receiver at different testing depths can be obtained from a field test. The measured travel time (t) in the inclined path can be corrected to the travel time, t_C, in the vertical path using Eq. (1) [15,19].

$$t_C = D\frac{t}{R} \tag{1}$$

here, t_C is the corrected travel time, D is the testing depth from the ground surface, t is the first arrival time from the test and R is the distance between the source and the receiver.

By plotting the corrected travel time versus the depth, the velocity of each layer can be obtained from the slope of the fitting curve using data points which show a similar trend, as shown in Fig. 1. Because the soil model is constructed via the subjectivity of the interpreter, the determined V_S profile can differ depending on the interpreter.

In the inversion method, the interpretation procedure is partially automated for effective soil modeling and the refracted ray path is considered [19,20]. The travel time data are fit in a

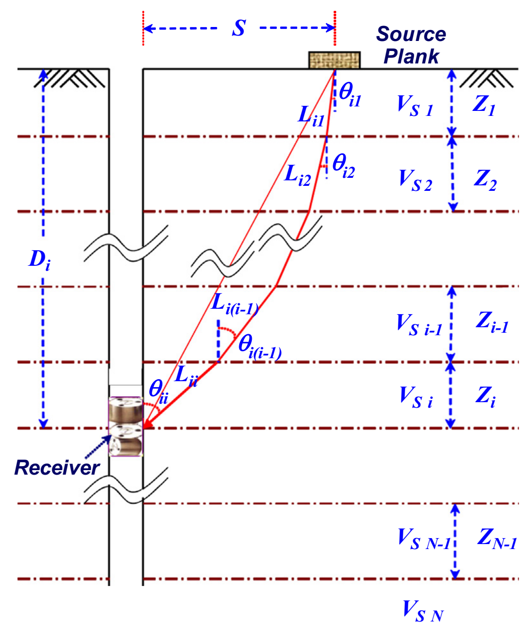

Fig. 2. Schematic diagram of modified interval and refracted ray path methods considering straight and the refracted ray paths respectively [16].

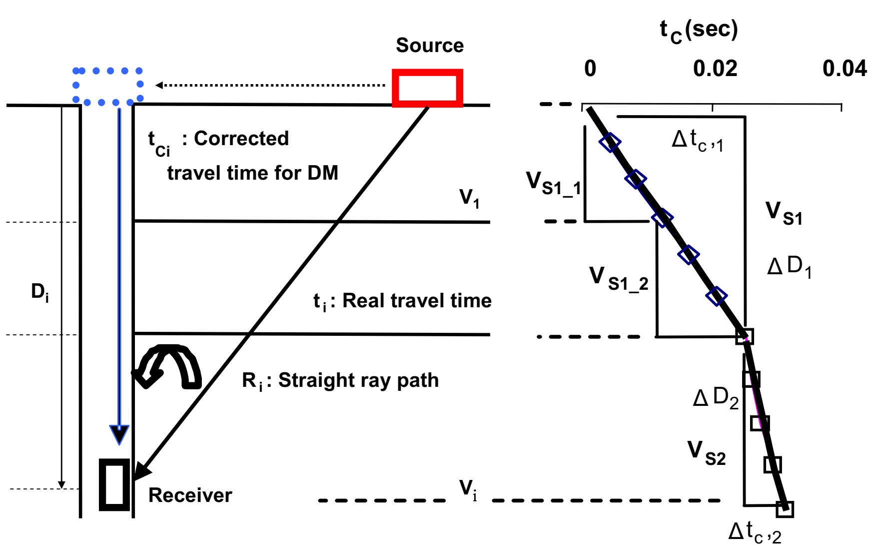

Fig. 1. Schematic diagram of the direct method correcting for the measured travel time considering the straight ray path showing the mean V_S velocity profile according to the slopes of the corrected travel times [16].