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IMPROVEMENT OF DATA INTERPRETATION METHOD FOR DOWNHOLE SEISMIC METHOD

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ABSTRACT

Mean refracted ray path method (MRM) which is combined the advantage of direct method and refracted ray path method is proposed. It can provide reasonable V_S profile automatically considering travel time measurement error. The overall procedure of MRM is similar to the direct method. However, corrected travel time data is based on the result of refracted ray path method for considering refracted ray path and the R^2 value of regression curve is employed for automation. According to the R^2 value, soil model is constructed and V_S value of each layer is evaluated from the slope of regression curve at each divided layer automatically by programmed routine. The reliability and applicability of the proposed method was verified by using numerical and field study.

Keywords: downhole seismic method, interpretation method, shear wave velocity, site investigation

INTRODUCTION

The shear wave velocity (V_S) profile is very important geotechnical parameter in practice. In addition to dynamic problems, the V_S value has also been used for static problems (Stokoe et al., 2004). For these reasons, the demand for obtaining reliable and detailed V_S profile is rapidly increasing in the field of geotechnical engineering. The downhole seismic method is very attractive because this method requires just one bore-hole to perform the test and uses a simple surface source.

Direct method (DM) has been widely used to determine general V_S profile, but this method provides mean V_S value of each roughly divided layer. Recently, the demand for evaluating detailed V_S profile of a site is increasing for geotechnical applications, and interval method (IM), modified interval method (MIM) and refracted ray path method (RRM) have been introduced (Kim et al., 2004). It has been known that the refracted ray path method provides the most reliable V_S profile for downhole seismic test. However, the V_S profile determined by RRM shows some meaningless repetitive fluctuations with depth when some errors are included in the estimated travel time data. Estimating the first arrival point of shear wave on signal traces is very difficult. Therefore, the obtained travel time data are sometimes inaccurate and is forced to determine erroneous V_S profile.

In this study, a new method which combines the advantages of direct method and refracted ray path method is proposed to reduce downhole seismic data more reliably. The proposed method can provide detailed V_S profile automatically considering errors in the travel time measurement. This proposed method was verified by using synthetic travel time data that were generated by forward modeling considering refracted ray path and by adding some errors to simulate the difficulties in travel time measurements. Finite element modeling was also performed to simulate and generate synthetic signals in the downhole test. The V_S profile determined by proposed method was compared with the model

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values together with the results of other conventional data reduction methods. Finally, the proposed method was applied to the data reduction of several field test data and the applicability and reliability were assessed by comparing the estimated V_S profile with SPT-N value, CPT profile, and drilling log.

CONVENTIONAL DOWNHOLE INTERPRETATION METHODS

There are two categories in downhole interpretation methods. One is determining the general V_S profile by obtaining mean V_S value of each divided soil layer in the constructed soil model. The other is determining V_S profile in detail at every testing interval. The former is direct method and inversion method and the latter is interval method, modified interval method and refracted ray path method.

The direct method is most widely used downhole interpretation method in Korea. The first arrival time of an elastic wave from the source to a receiver at each testing depth can be obtained from the field test. The measured travel time (t) in the inclined path can be corrected to the travel time, t_C, in the vertical. By plotting the corrected travel time versus depth, the velocity of each layer can be obtained from the slope of the fitting curve using the data points which have similar trend (Mok, 1987). In interval method, the wave velocity of a layer between two receivers or successive testing depths is obtained by dividing the travel distance difference by the travel time delay (Campanella and Stewart, 1992). In the modified interval method, it is assumed that the site is composed of stacks of horizontal layers divided as each testing interval and the elastic wave (shear wave in this study) propagates its own velocity on each divided layers as shown in Figure 1(a). The passage length of elastic wave on each layer is determined using Eq. 1 and the wave velocity at each testing layer is determined using Eq. 2 (Batsila, 1995).

$$L_{ij} = \frac{R_i}{D_i} \times Z_j \tag{1}$$

$$V_i = \frac{L_{ii}}{T_i - \sum_{j=1}^{i-1} \frac{L_{ij}}{V_j}} \tag{2}$$

where V_i is the wave velocity of i^{th} layer, $D_{i,l}$ is ith testing depth of lower receiver, DT_i is travel time delay between the upper and lower receivers, T_i is travel time at i^{th} testing depth, and L_{ij} is the length of ray-path on j^{th} layer of i^{th} testing at the lower receiver and Z_j is the thickness of j^{th} layer.

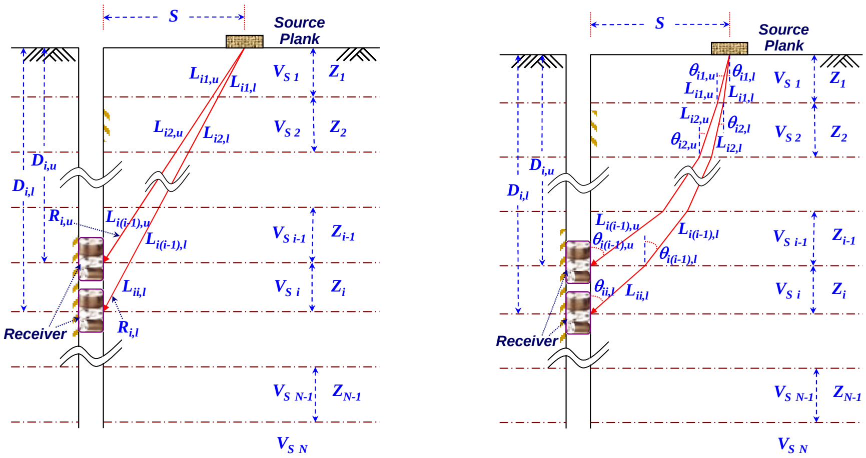


Figure 1 The schematic diagram of (a) modified interval method, (b) refracted ray path method.

In refracted ray path method, it is assumed that the wave propagates along a refracted ray path based on Snell's law as shown in Figure 1(b) and the following relations (Eq. 3 and Eq. 4) should be satisfied. The evaluation process is mainly same as modified interval method but the passage length of each layer is determined by considering refracted ray-path and Eq. 5 is applied instead of Eq. 1. This method requires the iteration process as the velocity of i^th layer should be assumed for determining refracted ray path in using Eq. 3 (Kim et al., 2004).

$$\frac{\sin\theta_{i1}}{V_1} = \frac{\sin\theta_{i2}}{V_2} = \cdots = \frac{\sin\theta_{ij}}{V_j} = \cdots = \frac{\sin\theta_{ii}}{V_i} \tag{3}$$

$$Z_1 \tan\theta_{i1} + \cdots + Z_j \tan\theta_{ij} + \cdots + Z_i \tan\theta_{ii} = S \tag{4}$$

$$L_{ij} = Z_j / \cos\theta_{ij} \tag{5}$$

where ij is incident angle from jth layer to next layer of ith ray path, and S is the distance from the source to the borehole.

COMPARISONS OF V_S PROFILES DETERMINED BY VARIOUS INTERPRETATION METHODS USING TRAVEL TIME DATA WITH ADDED ERRORS

In practice, it is very difficult to estimate the exact first arrival point of shear wave on signal traces and some errors are included. In order to examine this problem properly, comparison study on various downhole interpretation methods was performed on condition of having errors in travel time measurement. The source offset is 3m and the final testing depth is 35m with 1m testing interval. Theoretical travel time data were generated to the 0.01ms unit by forward modeling considering refracted ray path and some travel time errors were added to them. Errors were generated automatically using random function within fixed limitation and different errors could be added to the theoretical travel time at each testing depth. The fixed limitations in this comparison work were ± 0.05ms, ± 0.10ms, ± 0.25ms, ± 0.35ms, ± 0.50ms, and ± 1.00ms.

In case no error is added, the refracted ray path method provides exact V_S value, but it provided meaningless repetitive fluctuation V_S value with depth as increasing the errors. When the added error is higher than ± 0.10ms, it provides dissimilar results to the model as shown in Figure 2(a). From this parametric study, it can be found that we should measure travel time exactly within the maximum error of 0.1ms unit to determine reliable V_S profile when using refracted ray path method. As decreasing testing interval and increasing V_S value, the limiting error will be more rigorous. Direct method has been usefully applied when the condition of acquired signals (signal to noise ratio) is not good and the measured travel time is erroneous. It can adjust the error in travel time measurement by obtaining mean value at the divided interval. However, it is difficult to discriminate layer boundary reliably except the case of V_S value changes abruptly and the V_S profile can be determined by the subjectivity of the interpreter. Then, V_S profiles determined by four interpreters can be different as shown in Figure 2(b). Additionally, direct method overestimated the second layer because it considers just straight ray path.

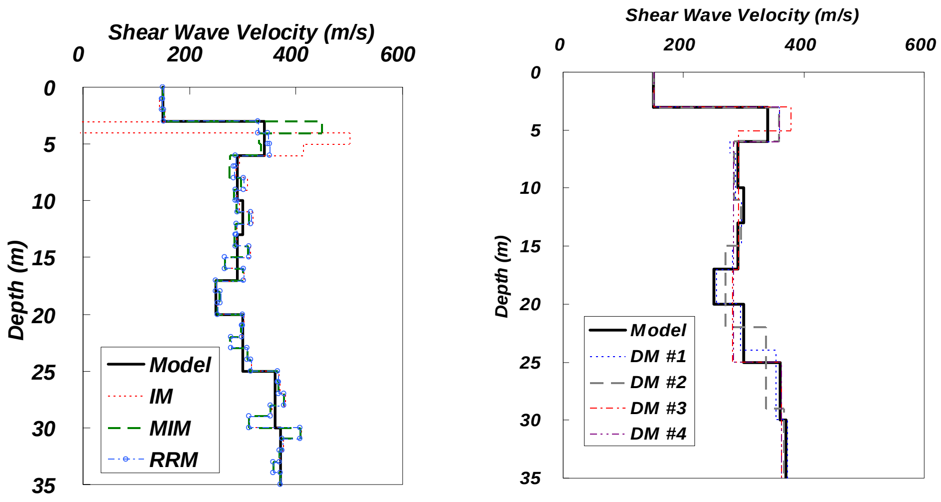
MEAN REFRACTED RAY PATH METHOD

From the comparative study, it was found that there is no perfect interpretation method in the case of added errors in travel time measurement, and it is also very difficult to monitor the travel time without error in the field. However, the suitable modeling of V_S profile is interpreter's duty even though the data to interpret is somewhat problematic. In this paper, mean refracted ray path method (MRM) is proposed to obtain reliable and effective V_S profiling in downhole seismic test. This method combines the advantages of direct method and refracted ray path method and it can provide V_S profile automatically considering errors in travel time measurement.

The overall procedure of propose method is similar to the direct method. After correcting measured travel time data for source offset, the soil layer is divided and V_S value of each layer is calculated. When correcting source offset effect, proposed method uses the result of the refracted ray path method instead of using simple correction as in direct method. Corrected travel time of i^{th} layer, t_{ci} , is represented as Eq. 6. Refracted ray path method provides V_S value at each testing interval considering refracted ray path. Procedure of correcting travel time using Eq. 6 is more reliable than that of direct method which considers just straight ray path.

$$t_{ci} = \frac{Z_1}{V_1} + \frac{Z_2}{V_2} + \cdots + \frac{Z_i}{V_i} \tag{6}$$

Where V_i is wave velocity of i^{th} layer determined by refracted ray path method, Z_i is the thickness of ith layer or testing interval.

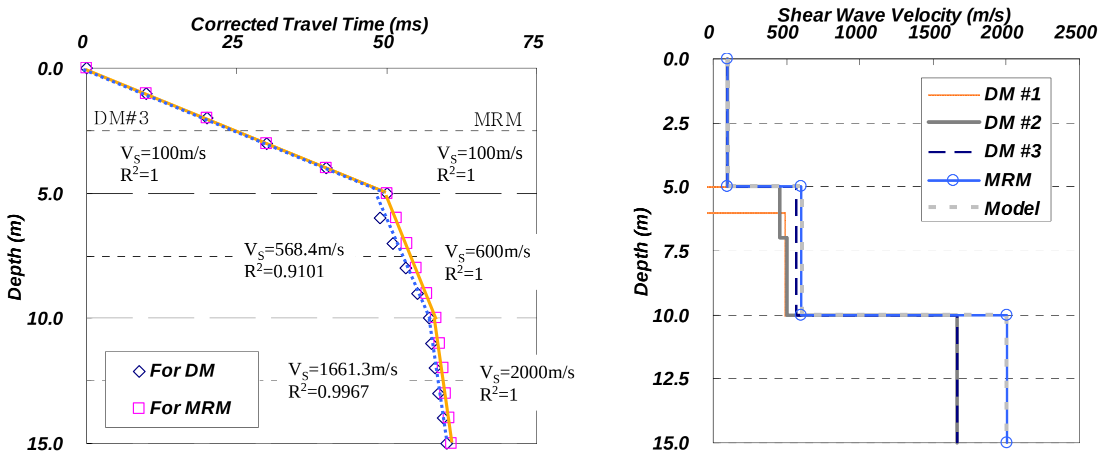


(a) (b)

Figure 2 Comparing V_S profiles using synthetic travel times added maximum 0.25ms errors determined by: (a) interval method, modified interval method and refracted ray path method, (b) direct method.

Figure 3 shows the comparison of corrected travel times calculated by direct and proposed methods and determined V_S profiles were also included. The model used for this comparison work is three-layered model whose layer thickness is 5m and velocity of each layer is 100m/s, 600m/s and 2000m/s, respectively. Source offset is 3m and testing interval is 1m. The theoretical travel time is calculated by forward modeling based on Snell's law. The wave velocity of each layer is determined by fitting process of series of travel time data which has similar slant. Calculated V_S value at each layer is inserted with related R^2 value if layer boundaries are equally divided with the model in Figure 3(a). The R^2 value means the similarity of grouped data. The written in the left is for the direct method and the written in the right is for the proposed method. In these methods, it is very important that corrected travel times with depth show same slant in a layer for the reliable data interpretation.

In the first layer, the corrected travel time data and calculated V_S value are all coincident in both direct and proposed methods because there is only one homogeneous layer from source to receivers. In the second layer, the corrected travel times for direct method show somewhat different trend even having same velocity in a layer and this makes it difficult to divide layer boundary exactly as shown in Figure 3(b). Though the boundary of layer is divided exactly, the R^2 value is very small as 0.9101 and calculated V_S is 568.5m/s (DM #3). In the third layer, the trend of corrected travel times for direct method are similar and related R^2 value is 0.9967, but the calculated V_S value of the third layer is 1661.3m/s which is much smaller than the model value. This problem is caused by considering just straight ray path. On the other hand, the corrected travel times for mean refracted ray path method show exactly same slant in each layer as related R^2 value is one and the calculated V_S values are coincident with the model values. This model study shows the superiority of source offset correction process in this proposed method.



(a) (b)

Figure 3 Comparison of the direct method (DM) and the proposed method (MRM) using synthetic travel time: (a) corrected travel time and calculated V_S value including related R^2 value in each layer, (b) The determined V_S profiles.

It is desirable that interpretation method is automated for excluding interpreter's subjection. In the proposed method, automatic data grouping procedure using R^2 value of regression curve is employed. According to the R^2 value, boundaries of layer are determined and V_S value of each layer is evaluated from the slope of regression curve at each divided layer automatically by programmed routine. In the case of the model in Figure 3, the model is divided three layers with R^2 value of one and V_S value of each layer is calculated automatically. In the case of some errors are added to the travel time data, if R^2 value for layer division is set to one, the model will be divided more than three layers and V_S values will be calculated with some errors. In order to divide model as three layers and calculate corresponding V_S value considering added error automatically for obtaining the most similar V_S profile to the model, R^2 value should be below one. Namely, according to the specified R^2 value, the V_S profile can be evaluated considering errors in the travel time measurements in the proposed method. All of the proposed procedures were programmed by MATLAB, and input values are measured travel time data from field test and the specified R^2 value. This automation scheme is not adequate for the direct method because the corrected travel times include the wrong correction effect for source offset using straight ray path as discussed in Figure 3. If the specified R^2 value is near 1, the detailed V_S profile will be determined because the data will be grouped only whose slants are very similar. But correction effect of errors in travel time measurement will be not prominent. On other hand, if the specified R^2 value is far below 1, the correction effect is prominent, but the determined V_S profile will be rough. Therefore, the R^2 value should be specified according to the accuracy of measured travel time data and the need for subdivision.

As increasing V_S value and the added travel time error, the R^2 value for recognizing the travel time data as one layer becomes smaller. In Table 1, the recommended R^2 values are tabulated according to the V_S value and added error in the case of testing interval of 1m. The R^2 values in Table 1 were calculated though the parametric study using synthetic travel time including errors. Usually, accuracy of travel time measurement is high at the shallow depth because the V_S value of soil is generally small and S/N ratio is high. As the testing depth increases, the V_S value of soil will be larger and S/N ratio becomes lower. Therefore, the R^2 value which is reference value for dividing soil layers needs to be specified differently at the upper and lower layers of the profile.

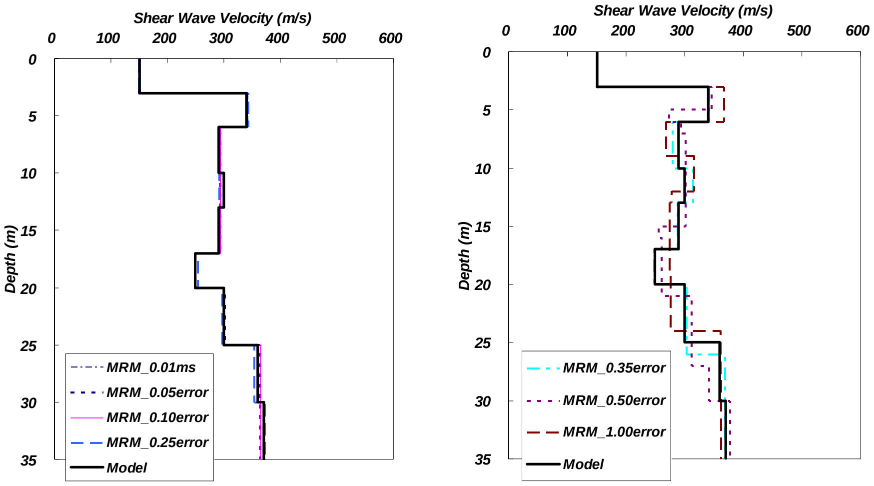
Table 1 The R^2 value according to the model V_S value and magnitude of travel time measurement error (testing interval is 1m).

model Vs value	limitation of added travel time measurement error (ms)				
	±0.01	±0.10	±0.25	±0.50	±1.00
200	0.99999	0.99998	0.99991	0.99982	0.99940
400	0.99999	0.99990	0.99964	0.99756	0.99270
600	0.99999	0.99986	0.99857	0.99348	0.98810
800	0.99999	0.99978	0.99836	0.98930	0.98490
1000	0.99999	0.99959	0.99385	0.97610	0.96050

* R^2 Values were calculated though parametric study using synthetic travel time including travel time measurement error.

VERIFICATION OF MEAN REFRACTED RAY PATH METHOD

Synthetic travel time data discussed previously in Figure 2 were used for the verification of proposed method and coded program. Figure 4 shows the V_S profiles determined by mean refracted ray path method. The input R^2 values were specified by referring to the Table 1. In case of using exact travel time, the determined V_S profile is coincident with the model. In the case of added errors lower than ± 0.25ms, the result is nearly coincident with the model. By comparing with the results determined by conventional methods shown in Figure 2, it is clearly noticed that proposed method is far superior to the conventional methods. Proposed method is designed to obtain reliable V_S profile by considering errors in travel time measurement adequately. However, it cannot be distinguished when the variations of V_S value in the model is too small to be corrected. Also, in case the added error is above ± 0.35ms, the layer boundaries and V_S value of each layer are not adequately determined compared to the model as shown in Figure 4(b), because the proposed method cannot overcome big errors in travel time measurements. However, it can be mentioned that the result determined by proposed method is more reliable compared to the result determined by conventional reflected ray path method which provides meaningless fluctuation of V_S values when error is included.



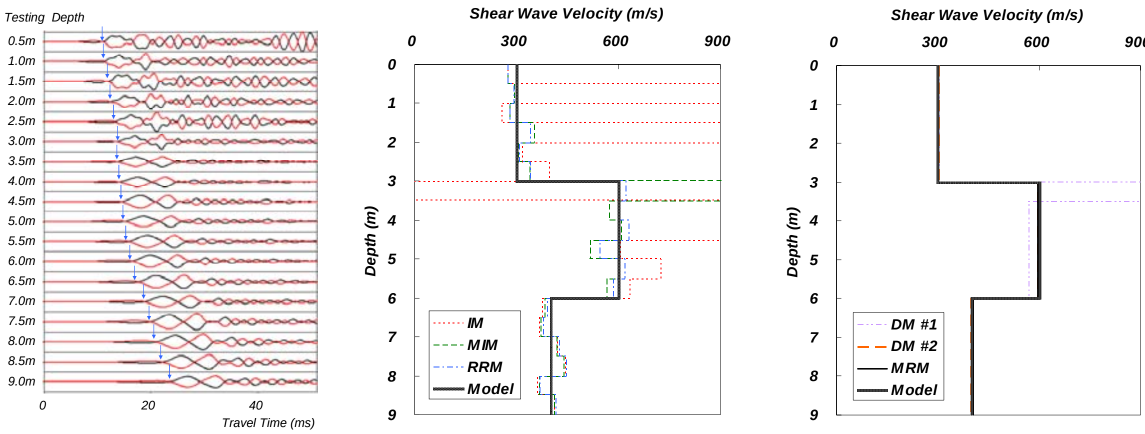
(a) (b)

Figure 4 The V_S profiles determined by proposed method using various synthetic travel times: (a) the case of added error is relatively small (± 0.05ms, ± 0.10ms, and ± 0.25ms), (b) the case of added error is relatively large (± 0.35ms, ± 0.50ms, and ± 1.00ms).

NUMERICAL SIMULATION OF DOWNHOLE SEISMIC METHOD

To understand the effect of errors in field travel time measurement and to verify the applicability of the proposed method, a numerical modeling of downhole seismic test was performed using the finite element method (FEM). The three-layered model that has different V_S values at each layer was designed. The size of model is 3m*5m*10m (W*L*H). An eight-node element (C3D8) with an infinite element (CIN3D8) was implemented. The form of each element is cubic and the size of each side is 0.2m. The interval of testing depth is 0.5m and source offset is 3m. The calculation step and record length were determined as 0.02msec and 50msec, respectively.

From this numerical simulation, right and left striking signal were acquired with depth as shown in Figure 5(a) and the estimated first arrival points were indicated by downward arrow. The V_S profiles determined by conventional methods such as interval, modified interval and refracted ray path methods are compared as shown in Figure 5(b). While the result of refracted ray path method have similar trend with the model, the result of interval and modified interval method do not match well with the model. However, the V_S profile determined by refracted ray path method shows the fluctuation in a layer because of the errors in the travel time measurement. Real field data has also the possibility of having more errors in travel time measurement because the signal to noise ratio is generally lower than synthetic waveform from numerical study. Therefore, it is considered that the refracted ray path method can cause some problems in interpretation of downhole data. On other hand, proposed method divides three layers exactly and provides mean V_S value well. The result matched well with the model as shown in Figure 5(c).



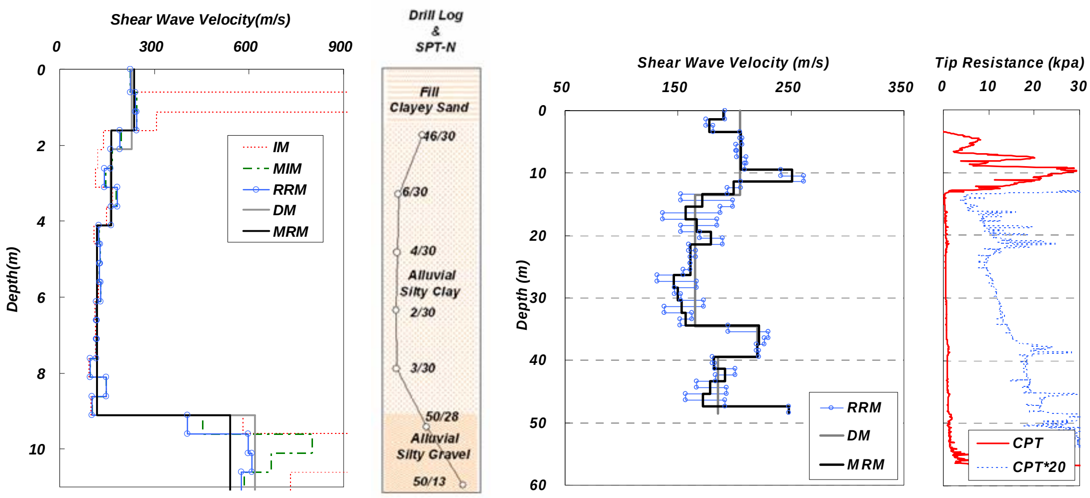
(a) (b) (c)

Figure 5 The V_S profiles determined by various downhole interpretation methods with the model based on the finite element modeling: (a) the synthetic signal traces (b) the results of interval method (IM), modified interval method (MIM) and refracted ray path method (RRM), (c) the results of direct method (DM) and proposed method (MRM).

FIELD CASE STUDIES

Downhole seismic method was performed at river side site in Kyeongju, Korea. Based on SPT N values, the stiffness of soil decreases slowly with depth up to 9.5m and the noticeably stiffness increase occurs at depths of about 8 to 11m as shown in the right side of Figure 6(a). The shear wave velocity profiles determined by various reduction methods are plotted in the left side of Figure 6(a). The refracted ray-path method provided the reliable results following the stiffness trends expected by SPT-N values. To obtain mean V_S profile, direct method and proposed method were applied. Four-layered model was constructed at both methods and the layer boundaries were nearly coincident with the drilling log. However, the calculated V_S values are somewhat different between them because the ray path assumption of each method is different. From this case study, it was found that considering refracted ray path is very important and the mean reflected ray path method has the possibility of providing most reliable results.

To evaluate the consolidation effect on soft clay, downhole seismic method was performed at soft clay site in Jinhae, Korea (Figure 6(b)). The detailed V_S profile was required for evaluating local consolidation condition of soft clay in this site. In the refracted ray path method, meaningless fluctuation was shown and it was caused by travel time measurement error. For correcting this error, the direct method and the mean refracted ray path method were applied. In direct method, the soil model was divided into just four layers and the determined V_S profile is so rough. It was not adequate to evaluate the local consolidation condition of soft clay. In the propose method, the relatively detailed V_S profile can be evaluated. The local consolidation condition of soft clay can be guessed from the obtained V_S profile.



(a) (b)

Figure 6 The results of downhole seismic method: (a) river side site, (b) soft clay site.

CONCLUSIONS

Mean refracted ray path method (MRM) which combines the advantages of direct method and refracted ray path method was proposed. It can provide reliable V_S profile automatically with consideration of travel time error. The travel time data is corrected based on the refracted ray path and the R^2 value of regression curve is employed for automation. When the estimated travel time data was somewhat inaccurate, meaningless repetitive fluctuations were shown in the V_S profile determined by the conventional methods. On the other hand, MRM provided the most reliable V_S profiles. From numerical and field case studies, the reliability and applicability of the proposed method was verified.

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