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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

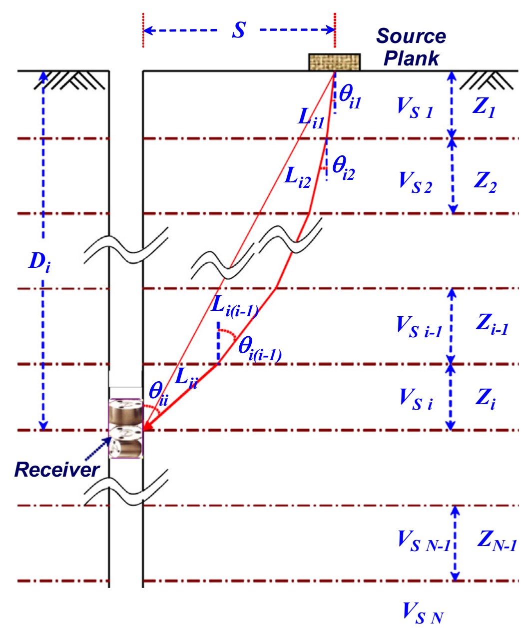


Fig. 2. Schematic diagram of modified interval and refracted ray path methods considering straight and the refracted ray paths respectively [16].

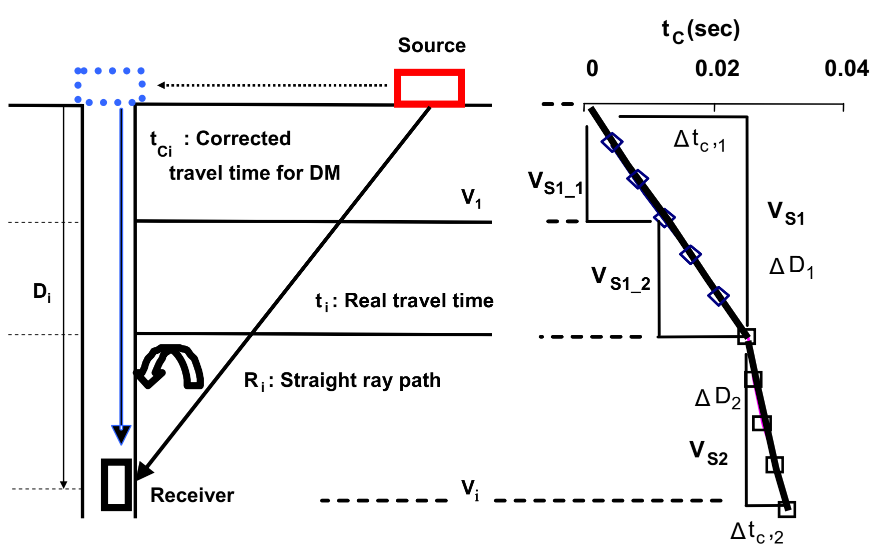


Fig. 1. Schematic diagram of the direct method correcting for the measured travel time considering the straight ray path showing the mean V_S velocity profile according to the slopes of the corrected travel times [16].

least-squares sense by a model made up of constant velocity layers. This method also relies on an iterative process, and this continues until the determined V_S profile is satisfied by the interpreter as compared with available geological and geophysical logs [20]. However, the process of constructing the soil model is still subjective and the determined V_S profiles are very rough. For both direct and inversion methods, it is somewhat difficult to delineate the detailed variation of the soil material with depth. Moreover, the methods do not mesh well in terms of correlation with other soil parameters.

2.2. Interval and modified interval methods

In the interval method, the wave velocity of a layer between two receivers is simply obtained by dividing the travel distance difference by the travel time delay using Eq. (2) [13,16].

$$V_i = (R_i - R_{i-1})/(T_i - T_{i-1}) \tag{2}$$

here, V_i is the wave velocity of the ith layer, R_i is the distance and T_i is the measured travel time from the source to the receiver at the ith testing depth.

In the modified interval method, it is assumed that the site is composed of stacks of horizontal layers divided into each testing interval and that the elastic wave runs at its own velocity within each divided layers [14,16]. The schematic diagram of the modified interval method is shown in Fig. 2a. The passage length of the elastic wave on each layer is determined using Eq. (3) and the wave velocity at each testing layer is determined using Eq. (4). In the interval and modified interval methods, it is assumed that the ray paths from the source to the receiver are straight.

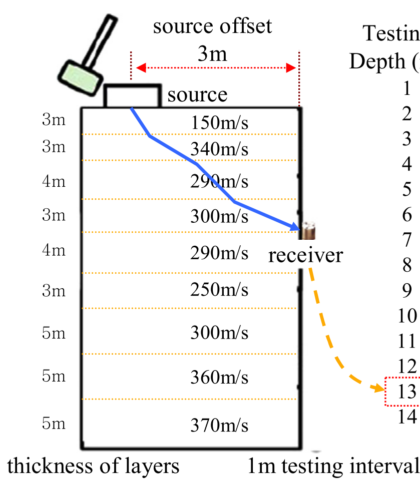
$$L_{ij} = \frac{R_i}{D_i} Z_j \tag{3}$$

$$V_i = \frac{L_{ii}}{T_i - \sum_{j=1}^{i-1} \frac{L_{ij}}{V_j}} \tag{4}$$

In these equations, V_i is the wave velocity of the ith layer, D_i is the ith testing depth, Z_j is the thickness of the jth layer, T_i is the travel time at the ith testing depth, and L_{ij} is the length of the ray-path on the jth layer of the ith test at the lower receiver.

2.3. Refracted ray-path method

In the refracted ray path method, it is assumed that the wave propagates along a refracted ray path based on Snell's law, thus



Testing Depth (m)	Calculated travel times (ms)	Random error within limitations ±0.05ms	±0.25ms	±0.50ms	Final synthetic travel times (ms)		
1	31.62	0.03	-0.02	-0.25	31.65	31.6	31.37
2	36.03	-0.03	-0.05	0.12	36	35.98	36.15
3	42.41	0.01	-0.20	0.23	42.42	42.21	42.64
4	37.07	0.03	0.18	0.42	37.1	37.25	37.49
5	38.40	0.03	0.18	0.10	38.43	38.58	38.5
6	43.04	0.04	0.01	-0.32	43.08	43.05	42.72
7	47.73	0.00	-0.17	0.38	47.73	47.56	48.11
8	52.47	0.00	0.12	0.47	52.47	52.59	52.94
9	57.24	-0.02	0.14	0.05	57.22	57.38	57.29
10	62.05	-0.03	-0.12	0.50	62.02	61.93	62.55
11	66.89	-0.05	-0.03	0.01	66.84	66.86	66.9
12	71.75	-0.04	0.21	0.15	71.71	71.96	71.9
13	73.46	0.02	-0.09	-0.20	73.48	73.37	73.26
14	75.25	0.04	0.06	0.03	75.29	75.31	75.28
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

Fig. 3. The procedure of generating the synthetic travel time including the travel time measurement error. Theoretical travel time was calculated by forward modeling based on the refracted ray path and added random errors.

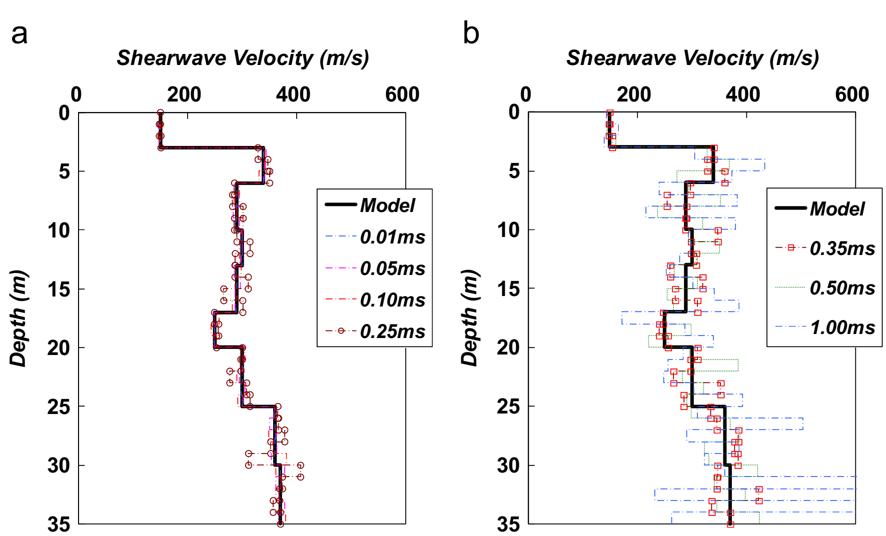


Fig. 4. Comparison of the V_S profiles determined by the refracted ray path method when the travel time measurement error was added. The maximum added error is (a) 0.01 ms (no error added), 0.05 ms, 0.10 ms and 0.25 ms, (b) 0.35 ms, 0.50 ms and 1.00 ms.

the following relationships (Eqs. (5) and (6)) should be satisfied [15,16]. The schematic diagram of the refracted ray path method is shown in Fig. 2b.

$$\frac{\sin\,\theta_{i1}}{V_1}=\frac{\sin\,\theta_{i2}}{V_2}=\cdots=\frac{\sin\,\theta_{ij}}{V_j}=\cdots=\frac{\sin\,\theta_{ii}}{V_i} \tag{5}$$

$$Z_1\,\tan\,\theta_{i1}+\cdots+Z_j\,\tan\,\theta_{ij}+\cdots+Z_i\,\tan\,\theta_{ii}=S \tag{6}$$

$$L_{ij}=Z_j/\,\cos\,\theta_{ij} \tag{7}$$

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

The evaluation process is generally identical to that of the modified interval method but the passage length of each layer is determined based on the refracted ray path, and Eq. (7) is used instead of Eq. (3). This method requires an iteration process because the velocity of the ith layer should be assumed for determining the refracted ray path when using Eq. (4). Under actual conditions, the generated wave on the ground surface travels through multi-layered profiles having different velocities and the ray path becomes refracted based on the stiffness difference between the layers. Thus, the RRM provides the most feasible V_S profile [14–16].

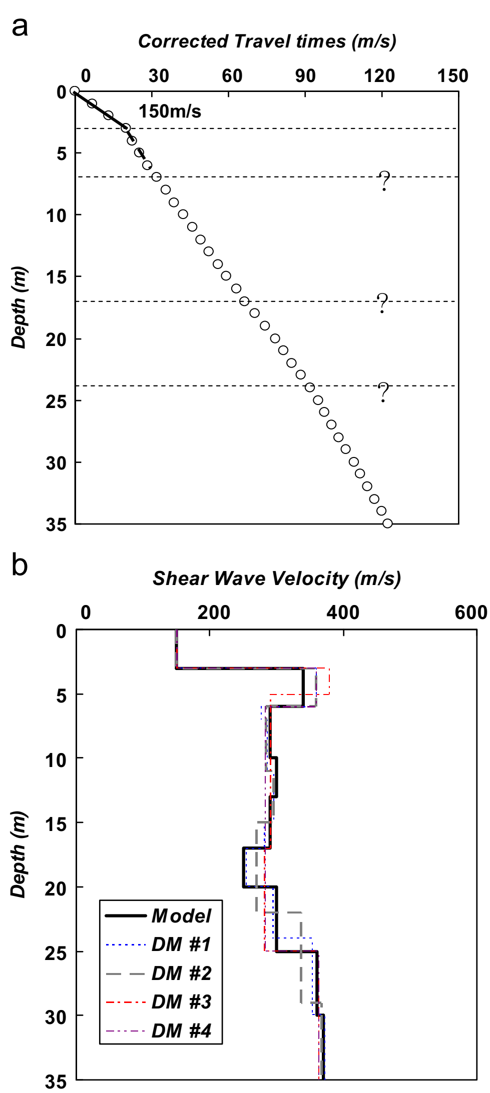


Fig. 5. Examination of the direct method using the synthetic travel times encompassing a maximum error amount of 0.25 ms: (a) the difficulty of dividing the layer boundary exactly, (b) comparing the determined V_S profiles with the model. The V_S profiles produced by four interpreters (DM #1–#4) are different and are not coincident with the model.

3. Comparisons of various interpretation methods using travel time data with measurement errors

In practice, it is very difficult to estimate the exact first arrival point of a shear wave on signal traces and some errors are included in the estimations. In order to examine the field practice conditions properly, a comparison study of various downhole data interpretation methods was performed using travel time data with measurement errors. The soil model and the schematic diagram

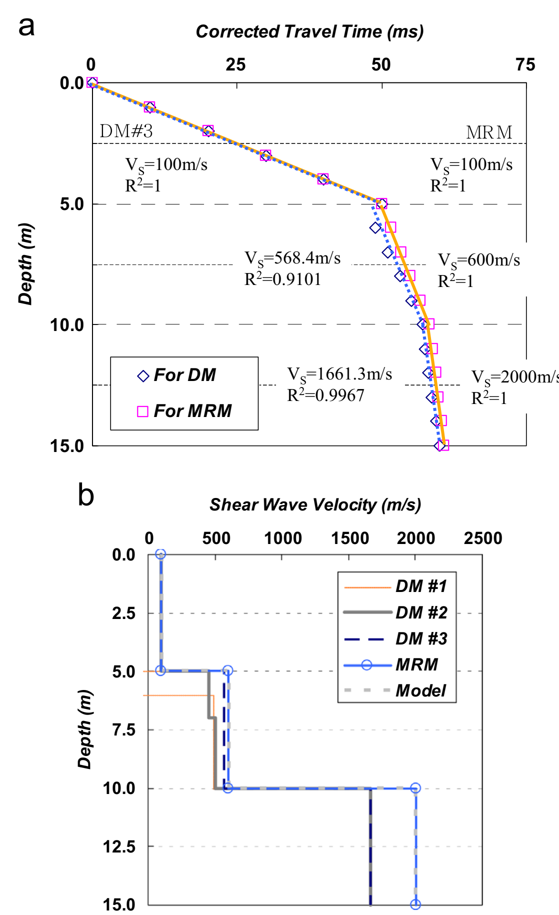


Fig. 6. Comparison of the direct method and the proposed method using the synthetic travel time: (a) the corrected travel time and the calculated V_S value including the related R^2 value and (b) the determined V_S profiles.

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

Model V_S 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 through parametric study using the synthetic travel time including travel time measurement error.

showing the synthetic travel time data are shown in Fig. 3. The source offset is 3 m and the final testing depth is 35 m with a 1 m testing interval. The theoretical travel time data were generated by forward modeling considering the refracted ray path and some measurement errors were added to them. Errors were generated automatically using a random function with a fixed limitation and were added to the theoretical travel time at each testing depth. The fixed limitations in this comparison work were ± 0.05 ms, ± 0.10 ms, ± 0.25 ms, ± 0.35 ms, ± 0.50 ms, and ± 1.00 ms. It was reported that the interval and modified interval method provides erroneous results even when the theoretical travel time data are used [16]. Thus, the interval and modified interval method were excluded in this comparison study.

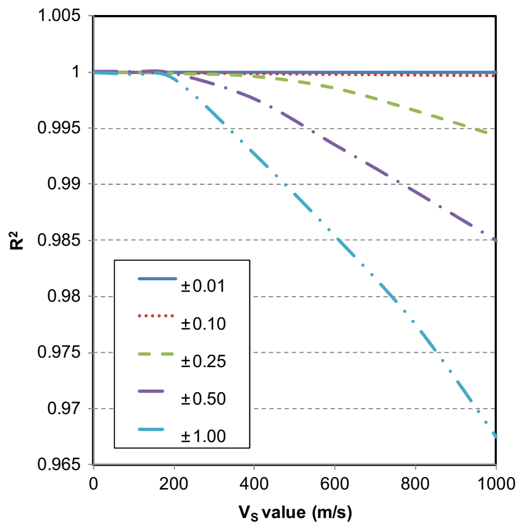


Fig. 7. The recommended R^2 values versus the model V_S values depending on the amount of the travel time measurement error (the testing interval is 1 m).

The V_S profiles determined by the refracted ray path method (RRM) are plotted in Fig. 4 and compared to the model value. When no error is added, the refracted ray path method provides an exact V_S value. As the errors increase, it provided meaningless repetitive fluctuations in the V_S value with depth. When the added errors are less than 0.10 ms, the refracted ray path method provided results similar to those of the model. On the other hand, when the added errors are greater than 0.10 ms, this method provided results that are dissimilar to those by the model.

The direct method has been successfully used when the quality of the acquired signals is poor and when the measured travel time is erroneous. This method allows an adjustment of the error in the travel time measurement through mean values at divided intervals. However, it is difficult to discriminate the layer boundary reliably except when the V_S value changes abruptly and the thickness of the layer is thick enough. The corrected travel time data from the synthetic data with a maximum error of 0.25 ms are plotted in Fig. 5 (a). This figure shows that the division of the soil layer is somewhat difficult except for the boundary between the first and second layer at 3 m. Moreover, V_S profiles determined by four interpreters can be

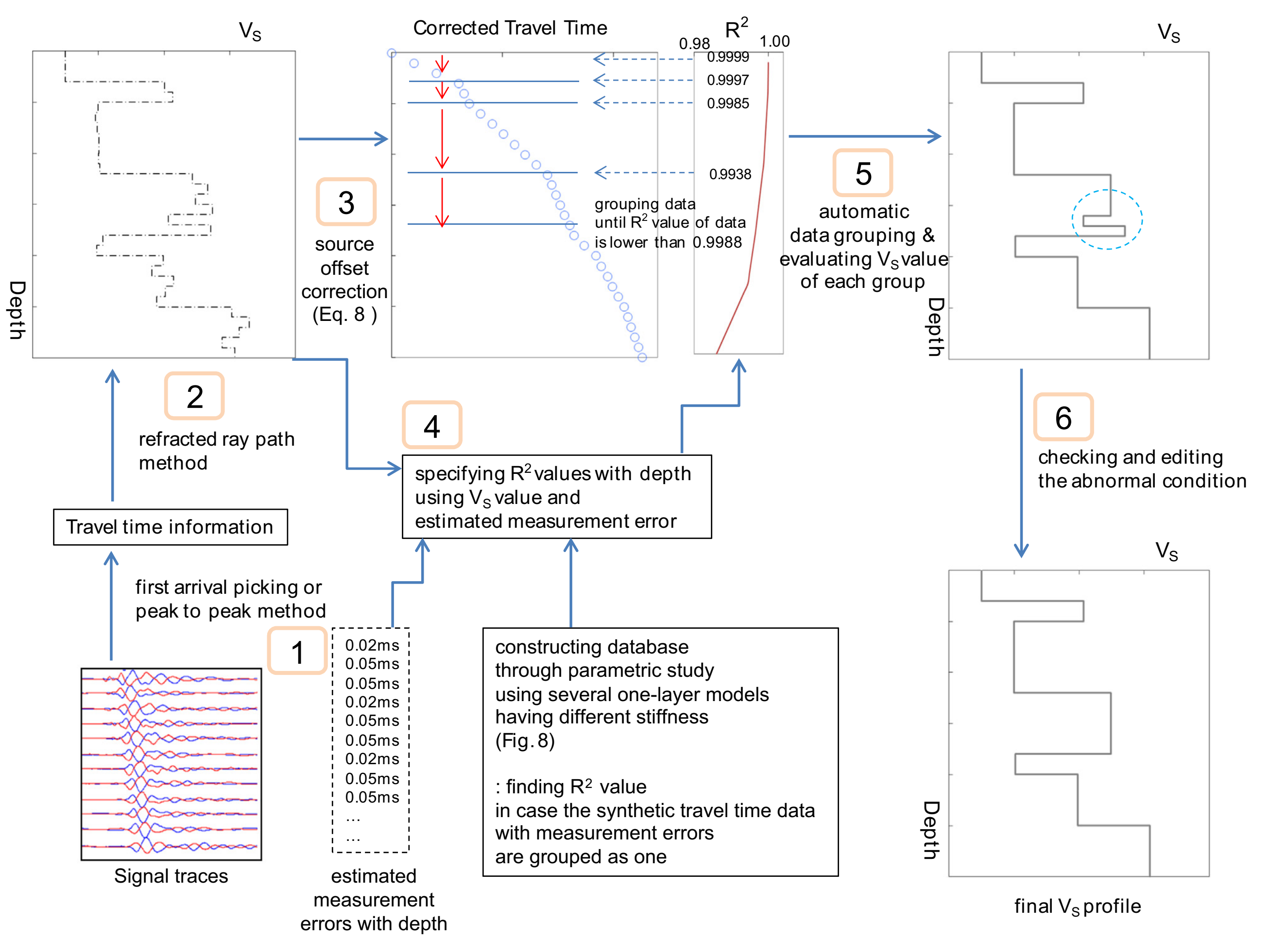


Fig. 8. Schematic diagram of the overall procedure of the mean refracted ray path method.

different, as shown in Fig. 5(b). Additionally, the direct method overestimated the second layer because it considers a straight ray path.

4. Mean refracted ray path method

As shown in the previous comparative study, it is very difficult to accomplish satisfactory data interpretation when some degree of travel time measurement error exists. However, the suitable modeling of the V_S profile is the duty of the interpreter, even when the field data are somewhat problematic. In this paper, the mean refracted ray path method (MRM) is proposed. This method combines the advantages of the direct method and the refracted ray path method. The main features of the proposed method are source offset correction and automatic data grouping.

4.1. Source offset correction

The procedure of the proposed method is similar to that of the direct method. After correcting the measured travel time data for the source offset, the soil layer is divided by the slope of the fitting curve and the V_S value of each layer is calculated. When correcting the source offset effect, the proposed method uses the result of the refracted ray path method instead of simple correction as used in direct method. The corrected travel time of the ith layer, t_{ci}, is represented as Eq. (8). The procedure of correcting the travel time using Eq. (8) is more reliable than that of the direct method which only considers the straight ray path using Eq. (1).

$$t_{ci} = \frac{Z_1}{V_1} + \frac{Z_2}{V_2} + \cdots + \frac{Z_i}{V_i} \tag{8}$$

here, V_i is wave velocity of ith layer determined by refracted ray path method, Z_i is the thickness of ith layer.

Fig. 6 shows a comparison of the corrected travel times as calculated by the direct and proposed methods. The determined V_S profiles are also included. The model used for this comparison work is a three-layer model whose layer thickness is 5 m with the velocity of each layer being 100 m/s, 600 m/s and 2000 m/s. The source offset is 3 m and the testing interval is 1 m. The theoretical travel time is calculated by forward modeling based on Snell's law. The wave velocity of each layer is determined by a fitting process of a series of travel time data with a similar slope. The calculated V_S value at each layer is inserted with related R^2 value in Fig. 6(a) when the layer boundaries are equally divided with the model. The R^2 value denotes the similarity of the grouped data. The left side denotes the direct method and the right side denotes the proposed method. In the first layer, the corrected travel time data and calculated V_S values are all coincident for both the direct and proposed methods because there exists only one homogeneous layer from the source to the receivers. In the second layer, the corrected travel times for the direct method show a somewhat different trend even with the same velocity in a layer. This makes it difficult to divide the layer boundary precisely, as shown in Fig. 6(b). Although the boundary of the layer is divided accurately, the R^2 value shows a poor result, at 0.9101, and the calculated V_S value is 568.5 m/s (DM #3). In the third layer, the related R^2 value for the direct method is as high as 0.9967, but the calculated V_S value is 1661.3 m/s, which is much smaller than the model value. These problems are caused by the straight ray path assumption in the direct method. When the source offset is larger and there is a sharp increase in the stiffness, especially at a shallow depth, this problem becomes more severe [16]. On the other hand, the corrected travel times for the mean refracted ray path method provide an identical slope in each layer, as the 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 the source offset correction process in this proposed method.

4.2. Automatic data grouping

It is desirable for data interpretation to be done without interpreter subjectivity. In the proposed method, an automatic data grouping procedure using the R^2 value of the regression curve is employed. According to the given R^2 value, the boundaries of the layer are determined and the V_S value of each layer is evaluated from the slope of the regression curve at each divided layer. Data grouping is conducted from the data near the ground surface. The range of the first layer expands until the calculated R^2 value is less than the specified R^2 value. For example, in Fig. 6 the calculated R^2 value is still 1 until the data to 5 m are grouped. However, if one more instance of data is included in the group, the R^2 value is reduced to 0.9842. When the calculated R^2 value exceeds the specified limit, the boundary of the first layer can be recognized up

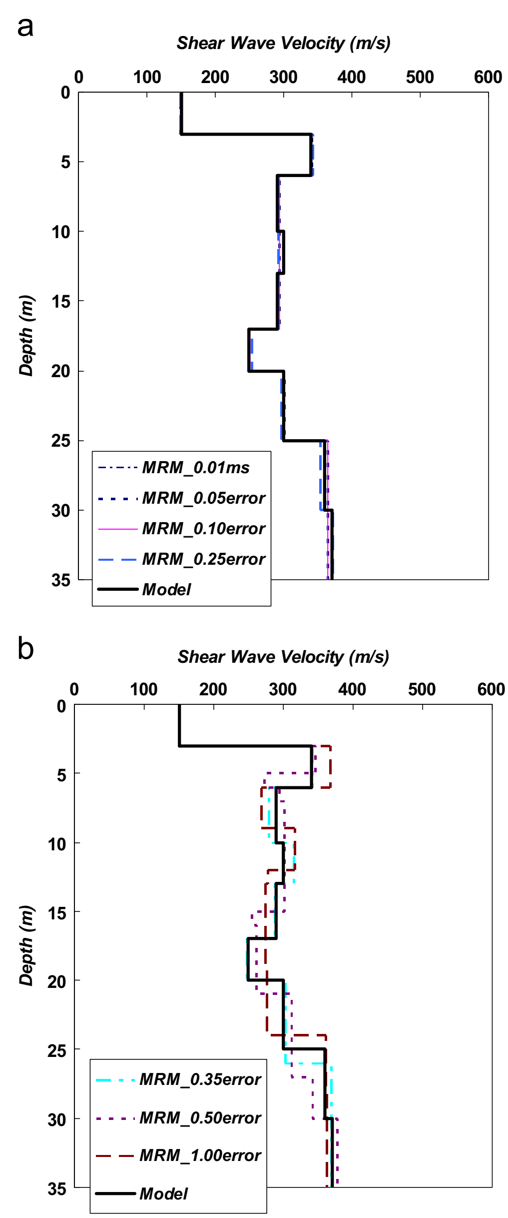


Fig. 9. The V_S profile determined by the proposed method using various synthetic travel times: (a) when the added error is relatively small (± 0.05 ms, ± 0.10 ms, and ± 0.25 ms), (b) when the added error is relatively large (± 0.35 ms, ± 0.50 ms, and ± 1.00 ms).

to previous data. Grouping for the next layer starts from the last data in the previous group, and the layer division procedure continues to the final testing depth. Once the number of layers is determined through this process, readjustment of data grouping near the determined layer boundaries continues until the calculated R^2 value of each group reaches its maximum so as to determine proper layer boundaries. The entire procedure is programmed using MATLAB GUI for automation.

If the specified R^2 value is close to 1, the detailed V_S profile will be determined. However, the correction effort of the error which arises inevitably during the measurement of the travel time cannot be achieved. On the other hand, if the specified R^2 value is much less than 1, the correction effect is prominent but the determined V_S profile will not be detailed. Therefore, the R^2 value should be suitably specified according to the accuracy of the measured travel time data and the necessity for a detailed subdivision. As the V_S values of the site and the travel time errors increases, the R^2 values must become smaller. Therefore, the R^2 value for dividing soil layers needs to be specified differently depending on the testing depth. The recommended R^2 values are tabulated in Table 1 and the fitted graphs are shown in Fig. 7. This database was constructed through a parametric study on several single layer models having different V_S value of 1 m testing interval.

To use this database, the V_S value and the estimated travel time measurement error are required. Estimating the amount of the travel time measurement error is not straightforward while the input V_S value is referred to the result of the mean refracted ray path method. There are several methods to obtain the travel time information from the acquired signal trace such as the shear wave arrival picking method, peak to peak method, cross-correlation method and so on [21]. The peak to peak and cross-correlation methods can determine travel time information objectively. But, the form of the signals, especially arrival part of shear wave, should be consistent to obtain reliable results. After all, the shear wave arrival picking method is used to be the only option for travel time measurement even though it is often unclear to pick a first arrival point exactly. Here, the amount of measurement error can be rated on a scale of 0.01–1.00 ms according to the ambiguity of picking a shear wave arrival point or the quality of signals.

The determined V_S profile can be unsatisfactory due to other errors that may have been missed. Meaningless fluctuation and abnormal V_S values can still exist in the V_S profile. The automatic

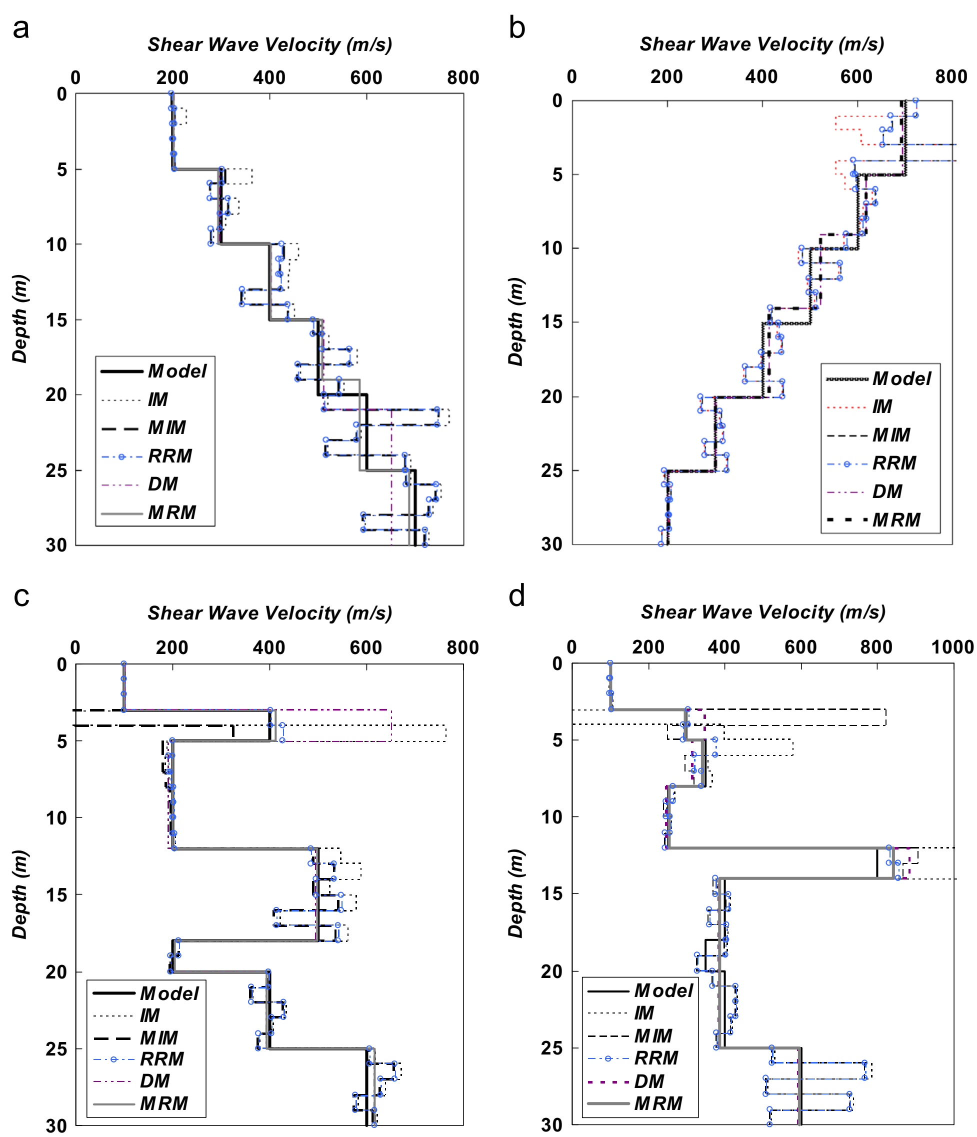


Fig. 10. Verification of the proposed method via a comparison of downhole interpretation methods using synthetic travel times encompassing a maximum error amount of 0.25 ms: (a) the V_S value gradually increases with depth, (b) the V_S value gradually decreases with depth, (c) two stiffer layers in the model, (d) the V_S value varies with depth irregularly.

evaluation does not work well if the measurement error is over 1.0 ms. Thus, a skilful field testing is required to obtain the reliable travel time information above all. If abnormal V_S values exist in the determined V_S profile, the V_S profile can be modified by changing the specified R^2 values and combining layers.

The overall procedure consists of six steps, as follows, and schematized in Fig. 8.

1) Obtaining the travel time data and estimating potential measurement error at each testing depth from the acquired signal traces.
2) Determining the interim V_S profile through the refracted ray path method.
3) Obtaining the corrected travel time data using a new source offset correction procedure (Eq. (8)).
4) Specifying the R^2 values with depth based on the interim V_S profile and the estimated amount of measurement error recommended in Table 1.
5) Dividing the layer boundaries automatically (automatic data grouping) and evaluating V_S value of each divided layer through a linear regression analysis considering the given R^2 value.
6) Checking and editing the abnormal conditions in the determined V_S profile.

5. Verification of the mean refracted ray path method

The synthetic travel time data discussed previously in Fig. 4 were used for the verification of the proposed method in conjunction with a coded program. Fig. 9 shows the V_S profiles determined by the mean refracted ray path method. By comparing the results determined by conventional methods, as shown in Figs. 4 and 5, it is clear that the proposed method is far superior. If the added errors are lower than ± 0.10 ms, the result is nearly coincident with the model. The proposed method cannot overcome large errors in travel time measurements, however it should be noted that the result determined by the proposed method is more reliable compared to the result determined by the conventional refracted ray path method which provides meaningless fluctuations of the V_S values.

Additional verification works were performed using various models. Fig. 10(a) and (b) shows the results of the models whose stiffness increases and decreases with depth gradually. The travel time errors were randomly included throughout the depth with a maximum of ± 0.25 ms. It should be noted that the mean refracted ray path method provides the most reasonable results. Fig. 10(c) and (d) shows the results of irregular soil models. The added errors in the travel time measurement are also within ± 0.25 ms. The results by the conventional methods show meaningless repetitive fluctuations, especially in the higher velocity layers. In the direct method, the results are not coincident with the model at a shallow depth because this method merely considers a straight ray path. On the other hand, the proposed method provides the most reliable results compared to the model.

6. Field case studies

6.1. Case study #1 (riverside site)

The downhole seismic method was undertaken at a riverside site in Kyeongju, Korea. The site consists of a fill layer, alluvial silty clay and silty gravel. Based on the SPT-N values, the stiffness of the soil decreases slightly with depth up to 8 m, past which a noticeable stiffness increase occurs at depths of about 8–11 m, as shown in the right side of Fig. 11(b). The obtained signal trace is illustrated in Fig. 11(a). The shear wave velocity profiles determined by various reduction methods are plotted on the left side of Fig. 11(b). At the layer boundary where the stiffness increases abruptly, the interval method cannot provide the velocity value. Moreover, the modified interval method provides a significantly large velocity value (which cannot be considered as correct). Even under these circumstances, the refracted ray path method provided reliable results following the stiffness trends predicted by the SPT-N values. To obtain a mean V_S profile, the direct method and the proposed method were applied. A four-layer model was assumed at both methods and the layer boundaries were nearly coincident with the drilling log. However, the boundary of the first layer determined by the proposed method matches the drilling log exactly. Moreover, the calculated V_S values are somewhat different between the two sets of results, as the ray path assumption of each method differed. In the fourth layer, the V_S value as determined by the direct method was slightly larger than that of the proposed method. This result is similar to the results of previous comparison studies using synthetic travel times. From this case study, it was found that considering the refracted ray path is very important.

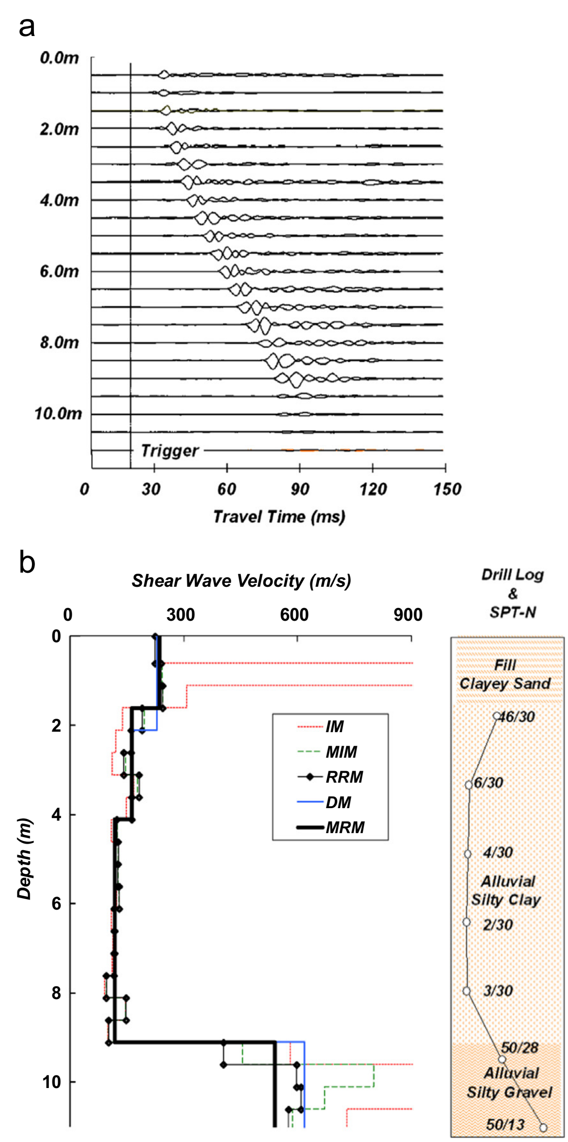


Fig. 11. The results of the downhole seismic method performed at a riverside site: (a) the signal trace acquired from a field test using a borehole receiver system, (b) the left figure shows the V_S profile determined by the proposed method as compared to the results of the conventional method while the right figure shows the drilling log.

In addition, the mean reflected ray path method provided the most reliable results.

6.2. Case study #2 (soft clay site)

To evaluate the degree of consolidation in soft clay, the downhole seismic method was performed at a soft clay site in Jinhae, Korea. The testing interval was 1 m and the source offset was 2.8 m. A good-quality signal was obtained up to the final testing depth of 48.4 m. The obtained signal trace is illustrated in Fig. 12(a). The V_S profiles determined by various data interpretation methods are compared in Fig. 12(b). It was necessary at this site to obtain the detailed V_S profile to evaluate the local consolidation condition of the soft clay. The V_S profile determined by the refracted ray path method showed meaningless fluctuations with depth which were caused by travel time measurement errors. To correct this error, the direct method and the mean refracted ray path method were applied. In the direct method, the soil model was divided into only four layers and the determined V_S profile was very rough. This demonstrates that this method is not adequate for evaluating the local consolidation condition of soft clay. A relatively detailed V_S profile could be evaluated by the proposed method. By comparing the V_S profile to the result of a cone penetration test, it was found

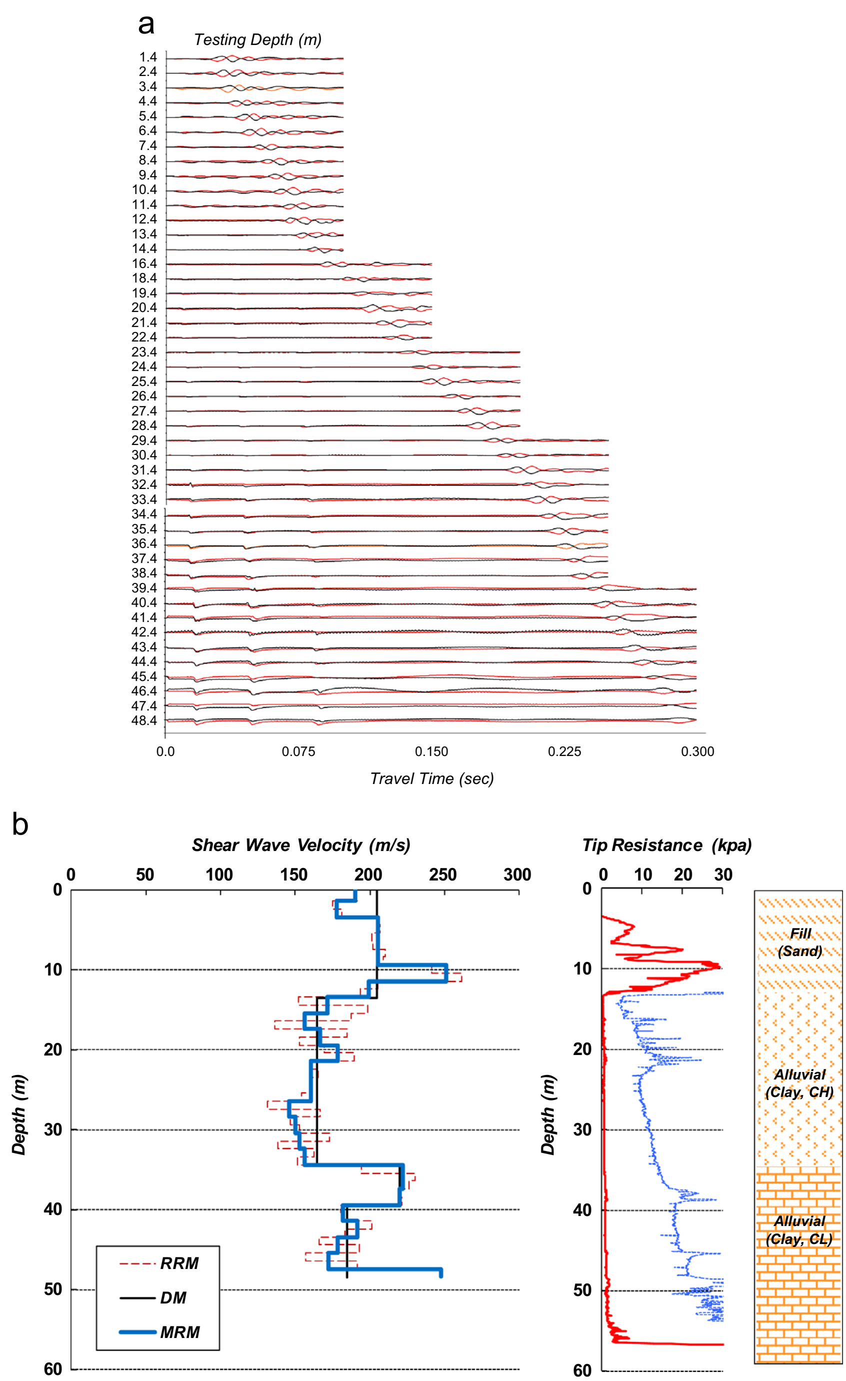


Fig. 12. The results from the downhole seismic method performed at the clay consolidation site: (a) the signal trace acquired from a field test using a penetration-type downhole receiver system, (b) the left graphs are the V_S profile determined by the proposed method and the results of the refracted ray path method and the direct method while the right figures are the result of a cone penetration test and the drilling log (dotted line in the right figure is 20 times multiplied data of original data).

that the proposed method is a very reasonable method for the interpretation of downhole testing data.

7. Conclusions

The downhole seismic method, mainly used to obtain the V_S profile in the field, is simple and cost effective borehole method. For the data interpretation, the direct method (DM) and the refracted ray path method (RRM) are generally used in practice, but the former provides too rough V_S profile with interpreter's subjectivity while the latter sometimes provides a profile with meaningless fluctuations.

In this study, the mean refracted ray path method (MRM) was proposed, which has advantages of both DM and RRM and provides a reliable V_S profile automatically while offsetting the errors in travel time measurement. The two features of the proposed method are as follows: the corrected travel time data is based on the results of RRM and the R^2 value of the regression curve is employed for automation. Various cases of profiles with synthetic travel time data containing measurement errors were used to verify the reliability of the proposed method. As the measurement errors increased, meaningless repetitive fluctuations in the V_S profile as determined by conventional methods also increased. On the other hand, the V_S profiles determined by the proposed method were matched well with the models. Finally, two field studies were performed and the advantages of the proposed methods compared to conventional data interpretation methods were assessed.

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