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Evaluation of Various Downhole Data Reduction Methods for Obtaining Reliable V_S Profiles

ABSTRACT: The downhole method has been widely used to measure in situ shear wave velocity profiles for the seismic response analysis of geotechnical sites. To analyze the downhole data, the direct and interval methods are mostly used in practice. In this study, the modified interval method based on a straight ray path and the inversion method based on Snell's Law ray path were introduced to improve the quality of the wave velocity profiles evaluated by the downhole seismic method. Various synthesized wave velocity profile models were developed to perform the parametric study and the arrival times were determined by a forward modeling scheme based on Snell's Law. By comparing the velocity profiles obtained by four different data reduction methods with actual velocity profiles, the accuracy and limitation of various data reduction methods were assessed. The direct method was difficult for evaluating the detailed velocity profiles, and the interval method was found to provide severe errors, particularly when a stiff layer is located beneath the soft layer. The modified interval method provides reliable results, except when a strong soft-to-stiff contrast exists. Snell's Law ray path method provides the most reliable velocity profiles. Finally, in situ downhole seismic tests were performed at three sites, and the importance of considering the ray path in the data reduction was emphasized by comparing the reduced shear wave velocity profiles with crosshole and standard penetration test results.

KEYWORDS: downhole test, shear wave velocity, data reduction, ray path, Snell's Law, parametric study, in situ testing

Introduction

The downhole method has been widely used to measure in situ compression and shear wave velocity profiles for the seismic response analysis of geotechnical sites. The schematic diagram of the downhole seismic test is shown in Fig. 1. The downhole method measures the travel time for body waves from the source on the surface to receivers at different depths in a single borehole. This method has advantages such as low cost, ease of operation, and the use of a simple surface seismic source. Because a boring is necessary for general site characterization, the downhole seismic test, which needs one borehole, is more economical than the crosshole test that needs another boring. A downhole seismic test can be combined with CPT using a seismic cone (Campanella and Stewart 1992; Joh and Mok 1998; Robertson et al. 1986; Schneider et al. 2001). For a reliable assessment of shear wave velocity profile in the downhole seismic test, two conditions should be satisfied: 1) accurate measurements of travel times of an elastic wave, and 2) a reliable data reduction method considering ray path. The former has been discussed in the literatures (Campanella and Stewart 1992; Larkin and Taylor 1979), and the latter will be the focus of this paper.

For the analysis of downhole seismic data, conventional methods including the direct method, the interval method, and the pseudo-interval method are currently used in practice (Kramer 1996; Martin and Mayne 1997; Stewart and Campanella 1993; Campanella and Stewart 1992). In the downhole seismic test, the generated wave on the ground surface travels through the multilayered profiles and the ray path would be refracted based on the stiffness difference between layers. However, in the conventional data reduction method, the effects of multilayered profiles and refracted characteristics cannot be considered. Even in the soft-to-stiff layer interfaces, the travel time to the bottom receiver is sometimes faster than that to the upper receiver, and the interval method cannot be applied in the data reduction. Due to the lack of a sophisticated and rigorous analysis method for developing velocity profile, the wave velocity profiles determined by the downhole seismic method are generally thought to be inferior to those evaluated by the crosshole method. To improve the quality of the wave velocity profiles evaluated by the downhole seismic method, new data analysis techniques have been developed (Bang 2001; Batsila 1995; Joh and Mok 1998; Mok 1987), including the modified interval method based on straight ray paths and the inversion method based on Snell's Law ray paths. To evaluate the applicability and advantages of new data reduction methods, it would be important to assess the effects of various parameters on the data reduction using synthesized layered profiles, and to compare the evaluated velocity profiles with the profile obtained by reliable field test methods.

In this study, the downhole data reduction methods including the conventional methods, such as direct method and interval method, and the new methods considering ray paths in the analysis, such as the modified interval method and the Snell's Law ray path method, were reviewed. Parametric analyses were performed using various synthesized wave velocity profiles, and the effects of various parameters and the accuracies of various analysis methods were assessed. Finally, the downhole seismic tests were performed at three sites in Kyeongju, Korea and accuracies of various downhole data reduction methods were assessed by comparing the reduced velocity profiles with crosshole and standard penetration test results.

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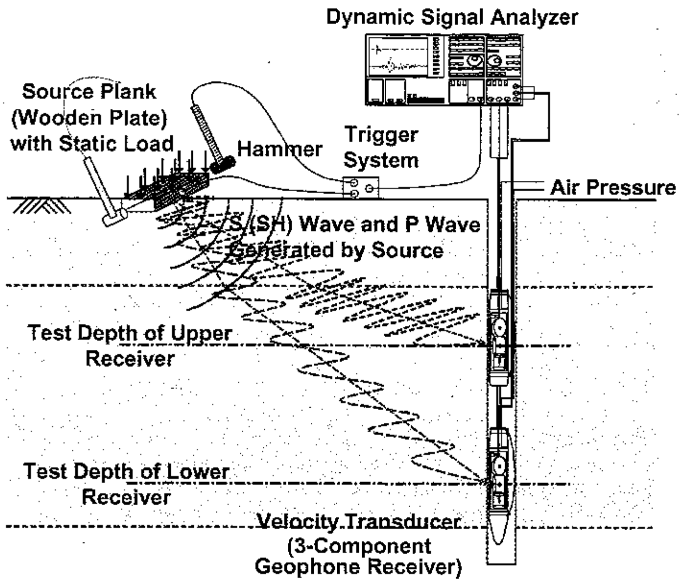

FIG. 1—*Schematic diagram of downhole tests.*

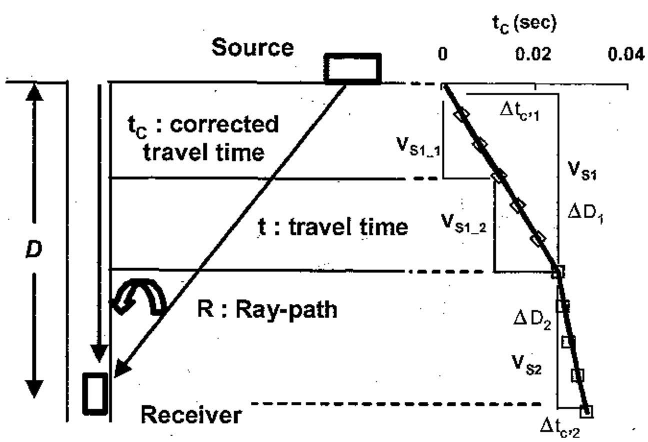

FIG. 2—*Illustration of the Direct Method.*

Interpretation Methods of Downhole Seismic Test Data

For the interpretation of downhole seismic data, the direct and interval methods are usually employed in practice (Kramer 1996; Martin and Mayne 1997; Stewart and Campanella 1993; Campanella and Stewart 1992). The modified interval and Snell's Law ray-path methods, which consider the ray path in the data reduction, have been recently developed (Bang 2001; Batsila 1995; Joh and Mok 1998; Mok 1987). Four interpretation methods of downhole seismic test data are briefly reviewed.

Direct Method

The first arrival time of an elastic wave from the source to a receiver at each testing depth can be obtained from the downhole seismic test. The measured travel time (t) in the inclined path can be corrected to the travel time, t_c, in the vertical path by using Eq 1 as shown in Fig. 2 (Auld 1977; Batsila 1995; Mok 1987).

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

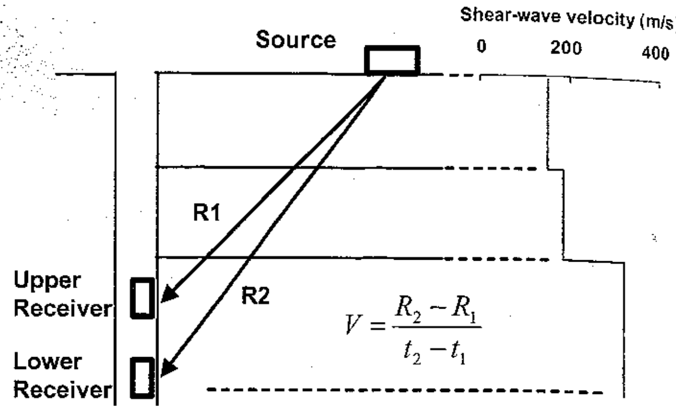

FIG. 3—*Illustration of the Interval Method.*

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

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 that have similar trend by Eq 1. The slope of the fitting curve represents the wave velocity in each covered range. As shown in Fig. 2, the corrected travel times can be fitted by two straight lines, and the velocity profiles of the site can be classified as two layers in an average sense. For the detailed velocity profiling, subdivision of ΔD can be applied, but the potential errors in travel times measurement and data interpretation can be increased.

$$V_d = \frac{\Delta D}{\Delta t_c} \tag{2}$$

where ΔD is depth interval showing similar slope and Δt_c is the corrected travel time difference of ΔD.

Interval Method

The interval travel time between two receivers installed at different depths can be obtained from the downhole seismic test (Fig. 3). The wave velocity of a layer between receivers is obtained using Eq 3 (Batsila 1995; Mok 1987; Sully and Campanella 1995)

$$V = \frac{R_2 - R_1}{t_2 - t_1} \tag{3}$$

where R_1, R_2 are the distances between the source and the upper and lower receiver, and t_1, t_2 are measured travel times at the upper and the lower receiver.

Interval method is simple in testing, measurement, and interpretation. However, this method cannot consider the wave velocities of upper layers along the ray path, and the wave velocity cannot obtain in the case of $t_2 - t_1$ being negative.

Modified Interval Method

The testing procedure and data set are the same as those used in the interval method. 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 layer as shown in Fig. 4 (Bang 2001; Batsila 1995; Joh and Mok 1998). The travel times of waves that pass through each layer from the source to the upper and lower receivers can be represented by Eq 4 and Eq 5. Using

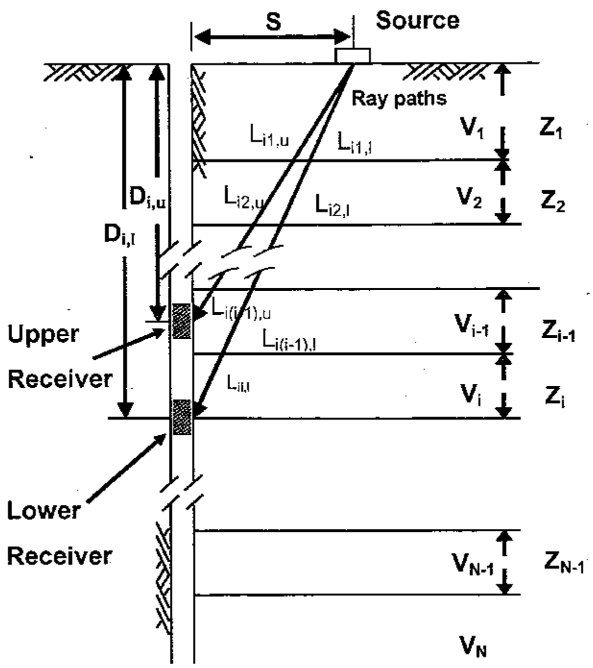

FIG. 4—*Illustration of the modified interval measurement.*

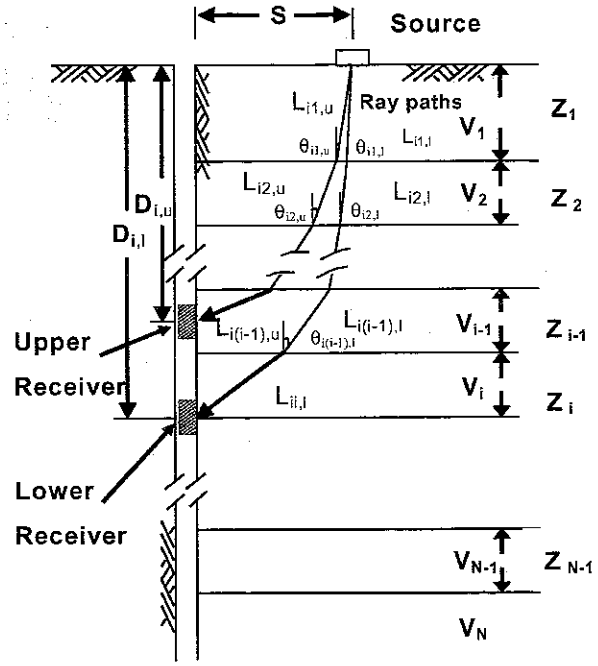

FIG. 5—*Illustration of the Snell's law ray-path method.*

the wave velocities of upper layers and the measured interval travel time between two receivers, the travel time at the lower receiver is obtained using Eq 6. The traveling length of elastic wave on each layer is also determined using Eq 7, according to the thickness of each layer. Based on this information, the wave velocity at each testing layer is determined using Eq 8. This method improves the data reduction scheme compared to the interval method by considering the wave velocities of layers along the path, but there is still limitation because it considers a straight ray-path.

$$T_{i,u} = \sum_{j=1}^{i-1} \frac{L_{ij,u}}{V_j} = \frac{L_{i1,u}}{V_1} + \frac{L_{i2,u}}{V_2} + \cdots\cdots + \frac{L_{i(i-1),u}}{V_{i-1}} \tag{4}$$

$$T_{i,l} = \sum_{j=1}^{i} \frac{L_{ij,l}}{V_j} = \frac{L_{i1,l}}{V_1} + \frac{L_{i2,l}}{V_2} + \cdots\cdots + \frac{L_{ii,l}}{V_i} \tag{5}$$

$$T_{i,l} = DT_i + T_{i,u} \tag{6}$$

$$L_{ij,l} = \frac{R_{i,l}}{D_{i,l}} \times Z_j \tag{7}$$

$$V_i = \frac{L_{ii,l}}{T_{i,l} - \sum_{j=1}^{i-1} \frac{L_{ij,l}}{V_j}} \tag{8}$$

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

Snell's Law Ray-Path Method

This method is similar to the modified interval method. However, it is assumed that the wave propagates along a refracted ray path based on Snell's Law, and the following relations should be satisfied as shown in Fig. 5 (Bang 2001; Batsila 1995).

$$\frac{\sin\theta_{i1}}{V_1} = \frac{\sin\theta_{i2}}{V_2} = \cdots = \frac{\sin\theta_{ij}}{V_j} = \cdots = \frac{\sin\theta_{ii}}{V_i} \tag{9}$$

$$Z_1 \tan\theta_{i1} + \cdots + Z_j \tan\theta_{ij} + \cdots + Z_i \tan\theta_{ii} = S \tag{10}$$

where θ_{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.

The wave velocity of the first layer can be determined in the same manner as the interval method, because the stiffness is assumed constant and the ray-path is straight. But in evaluation of the wave velocity of the second layer, the refracted ray-path should be considered. To determine the refracted ray-path, both the wave velocity of upper layer that is already determined in the previous step and the assumed wave velocity of the evaluating layer are required. The travel times of the seismic wave between source and receiver measured at each testing depth are the same as in the modified interval method. Using Eq 9 and Eq 10, new ray path is determined and the velocity is calculated using Eq 8 considering new ray path. The evaluation process is mainly the same as the modified interval method, but the passage length of each layer is determined by considering refracted ray-path and Eq 11 is applied instead of Eq 7.

$$L_{ij} = Z_j/\cos\theta_{ij} \tag{11}$$

The iteration process is continued until the assumed velocity matches the calculated one within the allowable limit, which is 0.01 % difference between two velocities. Once the velocity of concerning layer is determined, the procedure is continued to the next layer. The value determined by modified interval method is recommended to be an initial assumed velocity of the evaluating layer for better convergence in the iteration process. This method would be the most advanced interpretation method in the downhole data reduction, because it considers the refracted ray path determined by the velocities of upper layers along the path.

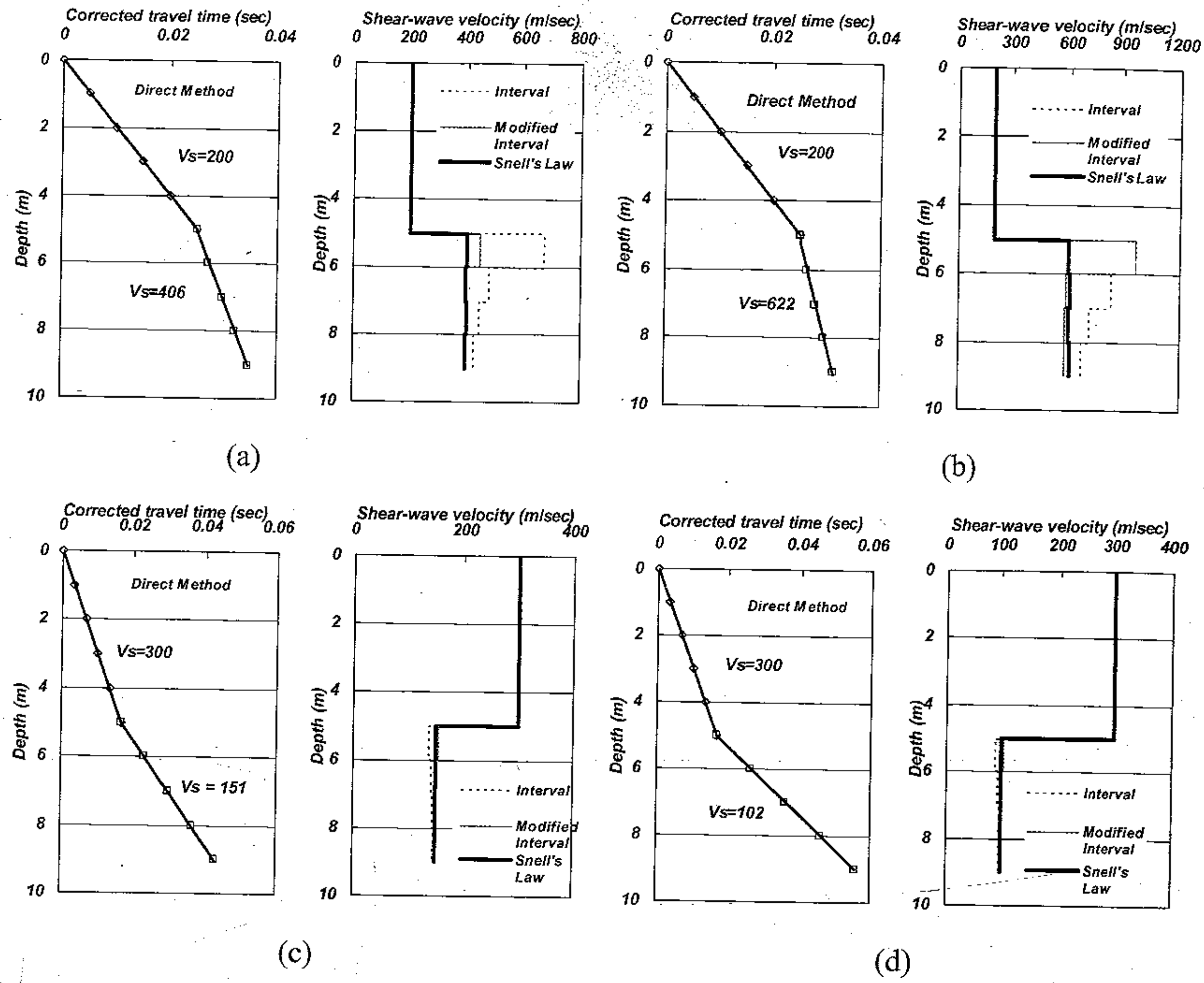

FIG. 6—*Shear-wave velocity profiles in Two Layer Model (3-m source to borehole spacing): (a) Two-layer Model 1-1; (b) Two-layer Model 1-2; (c) Two-layer Model 1-3; and (d) Two-layer Model 1-4.*

Comparisons of Analysis Methods Using Synthesized Profiles

To verify the reliability and limitation of each analysis method, parametric studies with various synthesized profiles were performed. Two, three, and multilayer models were selected and the first travel times from source to receiver were calculated by the forward modeling, which considers the Snell's Law based refracted ray path which satisfies the Eq 9 and Eq 10 based on the given data such as velocities of layers, source to borehole spacing, and testing depth. Based on the travel time information at the selected testing depth of each model, the shear wave velocity profiles were calculated by using four different interpretation methods discussed above. In this parametric study, the travel time information of lower receiver is the same as the upper receiver of next testing depth because the receiver spacing is assumed to be constant and same as the testing interval.

Two-Layer Model

The two-layer model is composed of upper (5-m) and lower (4-m) layers that have different shear wave velocities (V_S). The distance from source to borehole is 3 m, and the testing interval is 1 m. The shear wave velocities in each synthesized model and the calculated first arrival travel times at each testing depth by the forward modeling are shown in Table 1. V_S profiles determined by each analysis method are compared in Fig. 6. The corrected travel time versus depth and wave velocities from fitting curves for the direct method are shown to the left and the V_S profiles determined by interval, modified-interval, and Snell's Law ray-path methods are shown to the right.

Shear wave velocities determined by all of the methods in the first layer are consistent because the ray paths are identical in this uniform layer. In the case where the stiffness or velocity of lower layer is larger than that of upper layer (Fig. 6*a* and *b*), the estimated velocity profiles provide erroneous results compared with real synthesized profiles, except those obtained by the Snell's Law ray-path method. As increasing the stiffness ratio (V_{S2}/V_{S1}), the amount of error increases. Especially, at the depth of 5–6 m in Model 1-2, the interval measurement cannot provide a result because a negative travel time difference ($t_2 - t_1$) is determined (gray block in Table 1), and the modified interval method also causes significant error in that region. On the other hand, in cases where stiffness of upper layer is larger (Fig. 6*c* and *d*), all of the estimated velocity profiles determined by various data reduction methods match reasonably well with the real synthesized profiles.

The reason for difference between the calculated and real velocities in the interval method can be explained by Fig. 7. The shear wave velocity in the second layer is determined by the travel time

TABLE 1—*Shear wave velocities and calculated travel time in Two-Layer Models 1-1 to 1-4.*

		$V_{S1} < V_{S2}$				$V_{S1} > V_{S2}$			
		Model 1-1		Model 1-2		Model 1-3		Model 1-4	
Layer	Depth (m)	V_S (m/s)	Time (ms)	V_S (m/s)	Time (ms)	V_S (m/s)	Time (ms)	V_S (m/s)	Time (ms)
	1		15.81		15.81		10.54		10.54
	2		18.03		18.03		12.02		12.02
1	3	200	21.21	200	21.21	300	14.14	300	14.14
	4		25.00		25.00		16.67		16.67
	5		29.15		29.15		19.44		19.44
	6		30.46		29.10		25.88		29.29
	7		32.35		30.19		32.37		39.16
2	8	400	34.45	600	31.50	150	38.87	100	49.04
	9		36.67		32.93		45.40		58.93

* Source to borehole spacing is 3 m, testing interval is 1 m.

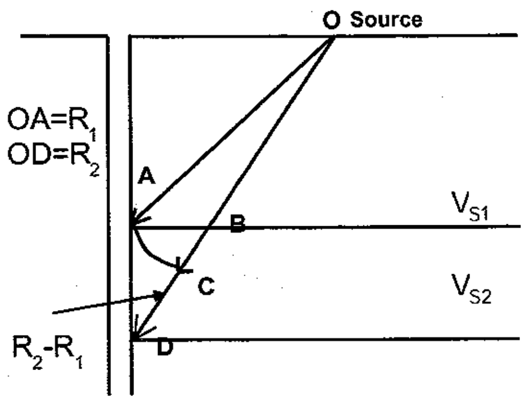

FIG. 7—*Interpretation of Interval Method for the case of a two-layer model.*

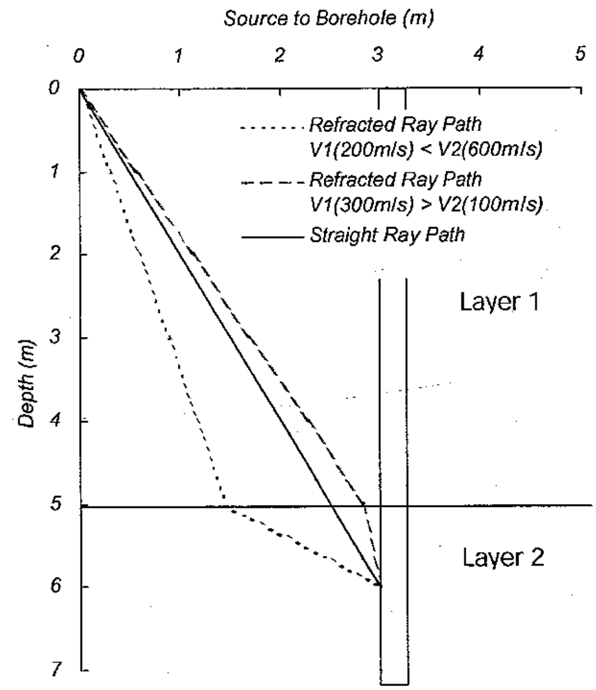

FIG. 8—*Comparison of straight and Snell's Law ray paths for the case of a two-layer model.*

difference $(t_2 - t_1)$ and the path difference $(R_2 - R_1$, the distance $CD)$ by using Eq 3. Even if the lengths of the travel path OA and OC are the same, the travel times from O to A and C are different because the shear wave velocities of first and second layers are different. Therefore, the wave velocities of upper layers along the path are required to consider for better interpretation in the interval method. The reason for difference between the calculation and real velocities in the modified interval method can be explained by the difference between the straight ray path and Snell's Law ray path. As shown in Fig. 8, for the case where the upper layer is stiffer than the lower layer, the difference between the straight ray path and the refracted ray-path is small and this error does not affect the V_S profile significantly. On the contrary, in the case where the lower layer is stiffer than the upper layer, the difference between the straight ray path and the Snell's Law ray-path is large, and this error prohibits from determining the right velocity value.

Effects of Source to Borehole Spacing

To investigate the effect of source-to-borehole spacing, the source-to-borehole spacing in the Model 1-2 was set to 0 m, 1.5 m, 3.0 m, and 4.5 m, and the results are shown in Fig. 9. As decreasing the source-to-borehole distance from 4.5 to 1.5 m (Fig. 9*b* and 9*c*), it can be noticed that the error, which is the difference between the calculated velocity and the real value in the model, is reduced but still some errors exist in both the interval and modified interval methods, particularly at the soft/stiff boundary. In the case of source-to-borehole spacing of 0 m (Fig. 9*a*), all data reduction methods provide the identical shear wave velocity profile same as the real velocity profile of Model 1-2. If the source and the borehole spacing approaches zero, the travel path can be assumed as a straight, and all methods should provide the same wave velocity profile. However, if the downhole source is close to the borehole in actual field tests, the wave may travel not through the soil layer but through the testing casing, and the false arrival time may be detected. Generally, the distance between the source and the borehole in the downhole seismic test is set to be about 2–5 m (Hoar and Stokoe 1978; Hunter et al. 2002), and the ray-path needs to be considered in interpretation of data.

Three-Layer Model

The shear wave velocities and the travel times determined from the forward modeling in the three-layer model are shown in Table 2. The thickness of each layer is 3 m. The distance from source to borehole and the testing interval are the same as those in

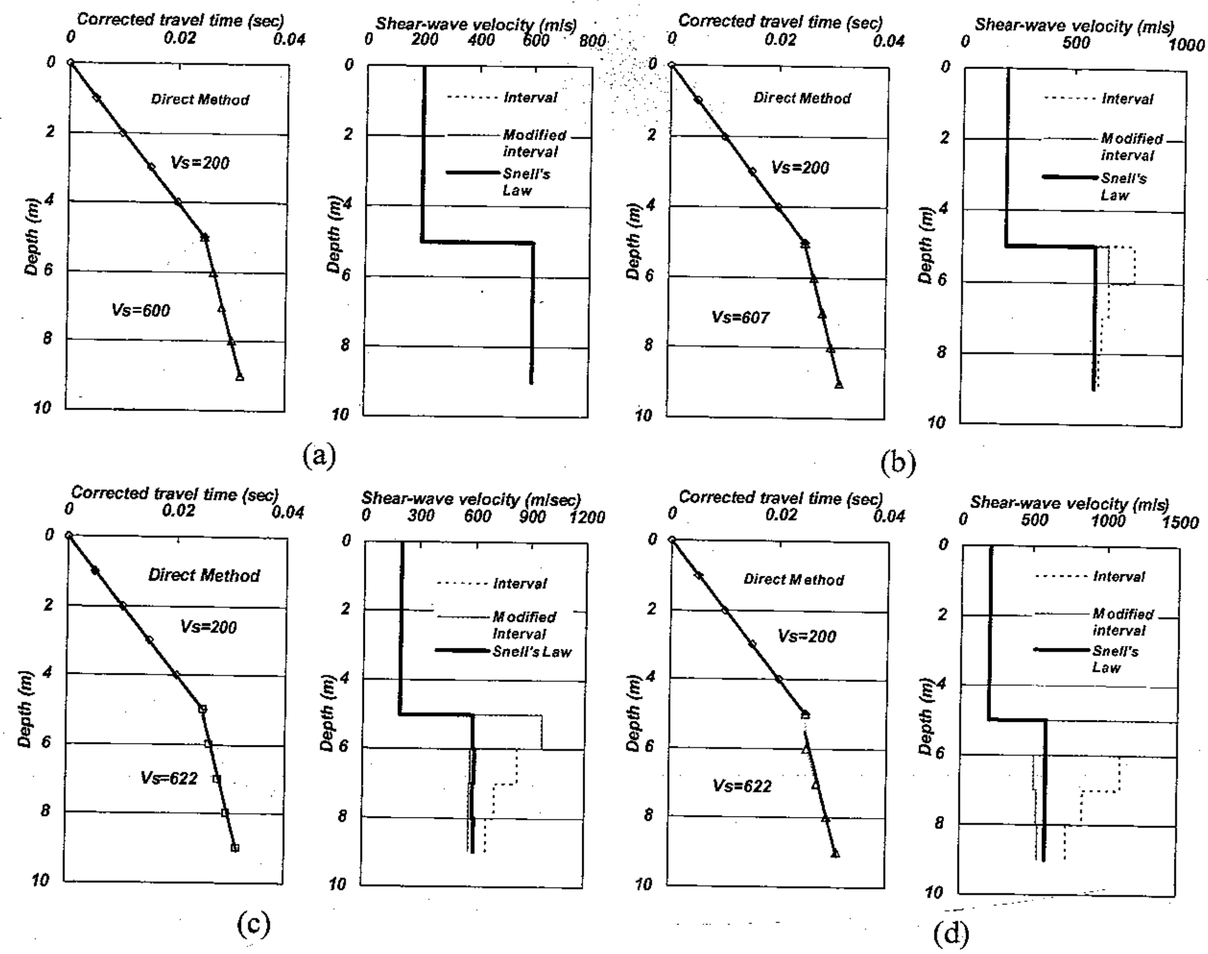

FIG. 9—*Effects of source to borehole spacing (Two-layer Model 1-2): (a) Source to Borehole = 0 m; (b) Source to Borehole = 1.5 m; (c) Source to Borehole = 3.0 m; and (d) Source to Borehole = 4.5 m.*

TABLE 2—*Shear wave velocities and the calculated travel times in Three-Layer Models 2-1 to 2-5.*

		$V_{S1} < V_{S2} < V_{S3}$				$V_{S1} > V_{S2} > V_{S3}$		$V_{S1}, V_{S3} > V_{S2}$		$V_{S1}, V_{S3} < V_{S2}$	
		Model 2-1		Model 2-2		Model 2-3		Model 2-4		Model 2-5	
Layer	Depth (m)	V_S (m/s)	Time (ms)	V_S (m/s)	Time (ms)	V_S (m/s)	Time (ms)	V_S (m/s)	Time (ms)	V_S (m/s)	Time (ms)
	1		10.54		10.54		3.95		15.81		15.81
1	2	300	12.00	300	12.00	800	4.50	200	18.03	200	18.03
	3		14.13		14.13		21.21		21.21		21.21
	4		14.76		13.33		20.27		30.61		20.27
2	5	500	16.14	800	14.06	500	21.46	100	40.08	500	21.46
	6		17.74		14.99		22.96		49.63		22.96
	7		18.56		15.33		26.09		51.84		26.09
3	8	800	19.57	1200	15.87	300	29.25	300	54.51	300	29.25
	9		20.65		16.46		32.44		57.40		32.44

the two-layer model. Models 2-1 to 2-3 show the cases for stiffness of layers increasing or decreasing gradually with depth, and V_S profiles determined by different analysis methods are compared in Fig. 10*a*–10*c*. Models 2-4 and 2-5 show that the cases for stiffness of the middle sandwiched layers vary differently from the general trend, and the V_S profiles are compared in Fig. 10*d* and 10*e*.

The similar trends as in the two-layer models are shown in the three-layer models. Significant errors are still produced in the results of the interval method in all cases. In the Model 2-1 (Fig. 10*a*) that is the case, the stiffness of layers increase gradually with depth and the error of third layer is smaller than that of second layer. This is because the difference between the straight ray path and the refracted ray-path is getting smaller with increasing the depth. However, in the Model 2-2 (Fig. 10b), which is the case where the stiffness ratio is larger than Model 2-1, the error is still significant and the interval method cannot provide the result at the boundary between the first and second layer. In the Model 2-3 (Fig. 10c) where the stiffness (V_S) decreases gradually with depth, the error is small as shown in the two layer models. In natural soil deposits, the stiffness usually increases with depth, and there is a

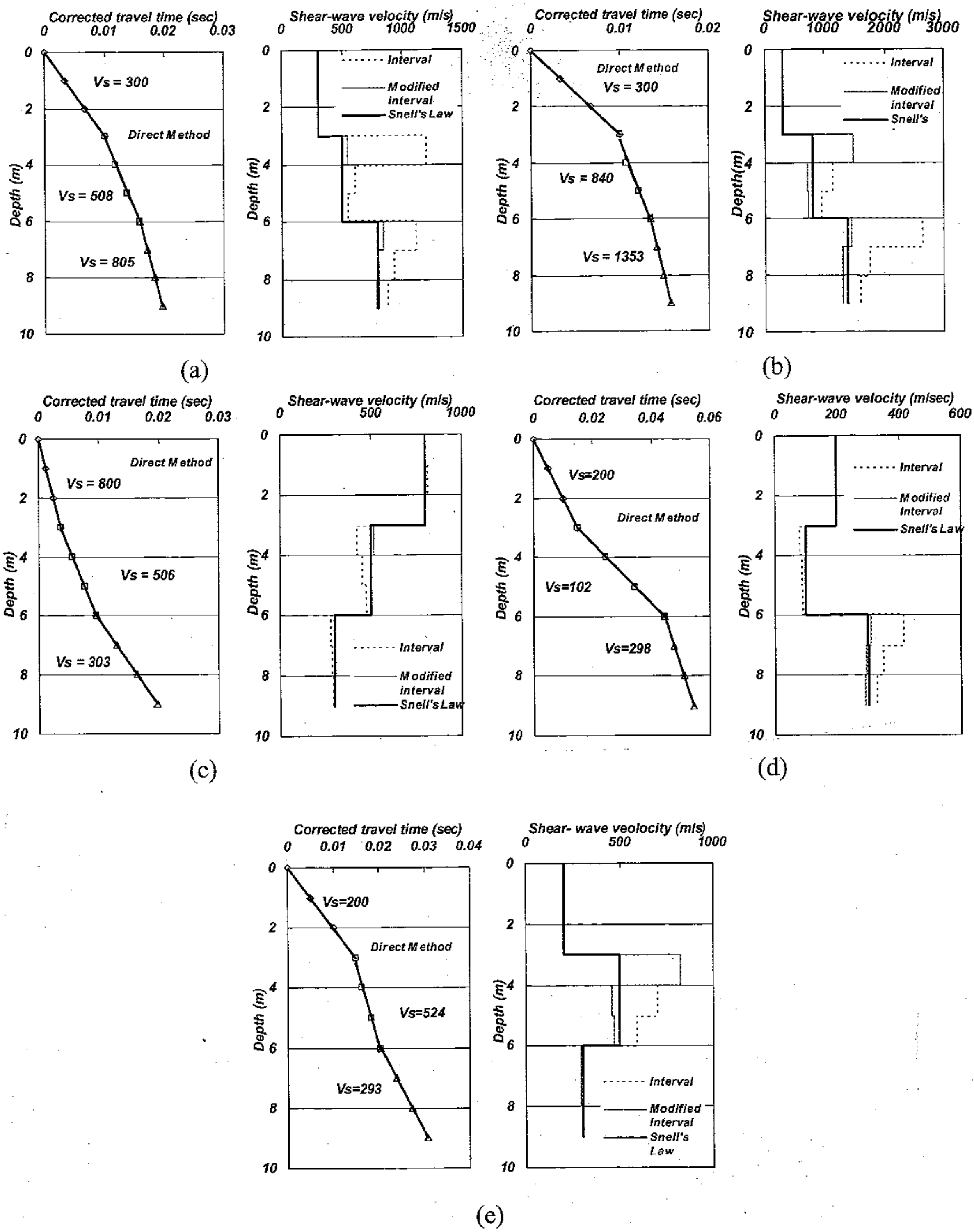

FIG. 10—*Shear wave velocity profiles for the three-layer model: (a) Three-layer Model 2-1; (b) Three-layer Model 2-2; (c) Three-layer Model 2-3; (d) Three-layer Model 2-4; and (e) Three-layer Model 2-5.*

possibility of significant error occurring at the layer interface where the abrupt stiffness increase happens in the interval and modified interval methods.

In the Model 2-4 (Fig. 10*d*), the errors between the first and second layer ($V_{S1} > V_{S2}$) are negligible as in the two layer model, but the errors between the second and third layers ($V_{S2} < V_{S3}$) are not significant compared with two layer model. The reason can be explained that the difference between straight and refracted ray path is reduced as shown in Fig. 11, when the soft layer is sandwiched between two stiffer layers. In the Model 2-5 (Fig. 10*e*), the errors provided by the interval and modified interval methods in the second layer are similar as in the two layer models, and all of the reduction methods provide the accurate wave velocities in the third layer.

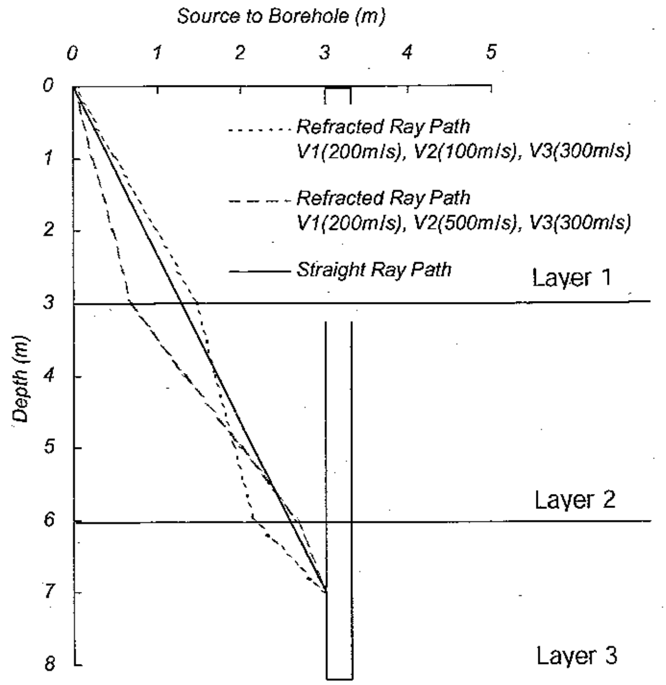

FIG. 11—*Comparisons of straight and Snell's Law ray path for Models 3-4 and 3-5.*

Effect of Testing Interval

Because downhole seismic test is not performed continuously, there will be a problem caused by setting a testing interval. In this section, the multilayer profiles that do not coincide with the test spacing between upper and lower will be discussed. In this case, there are no test data at the same layer boundaries, as shown in Fig. 12. The shear wave velocities and the travel times determined from the forward modeling in the multilayer model are also shown in Fig. 12. In Model 3-1, testing interval of 2 m is larger than the minimum layer thickness (1 m) in the model (Fig. 12*a*). In this case, errors can be found at the layer boundaries (depths 4 m, 7 m) and even Snell's Law ray-path method cannot provide exact profiles but just mean values in the testing spacing as shown in Fig. 13*a*. It is worth noting that the determination of reasonable testing interval is important before testing for the accurate measurement of velocity profile in the downhole seismic test.

In the two and three layer models, it was shown that the direct method provided reasonably good V_S profiles compared with the interval and modified interval methods. In practice, however, the accurate determination of arrival time is difficult, and the stiffness profile will be complex as shown in Fig. 12. Here, the direct method can provide the only average velocity profiles of several layers. In seismic ground response analysis, the determination of accurate V_S profile, particularly the stiffness contrast, is crucial and there might be a lack of accuracy in the direct method.

In Model 3-2 (Figs. 12*b* and 13*b*), the testing interval is small enough (0.5 m) compared with the minimum thickness of a layer in the model, but the testing location does not coincide with layer boundaries at depths of 5.5 and 8.5 m. In this case, the shear wave velocity profile determined by Snell's Law ray path method agrees well with synthesized velocity profile up to the depth 5 m, which is the layer boundary. However, at layer boundaries below, the Snell's Law ray path method provides the mean velocity of the upper and lower layers at depth of 5.5 m and 8.5 m. During the downhole seismic test, it is difficult to locate the exact layer boundaries, but

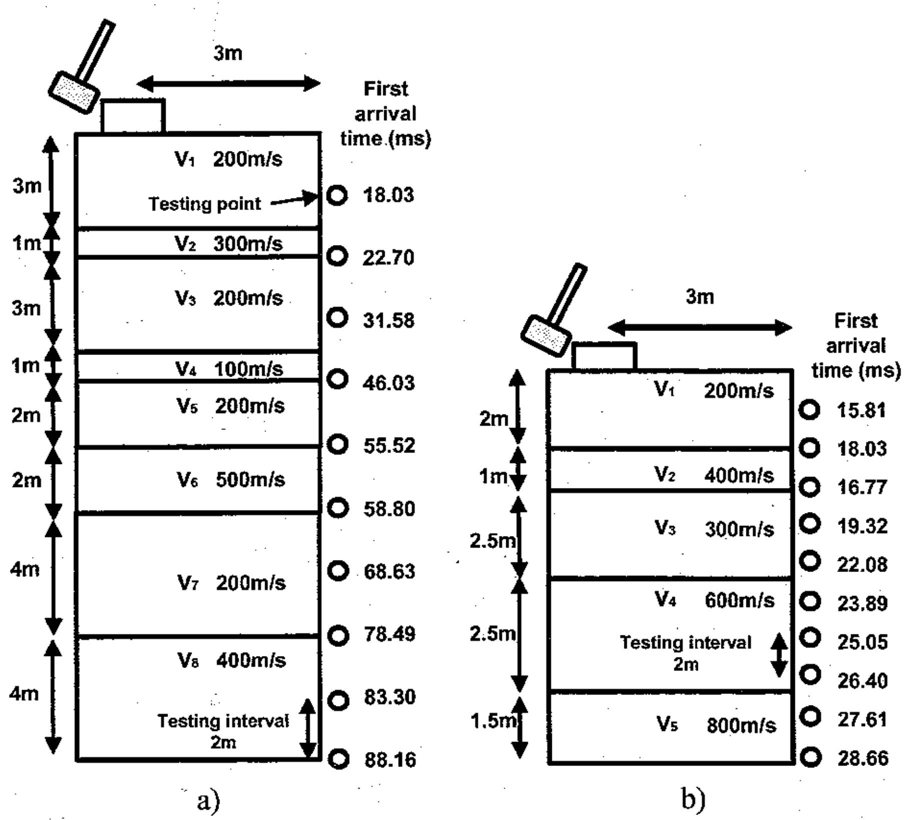

FIG. 12—*Illustration of the multilayer model to study the effect of testing interval: (a) Model 3-1; and (b) Model 3-2.*

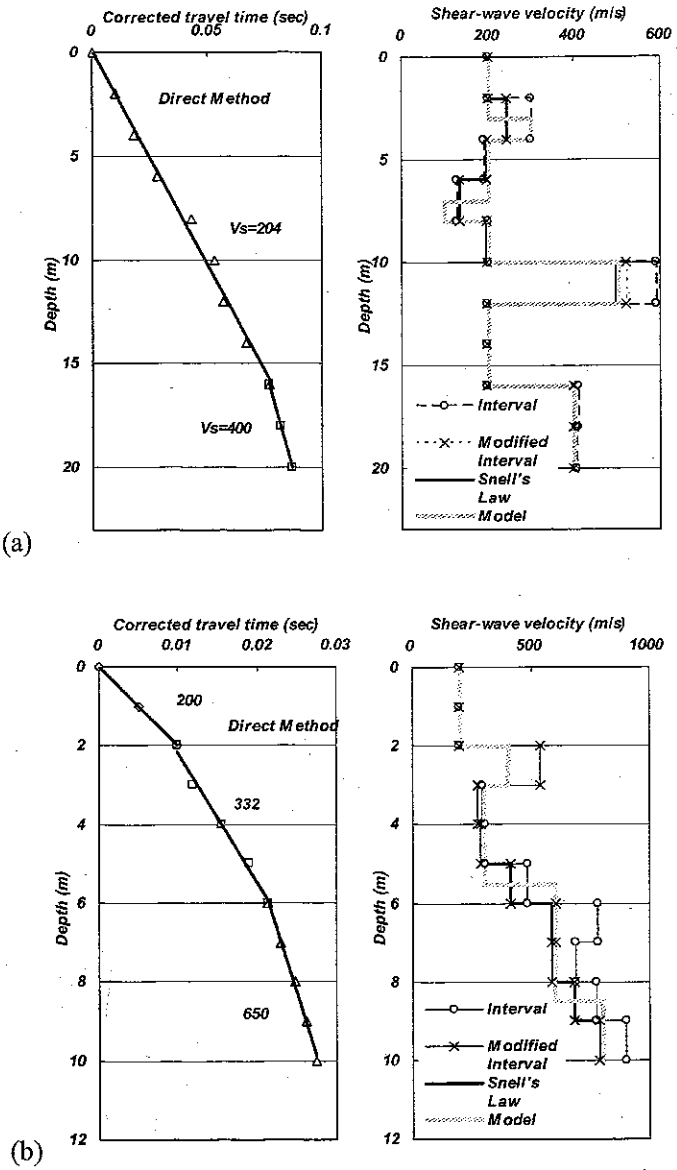

FIG. 13—*Shear wave velocity profiles for the multilayer model: (a) Model 3-1 (Testing interval is larger than a layer thickness); and (b) Model 3-2 (Testing location does not coincide with a layer boundary).*

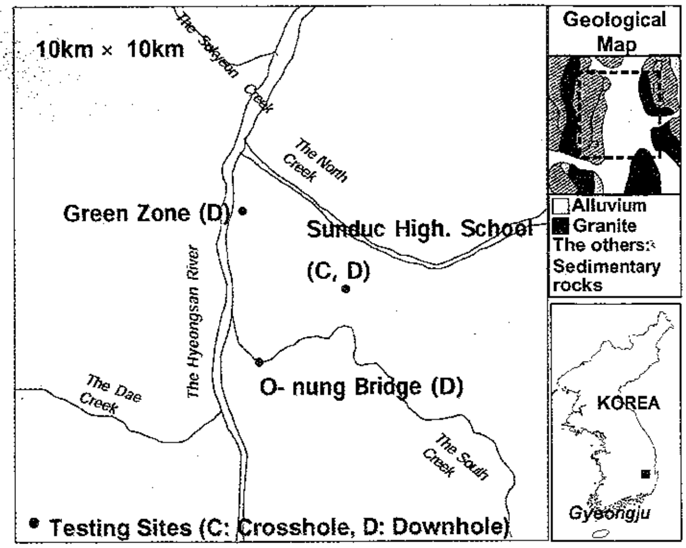

FIG. 14—*The location of testing sites.*

this problem can be partially overcome by dividing testing interval fine enough.

Field Studies

To evaluate the reliability of various downhole data reduction methods, downhole seismic tests were performed at three sites, and the shear wave velocity profiles determined by the various reduction methods were compared with the profiles determined by crosshole test or SPT N values. Figure 14 shows the locations of testing sites. The site investigation was performed mainly for the evaluation of seismic response of Kyeongju, Korea during the scenario earthquakes (Kim et al. 2002). Kyeongsang Basin in southeastern part of Korea where Kyeongju is located, is composed of sedimentary rock, volcanic rock by extensive volcanic activities, and intrusive granite. The topography of Kyeongju is characterized as a basin of the plains and low hills in which the downtown and farms are located, with surrounding mountains. Across the area the Hyeongsan River flows northward and several creeks from valleys join the river (Fig. 15). Therefore, the subsurface deposits of Kyeongju can be mainly composed of thick alluvium over bedrock influenced by rivers and creeks.

The soil profiles of three sites where the downhole seismic test was performed were obtained by rotary boring and are described in left sides of Figs. 15–17. The distance from source to borehole was set to about 3 m and the testing interval was 0.5 m to eliminate erroneous judgment in the interpretation of testing data. Two receivers were lowered simultaneously, and the receiver interval between the upper and lower receiver was 0.7 m. The polarized shear waves are generated at the ground surface by hitting each end of a $0.3 \times 0.2 \times 1$ m wood beam with a 5-kg weight sledge hammer. The travel times obtained at three test sites, which are measured by lower receiver at each testing depth, are listed in Table 3.

Sun-Duc High School Site

Both downhole and crosshole tests were performed at the Sun-Duc high school site at Kyeongju, Korea. The site consists of a fill layer, alluvial silty gravel, and soft rock. The shear wave velocity profiles determined by various downhole reduction methods are compared with crosshole data in Fig. 15. The shear wave velocity profile of the site shows a gradual increase with depth without abrupt change. The velocity profiles determined by the modified interval and Snell's Law ray-path methods agree well with each other, and those are also in good agreement with crosshole test data, which was obtained at the same borehole. Even if the same travel time measurement data listed in Table 3 are used in the analysis, the velocity profile determined by the interval method shows significant scatter. As discussed in the parametric study, both the Snell's Law ray path and modified interval methods provide the reliable velocity profiles in the soil deposit where the stiffness increases gradually with depth, but the interval method shows the lack of accuracy. The direct method can only provide the four mean average shear wave velocities in the profile.

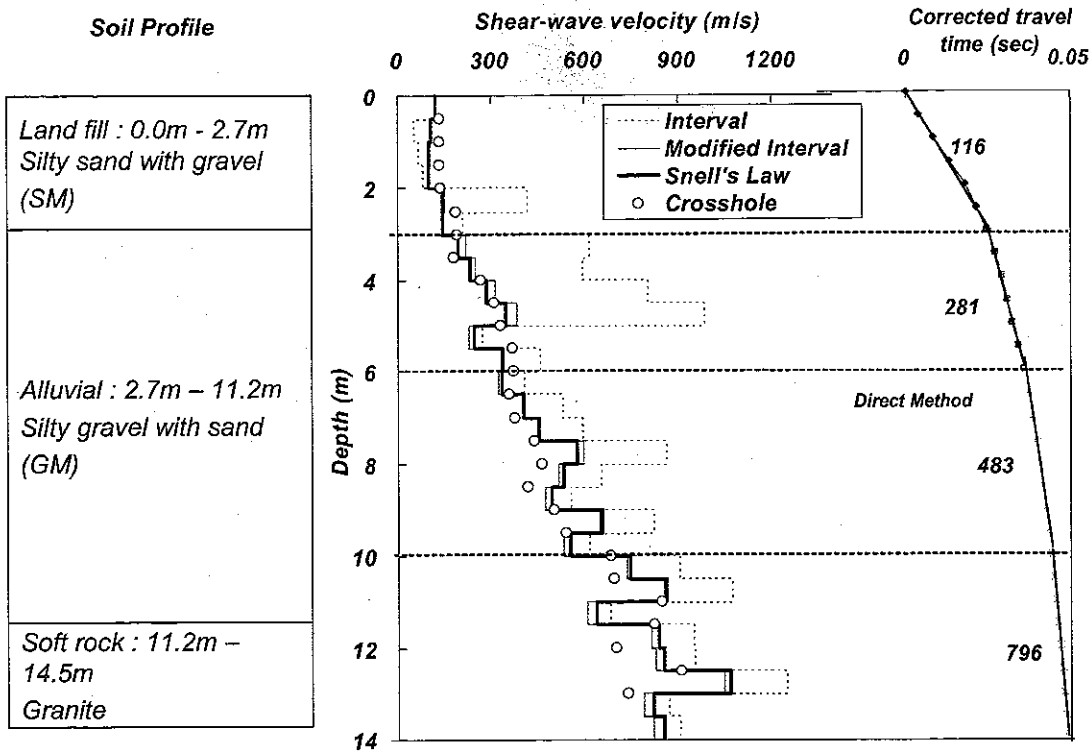

FIG. 15—*Soil profile and shear wave velocity profiles at the Sun-Duc school site.*

TABLE 3—*Measured travel time information at three test sites.*

Sun-Duc School Site		Grass Site		O-nung Bridge Site	
Depth (m)	Time (ms)	Depth (m)	Time (ms)	Depth (m)	Time (ms)
0.5	24.33	0.6	13.64	0.5	31.36
1.0	26.66	1.1	13.75	1.0	30.40
1.5	29.59	1.6	14.42	1.5	31.36
2.0	32.74	2.1	16.32	2.0	32.24
2.5	33.49	2.6	18.88	2.5	31.25
3.0	35.12	3.1	21.98	3.0	30.37
3.5	35.73	3.6	24.21	3.5	31.27
4.0	36.41	4.1	26.88	4.0	30.68
4.5	36.93	4.6	30.66	4.5	31.29
5.0	37.37	5.1	34.35	5.0	31.76
5.5	38.98	5.6	38.08	5.5	33.46
6.0	39.95	6.1	41.72	6.0	34.65
6.5	41.07	6.6	45.84	6.5	35.52
7.0	41.94	7.1	49.92	7.0	36.91
7.5	42.72	7.6	54.08	7.5	39.85
8.0	43.26	8.1	59.19		
8.5	43.99	8.6	62.40		
9.0	44.83	9.1	67.20		
9.5	45.41	9.6	68.12		
10.0	46.20	10.1	68.03		
10.5	46.73	10.6	68.30		
11.0	47.19	11.1	69.56		
11.5	47.90	11.6	70.40		
12.0	48.40	12.1	71.13		
12.5	48.92	12.6	71.92		
13.0	49.30	13.1	72.63		
13.5	49.87	13.6	73.32		
14.0	50.41	14.1	74.28		
		14.6	74.98		
		15.1	75.42		
		15.6	76.18		
		16.1	76.80		

* Travel times are measured by lower receiver at each testing depth.
* Source-to-borehole spacing is about 3 m and testing interval is 0.5 m.

Grass Site

Downhole seismic tests were performed to a depth of 16 m at the Grass site, Kyeongju, Korea. The site consists of a fill layer, alluvial silty clay, and silty gravel. Based on SPT N values, the stiffness of soil decreases slowly with depth up to 9.5 m, and the noticeable stiffness increase occurs at depths of about 8–11 m, as shown in Fig. 16.

The shear wave velocity profiles determined by various reduction methods were plotted in Fig. 16. Above the layer boundary at a depth of about 9 m, the velocity profiles determined by various methods match reasonably well. However, at the layer boundary where the stiffness increases abruptly, the interval method cannot provide the velocity value, and even the modified interval method provides the significantly large velocity value (which cannot be thought to be right value). To assess this problem, the signal traces of upper and lower receivers obtained near the layer boundary were plotted in Fig. 16. At a depth of 9.11 m and 9.61 m, the signals in the upper receiver arrive faster than those in the lower receiver. Whereas, at the depth of 10.11 m and 10.61 m, the signals in the upper receiver arrive later and the travel time delay became negative, indicating that interval method is unable to be used in the data reduction here. Even in this circumstance, the Snell's Law ray-path method provides the reliable results following the stiffness trends expected by SPT-N values, showing the great advantages in the downhole data reduction.

O-nung Bridge Site

Another downhole seismic test was performed at O-nung Bridge site, Kyeongju, Korea. The site consists of a fill layer and clayey gravel deposit. The results of this site also support the parametric

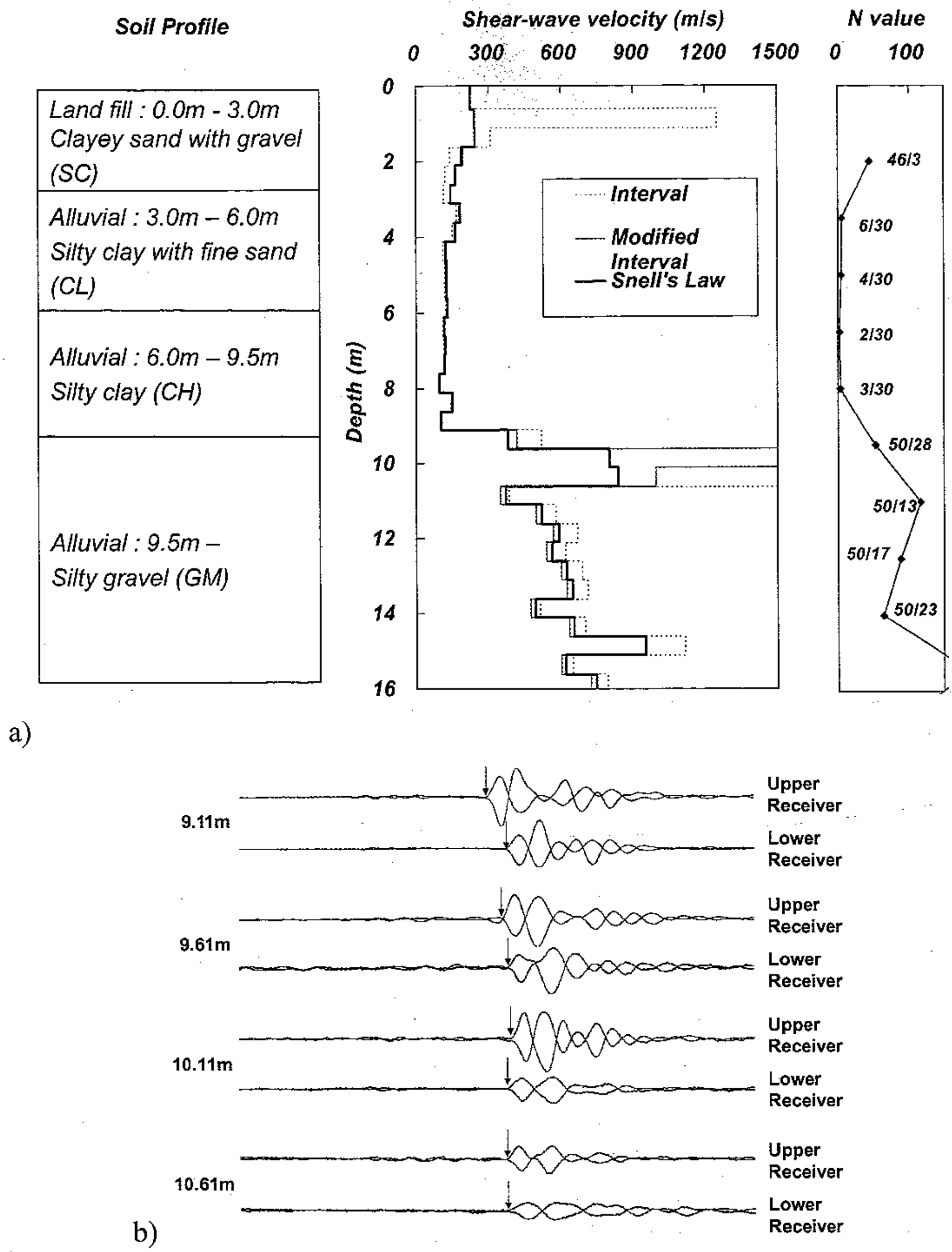

FIG. 16—*Field testing results of the Grass site: (a) soil profile, shear wave velocity profiles, and SPT-N values; and (b) signal trace of shear wave.*

study as shown in Fig. 17. In the case where the stiffness of soil increases at the shallow layer, the arrival times of lower receivers were faster than those of upper receivers. Therefore, the velocity of those layers can't be evaluated by using the interval measurement, and the results determined by the modified interval measurement are not satisfactory because the variation of shear wave velocity values is large and is not consistent with SPT-N values. However, the result determined by using Snell's Law ray-path method is thought to be reasonable. These phenomena that interval measurement and modified interval measurement give erroneous results often occur in field downhole seismic tests when the stiffness contrast is severe near the ground surface.

Conclusions

To evaluate the reliability of the various downhole data reduction methods, the parametric studies were performed using synthesized profiles. The modified interval and Snell's Law methods, which consider the ray path in the data reduction as well as the conventional direct and interval method, were considered. The direct method provides a mean value of surrounding layers, and it is difficult to evaluate the detailed velocity profile. The interval method was found to provide severe errors, particularly when the stiff layer is located beneath the soft layer. The testing errors in the interval method are reduced as decreasing source to borehole spacing. The

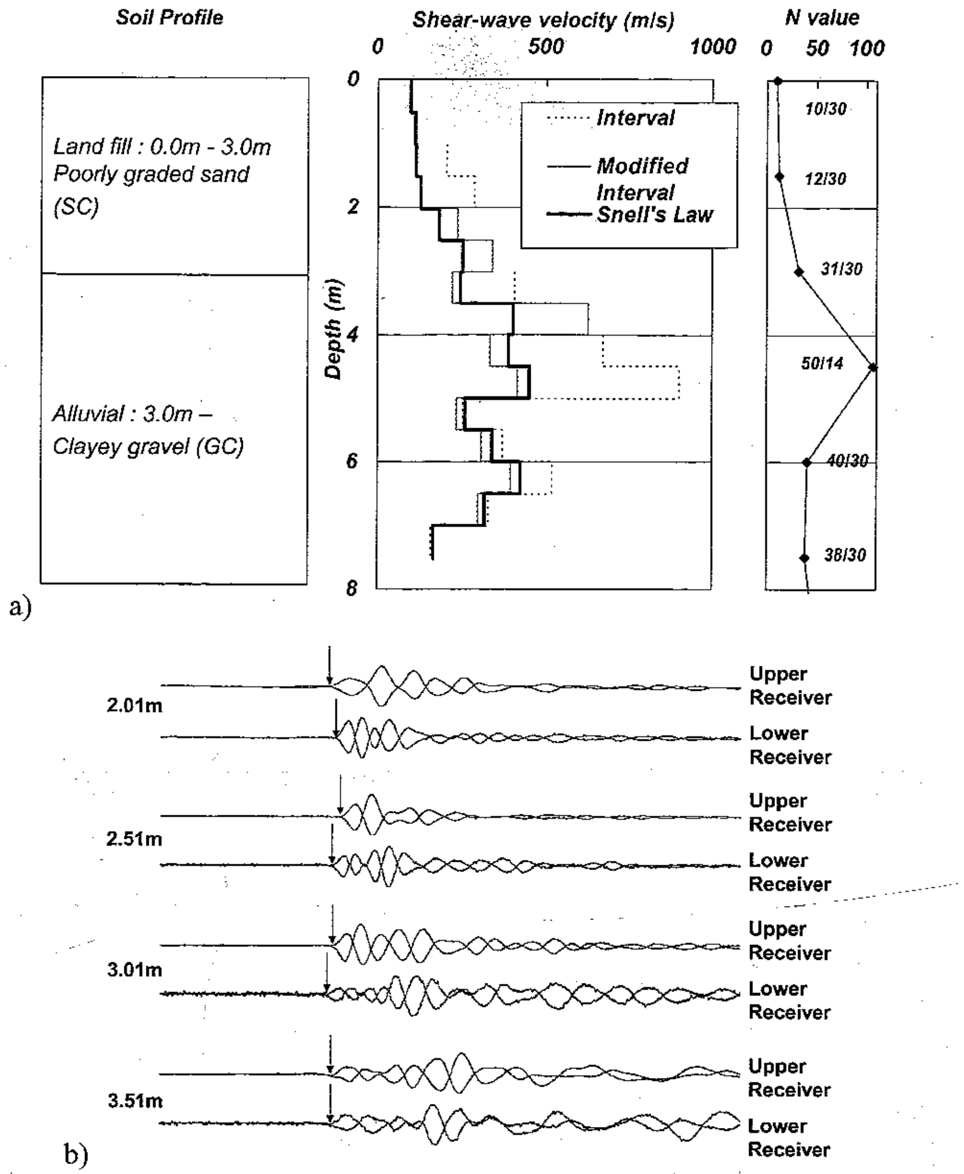

FIG. 17—*Field testing results at the O-nung Bridge site: (a) soil profile, shear wave velocity profiles, and SPT-N values; and (b) signal trace of shear wave.*

modified interval method, which considers a straight path, provides reasonable results for the most cases, but this method may cause errors at the layer interface where a large soft to stiff contrast exists. The Snell's Law ray path method provides the most reliable velocity profiles in all cases. Downhole seismic tests were also performed at three sites, and by comparing with crosshole and standard penetration test results, the importance of considering ray path in the data reduction was assessed.

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