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Effectiveness of multi-mode surface wave inversion in shallow engineering site investigations

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Key Words: surface wave, higher mode, sensitivity, phase velocity inversion, multi-mode, Vs structure

ABSTRACT

Inversion of multi-mode surface-wave phase velocity for shallow engineering site investigation has received much attention in recent years. A sensitivity analysis and inversion of both synthetic and field data demonstrates the greater effectiveness of this method over employing the fundamental mode alone. Perturbation of thickness and shear-wave velocity parameters in multi-modal Rayleigh wave phase velocities revealed that the sensitivities of higher modes: (a) concentrate in different frequency bands, and (b) are greater than the fundamental mode for deeper parameters. These observations suggest that multi-mode phase velocity inversion can provide better parameter discrimination and imaging of deep structure, especially with a velocity reversal, than can inversion of fundamental mode data alone.

An inversion of the theoretical phase velocities in a model with a low velocity layer at 20 m depth can only image the soft layer when the first higher mode is incorporated. This is especially important when the lowest measurable frequency is only 6 Hz.

Field tests were conducted at sites surveyed by borehole and PS logging. At the first site, an array microtremor survey, often used for deep geological surveying in Japan, was used to survey the soil down to 35 m depth. At the second site, linear multichannel spreads with a sledgehammer source were recorded, for an investigation down to 12 m depth. The *f-k* power spectrum method was applied for dispersion analysis, and velocities up to the second higher mode were observed in each test. The multi-mode inversion results agree well with PS logs, but models estimated from the fundamental mode alone show a large underestimation of the depth to shallow soft layers below artificial fill.

INTRODUCTION

As a fast, inexpensive, and non-destructive method for obtaining subsurface shear-wave velocity structure for shallow site characterisation, Array Microtremor Surveying (AMS) and Surface Wave Surveying (SWS or MASW: Multi-Channel Analysis of Surface Waves) have received much attention in recent years. One of the kernel technologies for these two survey methods is phase velocity inversion (or dispersion inversion), which tries to estimate the subsurface shear-wave velocity structure from a Rayleigh wave dispersion curve. In principle, AMS differs only in data acquisition from SWS.

Until the early 1990s, studies of dispersion inversion were often found in seismology (Horike, M., 1985; Okada et al., 1990; Yamanaka and Ishida, 1996). From the late 1990s, the practical use of AMS (Yamanaka et al., 1999; Feng et al., 2003) and MASW (Xia et al., 1999; Park et al., 1999, 2001) encouraged studies with application to civil engineering. Conventionally, the inversion method employs only the fundamental-mode Rayleigh wave dispersion curve. As many studies have shown, this method normally works well with relatively simple velocity structures, but fails when the subsurface structure has a velocity reversal (O'Neill, 2003). However, a velocity reversal arising from a soft layer below a stiff one is common and very important in civil engineering. Studies have show that the use of higher modes, together with the fundamental, can improve the survey accuracy and vertical resolution of the estimated models (Beaty et al., 2002; Xia et al., 2003; Bohlen et al., 2004).

In this paper, we show why multi-mode phase velocity inversion is needed, and how it improves the survey accuracy. Firstly, the characteristics of the phase velocity of higher modes of Rayleigh waves, for a subsurface model with a velocity reversal layer, are demonstrated through numerical sensitivity analysis, using the concept of Feng et al. (2001). The synthetic data is then inverted using a Genetic Algorithm (GA) employing various numbers of modes and frequency ranges. Finally, two field tests demonstrate the applicability of multi-mode phase velocity surveying at real engineering sites.

SENSITIVITY ANALYSIS OF HIGHER MODES

In order to study how the Rayleigh waves of each mode contribute to reconstructing the subsurface structure, we applied sensitivity analysis to the models shown in Figure 1. The shear-wave velocity of the fourth layer of the model is especially important in civil engineering, because a threshold of 350 m/s

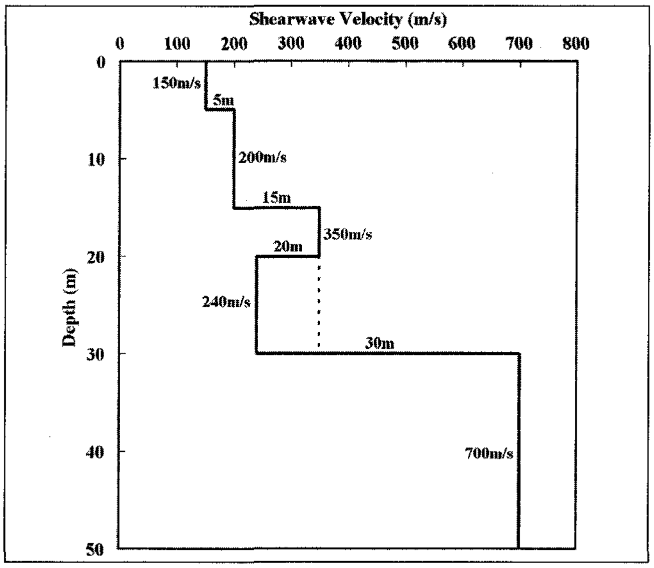

Fig. 1. Layered model used for the sensitivity analysis, with a velocity reversal at 20 m depth. The dashed line shows a normally dispersive model in which the shear-wave velocity increases with depth.

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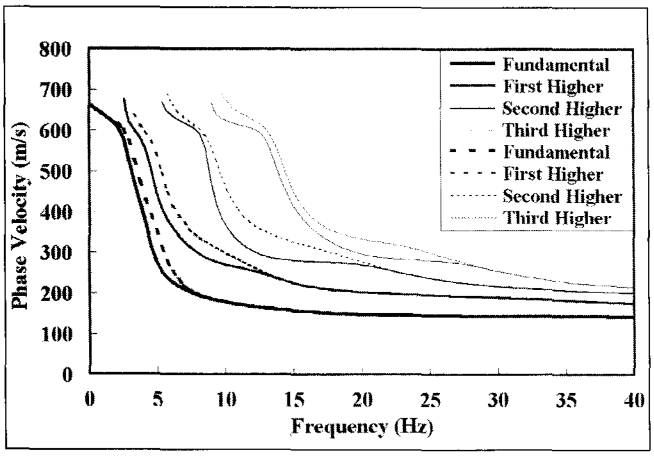


Fig. 2. Multi-mode Rayleigh wave phase velocity dispersion curves for the models shown in Figure 1. The solid lines correspond to the model with a velocity reversal, and the dashed lines to the normally dispersive model.

dictates whether the overlying third layer can be used as a foundation layer for buildings. Figure 2 shows the dispersion curves corresponding to the models in Figure 1.

According to Feng et al. (2001), the phase velocity sensitivity is defined as

$$S_{Vi} = \frac{1}{c(f)}\frac{\partial c(f)}{\partial V_{si}}\delta V_{si} \approx \frac{c(f,V_{si}+\alpha\cdot V_{si})-c(f,V_{si})}{c(f,V_{si})}\cdot 100\% \qquad (1)$$

$$S_{Hi} = \frac{1}{c(f)}\frac{\partial c(f)}{\partial H_i}\delta H_i \approx \frac{c(f,H_i+\beta\cdot H_i)-c(f,H_i)}{c(f,H_i)}\cdot 100\% \qquad (2)$$

where c is the phase velocity (m/s), f is the frequency (Hz), V_{si} and H_i are the shear-wave velocity (m/s) and thickness (m) of layer i respectively, and α and β are perturbation factors applied to the model parameters. S_{vi} and S_{hi} are the sensitivities of phase velocity with respect to shear-wave velocity and thickness respectively, and, as shown by the definitions, instead of partial derivatives, the sensitivities are defined as a percentage change. In practice, α and β are both given the value of 10%, and the sensitivity is the percentage change of phase velocity for a shear-wave velocity (or thickness) change of 10%.

Figure 3 shows the sensitivity of the fundamental mode to the shear-wave velocity of each layer. Except for the first and second layer, the sensitivities of the fundamental mode are concentrated in a very narrow frequency band around 5 Hz. In particular, the sensitivity curves for the third and fourth layers overlap considerably. This indicates that there would be much equivalence or non-uniqueness among these model parameters, that is, a linear dependency. It would be difficult to recover these accurately in an inversion that only uses the fundamental mode phase velocity. On the other hand, as shown in figure 4, the sensitivity of the first higher mode is distributed over a frequency range of 5–12 Hz with better separation for the third and fourth layer shear-wave velocities. Figures 5 and 6 show that the sensitivities of the second and third higher modes are distributed over a higher and wider frequency band.

Focusing on the sensitivity of each mode to the shear-wave velocity and thickness of the fourth layer (Figures 7 and 8 respectively), it can be seen that the peak sensitivity shifts to higher frequency with increasing mode number. In addition, the sensitivities are distributed over a wider frequency band, and the separation between peaks becomes better.

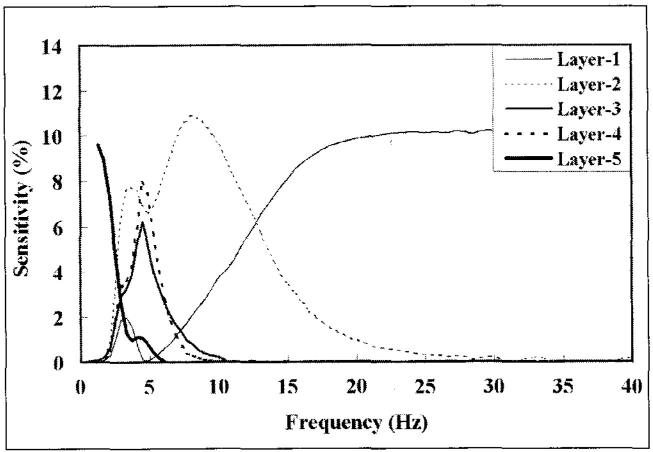


Fig. 3. Sensitivity of the fundamental mode to the shear-wave velocity of each layer.

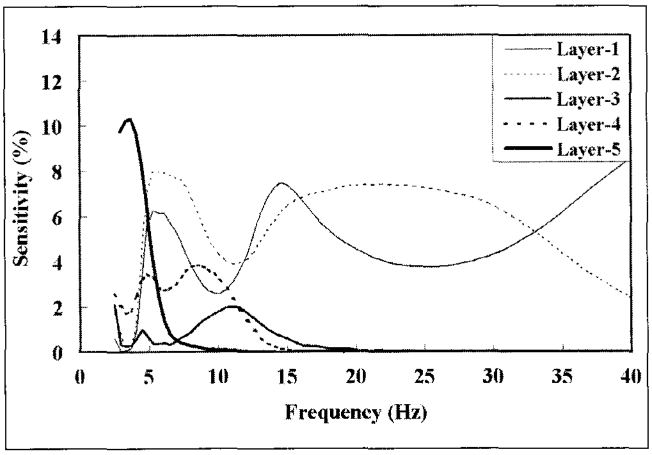


Fig. 4. Sensitivity of the first higher mode to the shear-wave velocity of each layer.

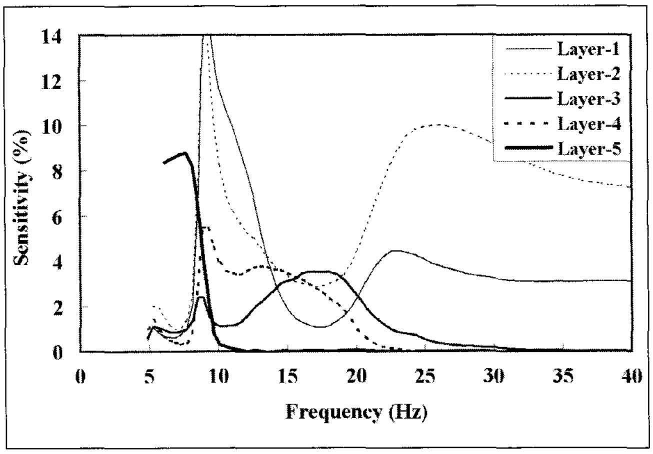


Fig. 5. Sensitivity of the second higher mode to the shear-wave velocity of each layer.

From the above analysis, we can draw two important conclusions: (a) the sensitivities of different modes concentrate in different frequency bands, indicating that multi-mode phase velocity inversion can provide a better resolution for each layer parameter, and; (b) for deeper layers, the sensitivity of higher mode dispersion concentrates in increasingly higher frequency bands. Because phase velocity dispersion is better resolved from field data at higher frequencies, this suggests the possibility of using higher modes to define deep structure more accurately than with the fundamental mode alone.

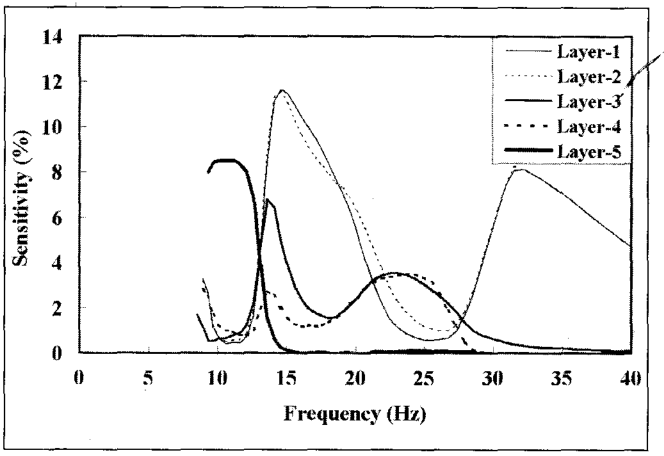


Fig. 6. Sensitivity of the third higher mode to the shear-wave velocity of each layer.

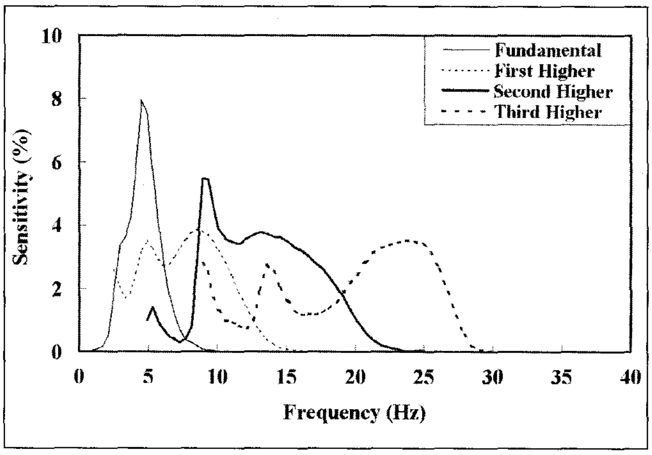


Fig. 7. Sensitivity of each mode to the shear-wave velocity of the fourth layer.

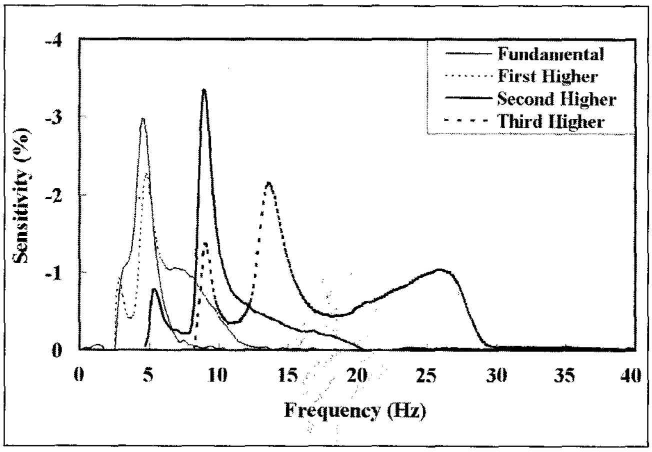


Fig. 8. Sensitivity of each mode to the thickness of the fourth layer.

SYNTHETIC DATA INVERSION

A numerical test of multi-mode phase velocity inversion was conducted on the velocity reversal model shown in Figure 1. The numerical test was done in two steps: first, the theoretical Rayleigh wave phase velocity of the model was calculated; then inversion was performed using the same forward calculation algorithm, to see if we could reconstruct the model from the phase velocity. Depending on the frequency band and number of modes of phase velocity used, the test was divided into four cases: (A) 1–40 Hz fundamental mode only; (B) 1–40 Hz fundamental and first higher modes; (C) 6–40 Hz fundamental mode only; (D) 6–40 Hz fundamental and first higher modes. A Genetic Algorithm (GA) was used for the inversion and no phase velocity noise was considered in this test. Normally, the output model of the GA varies depending on the random number seed used in the GA, and the variation between output models indicates the uniqueness of the inversion. In this test, we conducted the same inversion five times with different random number seeds.

As discussed in the sensitivity analysis, the sensitivities of all modes to each layer, except the first and last layers, are distributed within frequency range of 1–40 Hz. The main sensitivity of the fundamental mode is below 6 Hz and that of the first higher mode is above 6 Hz. Therefore, cases A and B represent ideal cases in which the fundamental and higher mode phase velocities have been measured accurately across the important frequency band. On the other hand, cases C and D represent more realistic scenarios, in which we have obtained only part of the relevant phase velocity data.

The inversion results for each case are shown in Figures 9 to 12. The five models in each figure are the results of five independent inversions with different random number seeds, and the 'True Model' is the target profile. The 'Misfit' is the RMS error between the phase velocity of the 'True Model' and that of the inverted profile. As can be seen in Figures 9 and 10, for case A, although the frequency band of the phase velocity is sufficient to incorporate all the layer sensitivities, because the fundamental mode lacks resolution, the resulting models differ widely. On the other hand, case B shows that the inversion using the fundamental and first higher modes together has reconstructed the target profile with higher accuracy. In case C, because the phase velocities used provide almost no information about the deep layers, the inversion has failed to reconstruct the target profile. The results of case D show that although the phase velocity of the fundamental mode provides no information about the deep structure, when the first higher mode is incorporated, the inversion has reconstructed the target profile, albeit with a slight increase in variation between models.

FIELD DATA INVERSION

Two field tests were conducted to study the effectiveness and applicability of the multi-mode phase velocity inversion. Test A is a small-scale array microtremor survey (AMS) and Test B is a multi-channel surface wave survey (MASW). At both sites, soil classification and shear-wave velocity structure had been previously investigated by coring and by P- and S-wave velocity logging.

Test A: AMS application

An important issue for applying multi-mode phase velocity inversion to AMS is whether higher modes can be measured accurately. As mentioned in the introduction, the AMS method differs from MASW only in data acquisition. Instead of recording waves from an artificial source, the AMS method records microtremors in the ground and estimates phase velocities from these signals.

The test area is a large civil engineering project site. As show in figure 13, the soil profile comprises over 10 m of sands and gravels, underlain by layers of silts and sands, with a sandy mudstone base at approximately 30 m depth. The mudstone, which forms the basement, is of Tertiary age, the silt layers are Quaternary deposits, and the sand layer on the top is artificial fill. From P-S velocity logging, the shear-wave velocity in the mudstone is over 500 m/s and that in the overlying layers is less than 200 m/s.

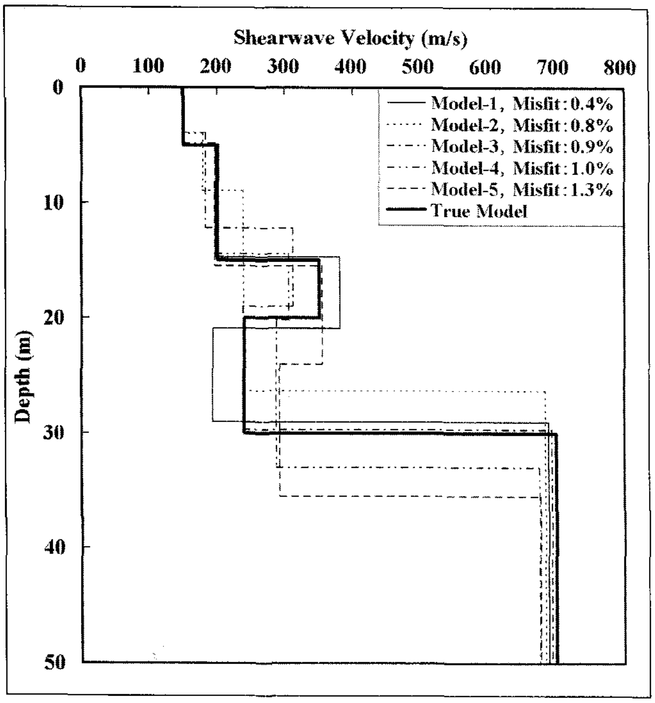


Fig. 9. Results of synthetic inversions using the fundamental mode only, from 1–40 Hz.

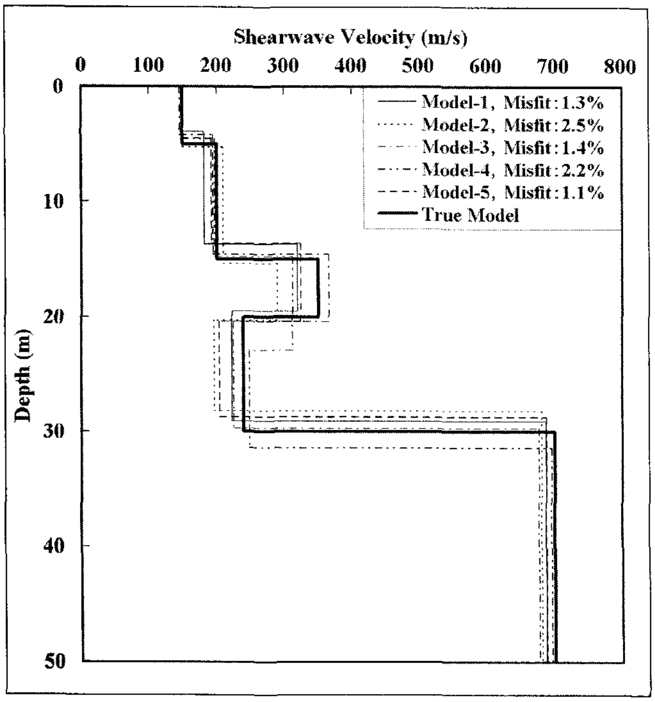


Fig. 10. Results of synthetic inversions using the fundamental and first higher modes over 1–40 Hz.

Array Type	Radius*	Obs. Duration
Double-Triangle (L)	21 m	30 minutes
Double-Triangle (S)	7 m	30 minutes
Pentagon (L)	21 m	30 minutes
Pentagon (S)	7 m	30 minutes

*** Radius of the circumcircle**

Table 1. Array geometry and observation times.

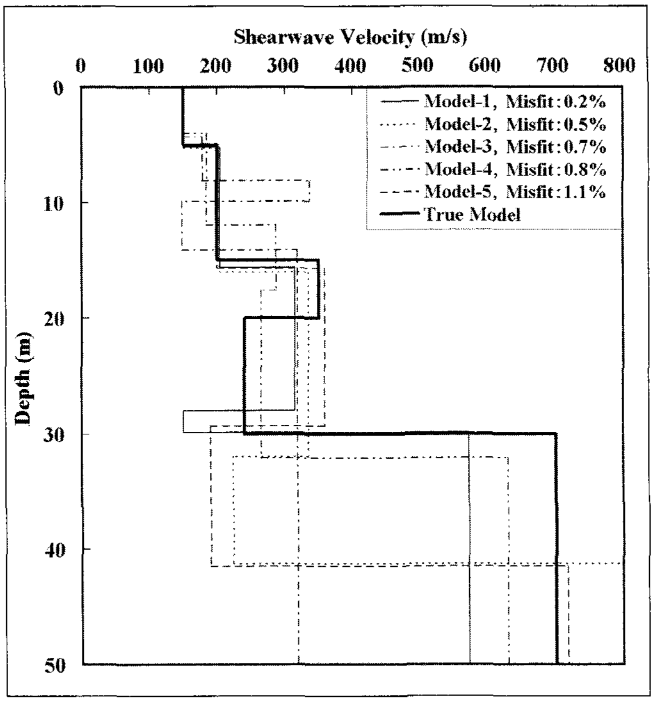


Fig. 11. Results of synthetic inversions using the fundamental mode only, over 6–40 Hz.

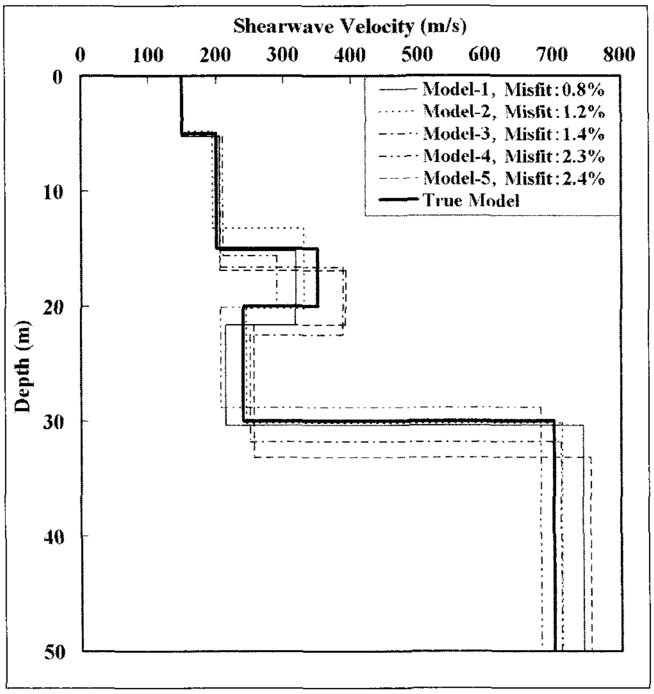


Fig. 12. Results of synthetic inversions using the fundamental and first higher modes over 6–40 Hz.

Vertical microtremors were observed with two double-triangle arrays and two pentagon arrays, and the observation duration for each array was 30 minutes (see Figure 14 and Table 1). A high-resolution *f-k* power spectrum method (Capon, 1969) was employed for the dispersion analysis. Because the four data sets were observed independently, the dispersion analysis of each data set was also conducted independently. Figure 15 shows the phase velocities from the *f-k* analysis, in which up to five coherent power spectrum ridges can be identified. These were interpreted as the fundamental and higher modes and inverted.

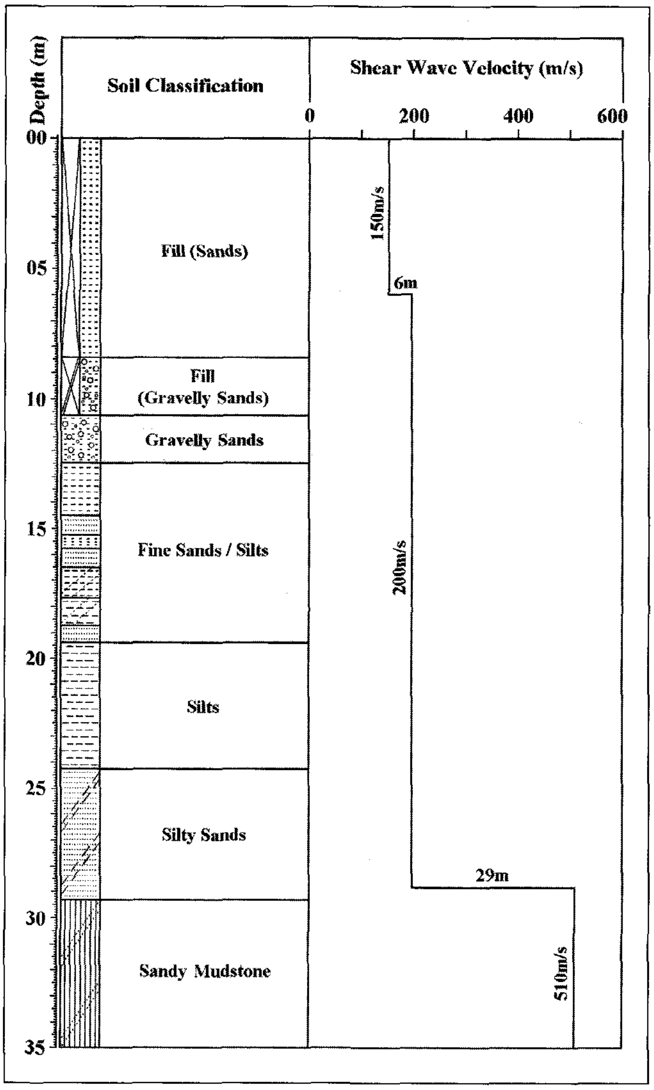


Fig. 13. Soil classification and shear-wave velocity structure from P-S logging at test site A.

A Genetic algorithm (GA) was employed for the inversion, using phase velocities from three modes of Rayleigh wave motion. Figure 16 shows the estimated profiles from three independent GA inversions, with the P-S logging result also plotted for comparison. All inversions are in good agreement with the borehole result. Figure 17 shows the observed and theoretical dispersion curves from the AMS data, along with the dispersion calculated from the P-S log. We can see that the calculated phase velocities of all the models fit the observed data well.

Test B: MASW application

This field test was conducted in Chuo Kaihatsu's Sodegaura Test Field. The subsurface structure at the site comprises a thin layer of fill, underlain by various soil layers. P-S wave velocity logging shows that the surface layer has a high velocity, with a low shear-wave velocity zone between 4 m and 10 m depths forming a velocity reversal structure (Figure 21).

Figure 18 shows the field set-up of the source and receiver positions. The data were acquired on a 23-m survey line with a receiver interval of 1 m. A sledgehammer was used as a vertical source for the data acquisition, and five shot gathers with source offsets from 11m to 27m were recorded. Because of limited space, sources were only placed on one end of the survey line. Figure 19 shows an example of the recorded data, which have been trace-normalised. The data are of good quality, although some random noise can be seen in the far-offset traces at late times.

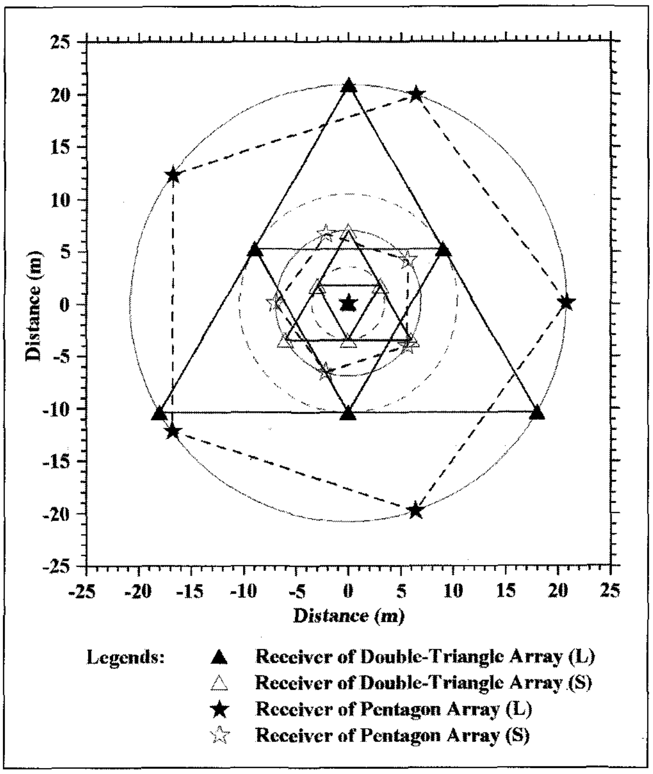


Fig. 14. Array geometry and size for microtremor observations at test site A.

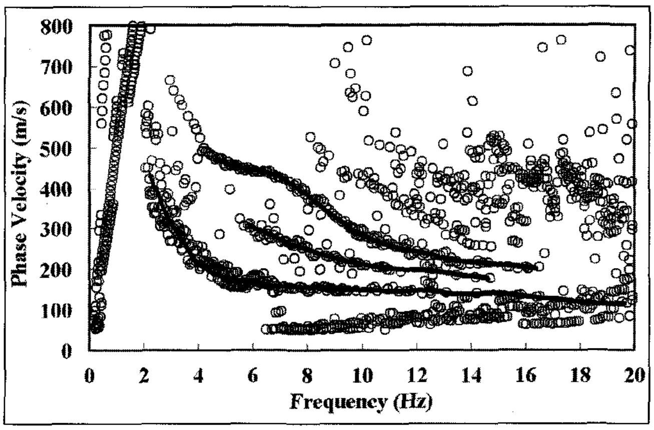


Fig. 15. Results of dispersion analysis for the four independent arrays at test site A.

For dispersion analysis, first, the cross-spectrum of each trace with a reference trace was calculated to form a cross-spectrum gather for each shot location, and these were then stacked over the five shots to improve the signal-to-noise level. Finally, a 1D high-resolution *f-k* method was applied to compute the phase velocity dispersion. In order to construct a 2D profile over the line, spatial windows of 12 traces were analysed and moved along at 2 m intervals, with the nominal position taken as the centre of the trace window. Figure 20 is an example of the *f-k* dispersion analysis. As the figure shows, we can clearly see the higher-mode dispersion curves, as well as the fundamental-mode curve.

Because a large number of inversions are needed to generate a 2D section, to reduce the calculation time, we used a hybrid method that combines the Genetic Algorithm (GA) and Least Squares technique (LSQ). The GA is only allowed to progress to a

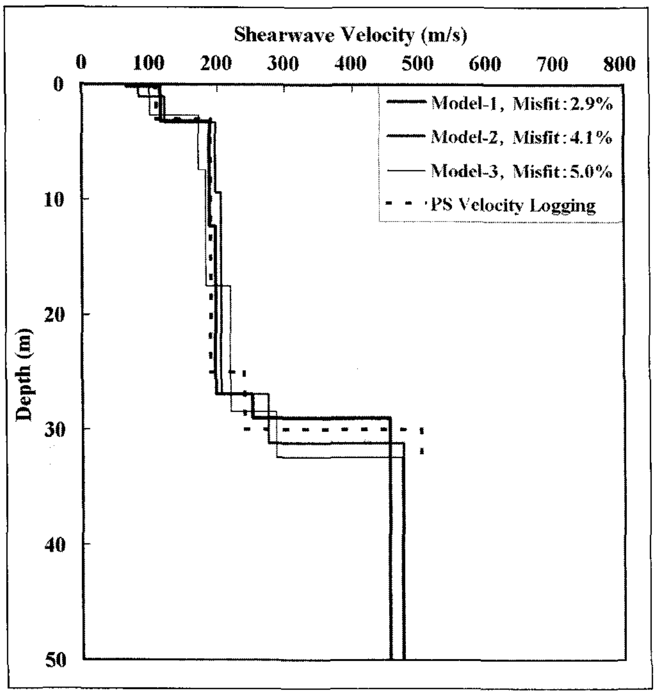


Fig. 16. Results of the three-mode phase velocity inversion using a Genetic Algorithm at test site A.

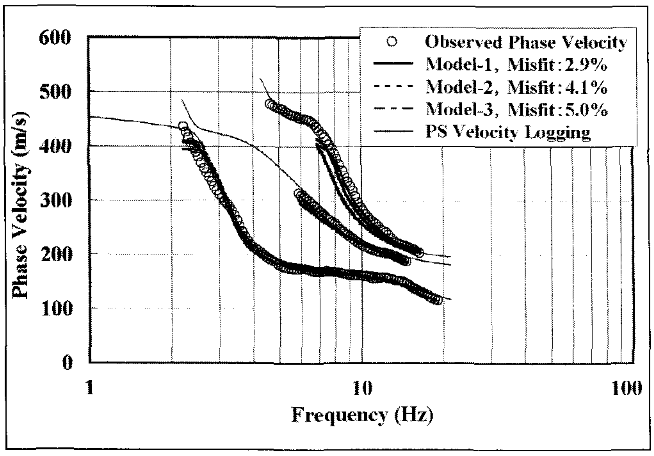


Fig. 17. Observed and theoretical multi-mode phase velocity dispersion at test site A.

few generations (15 generations, or RMS misfit less than 3.5%), and then the output of the GA is used as the initial model for the LSQ, which is fixed to five iterations. Inversion of both the fundamental mode, and fundamental plus up to second higher mode, were tested. Because the theoretical phase velocity calculations were based on the plane-wave matrix method for a 1D model (Haskell, 1953), the result of the inversion is only an approximation to the structure at each model point.

Figure 21 shows the borehole log results and the estimated 1D shear-wave velocity model at the borehole location from the phase velocity inversion. The dispersion curves for this inversion have been estimated from the trace 5 to trace 16 data (i.e., 6 traces on each side of the borehole). The model given by the multi-mode inversion agrees much better with the soil classification and the result of the P-S log than the fundamental mode only inversion. Models estimated with the fundamental mode alone show a large underestimate of the depth, and slight overestimate of shear-wave velocity, in the shallow soft layers below the artificial fill. Figure 22 is the shear-wave velocity pseudosection based on the series of 1D models along the survey line. As the figure shows, the low-velocity layer appears to have a slight dip, which has also been confirmed by other boreholes.

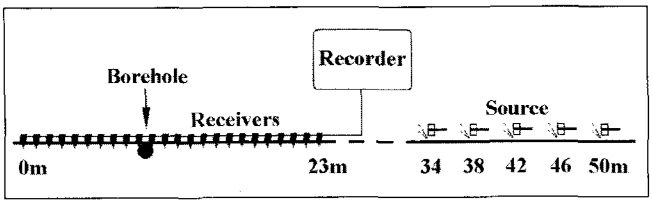


Fig. 18. Field layout for data acquisition at test site B.

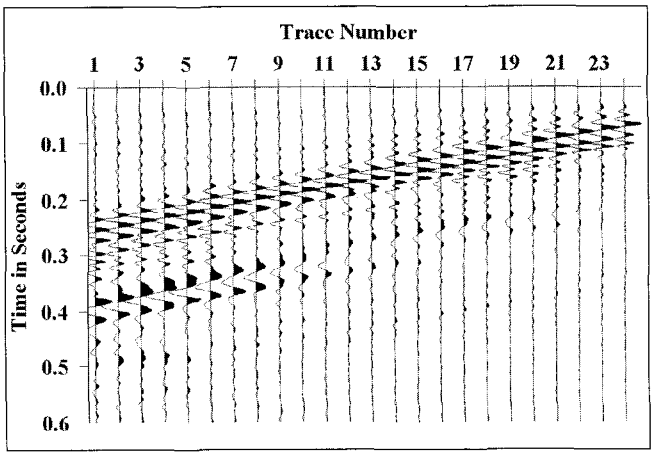


Fig. 19. An example of a shot gather at 11 m offset, recorded at test site B.

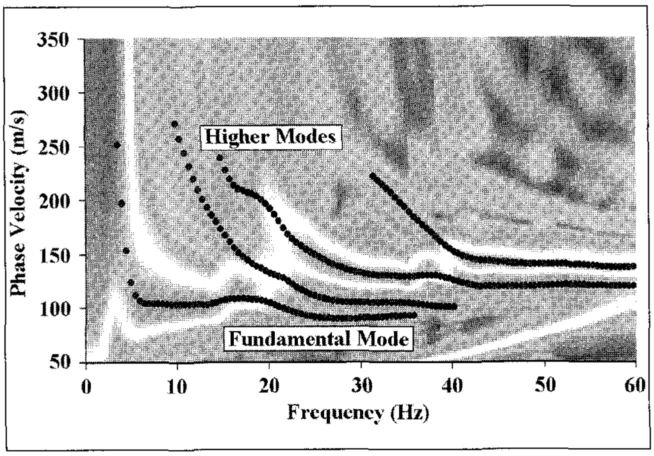


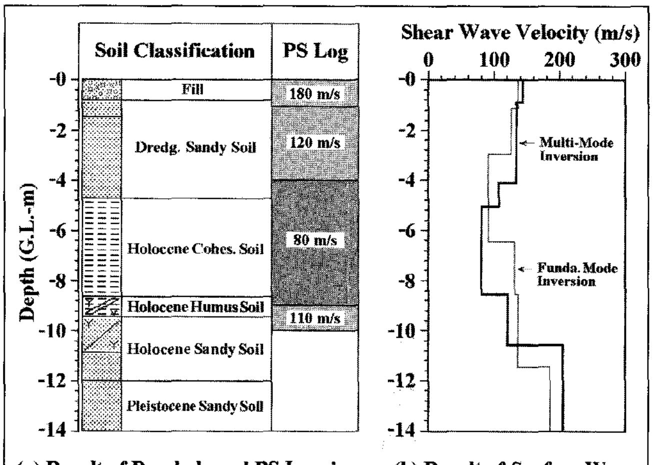
Fig. 20. An example of the *f-k* dispersion analysis at test site B.

DISCUSSION AND CONCLUSIONS

A sensitivity analysis and inversion of both synthetic and field data employing multi-mode surface wave dispersion demonstrates the improved effectiveness of using multi-mode data, rather than the fundamental mode alone, in shallow site investigations. The sensitivity analysis and numerical tests show that the multi-mode phase velocity inversion can provide a better resolution for each layer parameter, thus improving the survey accuracy and vertical resolution. Furthermore, within the measurable frequency band, higher modes provide more information on deeper structure. The field tests show that the results from multi-mode phase velocity inversion agree well with nearby P-S logs, supporting the effectiveness and practical applicability of the method.

The results also show that the multi-mode phase velocity inversion is especially effective with a subsurface structure having a velocity reversal, both shallow and at depth. Low-velocity layers are of special importance in civil engineering because such soft horizons can give rise to various problems, such as settlement or liquefaction during an earthquake. Traditional refraction surveys cannot resolve such structures, and conventional surface wave surveys, employing the fundamental mode only, also produce poor results. At field test B, models based on the fundamental mode alone show a large underestimate in the depth to shallow soft layers below the artificial fill. Multi-mode phase velocity inversion provides a more accurate result.

Throughout this study, theoretical dispersion curves were calculated using plane-wave matrix methods, and the energy of each mode is not considered. However, depending on the subsurface structure, higher modes may not be generated with appreciable strength, or the dominant mode may change with frequency. Moreover, the dispersion curves may be difficult to identify accurately in noise-contaminated data. The uncertainty associated with picking of higher modes will reduce the uniqueness of the inversion result. Therefore, improvement in the accuracy of estimating higher-mode dispersion is the primary concern in the practical advancement of multi-mode phase velocity inversion. With multi-channel surface wave surveying and careful picking of the energy peaks, the MASW and *f-k* power spectrum methods can generally provide a good result, but for array microtremor surveying, multi-mode analysis is highly dependent on suitable array design. The field test A reported here is one of a series of field tests originally designed for other purposes, but the array type and size are hardly optimum for multi-mode analysis, and further research is required in this area.



(a) Result of Borehole and PS Logging (b) Result of Surface Wave

Fig. 21. (a) Boring and P-S velocity logging results, and (b) Shear-wave velocity models estimated from both multi-mode and fundamental-mode-only surface wave dispersion.

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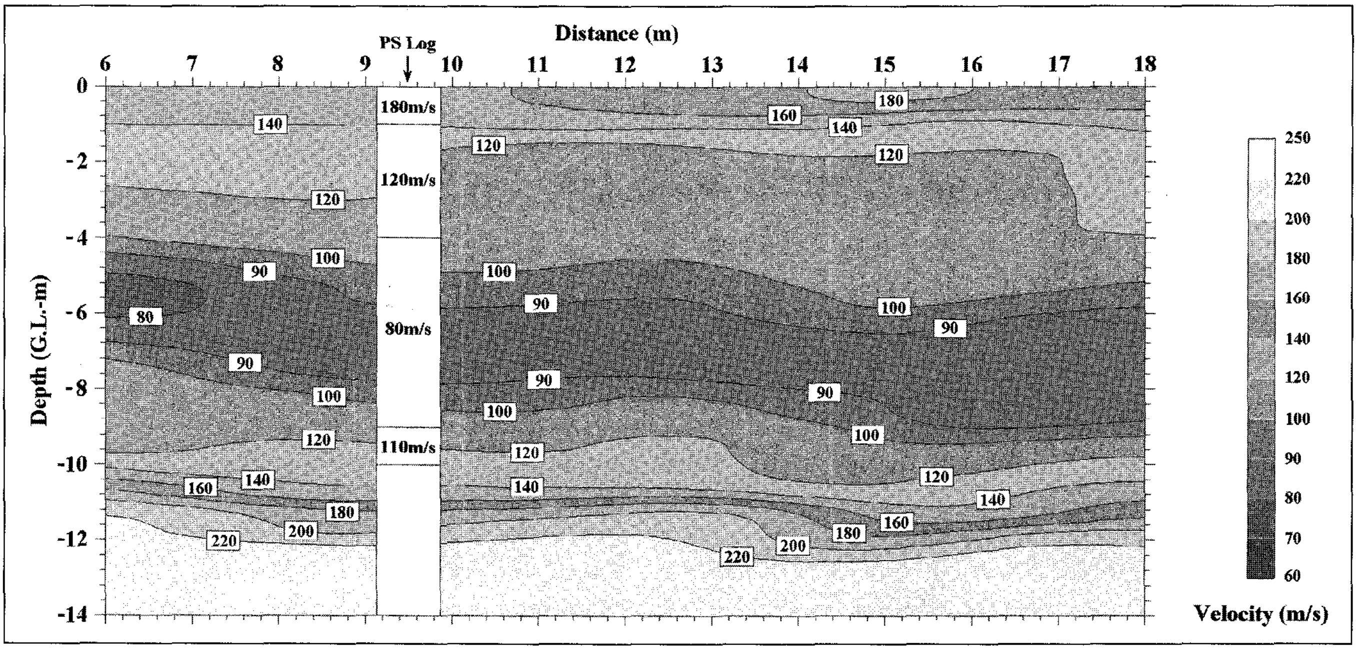

Fig. 22. Shear-wave velocity pseudosection, contoured from a series of 1D multi-mode inversion models at 2-m spacing.

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マルチモードレイリー波位相速度インバージョン及び適用例

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要　旨: 著者らは微動アレイ探査と表面波探査等レイリー波の速度分散特性を利用する探査手法の精度を改善するために、マルチモードインバージョン手法を考案し、感度分析、数値実験及び実データから手法の有効性を検討した。感度解析の結果、位相速度における各層の影響周波数範囲はレイリー波の基本モードより高次モードの方が分離しやすく、インバージョンにおいてよりユニークな解が得られることを示唆している。また、モデルの各層の感度分布は波のモード次数の増加につれて高周波数域に移り、周波数範囲が同じ場合、高次モードを利用することで、より深部構造の調査が可能性であることを示唆した。数値実験と実データを用いる検討結果、本手法による探査精度の改善が確認でき、特に逆転層を有する地盤の調査に有効的であることが分かった。また、本手法を微動アレイ探査に適用する場合、高次モードに適するアレイ観測と解析手法の開発が課題となると考えられる。

토목관련 천부층 조사에서 다중 모드 표면파 역산의 효과

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요　약: 최근 들어 토목관련 천부층 조사에 다중 모드 표면파 위상 속도의 역산이 많은 관심을 받고 있다. 감도 분석, 그리고 합성탄성파자료와 현장자료의 역산 결과는 이 방법이 기본 모드만을 이용하는 것에 비해 매우 효과적임을 보여주고 있다. 다중 모드 레일리 파의 위상속도들에서 층의 두께와 전단파 속도에서의 조그만 변화는 고차 모드의 감도들을 (a) 다른 주파수 대역들에 모이게 하고 (b) 심도가 깊어질수록 기본 모드보다도 더 크게 한다. 이 관찰을 통해 다중 모드 위상 속도 역산을 이용하면 기본 모드 자료들만의 역산에 비해 변수값들을 더 잘 구분해 낼 수 있고 깊은 구조, 특히 속도 역전이 일어난 구조에 대해 보다 나은 영상을 얻을 수 있음을 알 수 있다.

20 m 깊이에 저속도층이 존재하는 모델에서 이론적인 위상 속도들의 역산은 1 차 모드만 첨가될 때 단지 연암층만을 영상화할 수 있다. 이 사실은 측정 가능한 가장 낮은 주파수가 단지 6 Hz 일 때 특히 중요하다.

현장시험들이 시추공과 PS 검층을 이용하여 조사된 지역들에서 행해졌다. 첫번째 지역에서는 일본에서 심부 지질조사에 주로 이용되는 microtremor 배열 탐사가 35 m 깊이까지 토양층을 탐사하기 위해 사용되었다. 두번째 지역에서는 12 m 깊이까지 조사하기 위해 sledgehammer 음원과 선형 다중 채널 수진기 전개를 이용하여 자료가 얻어졌다. 분산곡선 분석을 위해서 주파수-파수 파워 스펙트럼법이 사용되었고 각각의 시험에서 2 차 모드의 속도까지 구해졌다. 다중 모드 역산 결과는 PS 검층기록과 잘 일치한다. 하지만 단지 기본 모드만을 이용하여 얻어진 결과는 매립지 아래의 천부 연암층까지의 깊이를 매우 작게 평가하였다.

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