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MULTI-DIMENSIONAL VS-PROFILING WITH MICROTREMOR H/V AND ARRAY TECHNIQUES

Kohji TOKIMATSU[1], Hiroshi ARAI[2] and Mayuko YAMAZAKI[3]

SUMMARY

A practical method is presented for determining three-dimensional shear wave velocity profiles from microtremor horizontal-to-vertical (H/V) spectral ratio techniques with a single station, which is coupled with the frequency-wave number (F-k) spectral analysis techniques using microtremor array measurements. To demonstrate the effectiveness of the proposed method, microtremor measurements with a single three-component sensor as well as those using arrays of sensors are conducted in Kushiro city. Conventional microtremor measurements performed at about 300 stations result in spatial variation of microtremor H/V spectral ratios in the city. The F-k spectral analysis of the array records yields dispersion characteristics of Rayleigh waves, and the inversion of these data results in shear wave velocity profiles down to the bedrock at six stations in the city. Three-dimensional Vs-profile in the city is then estimated from inversion using H/V spectra with the Vs-values determined by the F-k analysis of microtremor array data at the six sites. This reveals a three-dimensional Vs profile, together with an unknown hidden valley that crosses the central part of the city. The estimated Vs profiles are consistent with available geological information and boring logs, indicating the effectiveness of the proposed method.

INTRODUCTION

The shear wave profile is the key parameter for evaluating dynamic site response characteristics. It is, however, difficult to estimate Vs profiles down to the bedrock using conventional geophysical methods, particularly when two- or three-dimensional soil profiles are to be required, as most of the conventional geophysical methods require boreholes and may not always be performed conveniently and economically.

The frequency-wave number (F-k) spectral analysis of microtremors may be a cost-effective alternative, considering its potential to explore shallow to deep soils without any boreholes. Recent studies (e.g., Horike [1], Okada and Matsushima [2], Tokimatsu et al. [3]), in fact, have shown the following:

[1] Professor, Tokyo Institute of Technology, O-okayama, Meguro-ku, Tokyo, JAPAN. Email: kohji@o.cc.titech.ac.jp
[2] Senior Research Engineer, Earthquake Disaster Mitigation Research Center, National Research Institute for Earth Science and Disaster Prevention, Kobe, JAPAN. Email: aria@edm.bosai.go.jp
[3] Graduate Student, Tokyo Institute of Technology.

(1) Rayleigh waves dominate in the microtremor vertical motions.

(2) F-k spectral analyses of microtremor vertical motions measured with arrays of sensors yield dispersion characteristics of Rayleigh waves.

(3) Inverse analysis of the microtremor vertical dispersion data detected by F-k spectral analysis of microtremor vertical motions can result in a shear structure below the site.

It is also shown that surface waves (both Rayleigh and Love waves) also dominate in the horizontal motions and that the horizontal to vertical (H/V) spectral ratios of microtremors (Nakamura and Ueno [4]), which can be determined more conveniently than dispersion characteristics, correspond to those of Rayleigh waves or surface waves and thus reflect the shear structure at the site (e.g., Tokimatsu and Miyadera [5], Tokimatsu [6], and Arai and Tokimatsu [7]). Thus, the inversion of microtemor H/V spectra by assuming either Rayleigh or surface waves dominate in microtremors may result in a Vs profile of the site. Recently, Arai and Tokimatsu [7] successfully determined Vs profiles from the inversion of H/V spectra, provided that either the V_S values or the thicknesses of the deposit below the site are known.

The above findings indicate that the conventional microtremor H/V techniques conducted in an area, if used with Vs profiles determined from microtremor measurements using array of sensors at several locations in the area, has potential capability of evaluating two- or three-dimensional Vs profile in the area in an economical manner. The object of this study is to explore and demonstrate such a possibility based on field investigation conducted in Kushiro city.

MICROTREMOR MEASUREMENTS AND GEOLOGICAL SETTING

Microtremor Measurements

The test equipment used for both measurements, i. e., conventional and array observation, consists of amplifiers, lowpass-filters, 16-bit A/D converters, and a note-size computer, all built-in a portable case; and three-component velocity sensors with a natural period of either 1 or 5 s. For the conventional observations, microtremor ground motions were measured for 15 minutes, and digitized at an equal sampling rate of 100 Hz. For the array observation, five or six sensors were placed on the ground surface to form a circular array with a sensor in the center. Because the effective wavelength is 2-6 times the array radius, several arrays with different array radius were used at each site. The microtremor ground motions were measured simultaneously with each array and digitized at equal sampling rates of 50-500 Hz. The sampling rate varied, depending on site geological conditions and array radius used. About 10-20 sets of data consisting 2048, 4096, or 8192 points each were made from the recorded motions and used for the subsequent spectral analysis.

Geological Setting of Investigated Region

Fig. 1 shows a map of Kushiro city, indicating the stations where conventional microtremor measurements were made. The number of stations investigated in the area is over 300. The distance between adjacent two stations ranged from about 10 - 300 m, depending on the variation of microtremor H/V spectra with distance. Also shown in the figure are the six sites where microtemor array measurements were made. These sites are hereby labelled as KHB, KMB, KBS, SWI, ASH, and JMA. The minimum array radii used were 3 m at all sites, and the maximum array radii were 200, 120, 180, 50, 75, and 160 m at KHB, KMB, KBS, SWI, ASH, and JMA, respectively.

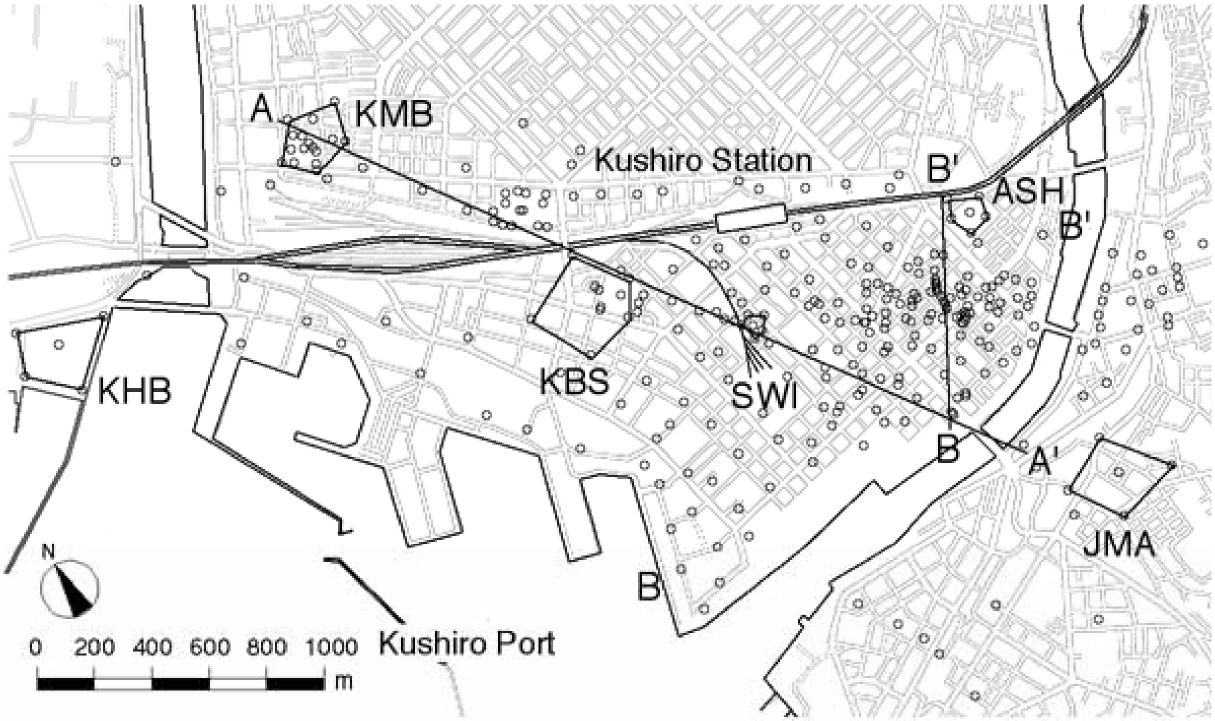

Fig. 1 Map showing observation sites in Kushiro

Fig. 2 shows a schematic diagram showing geologic cross section along Line A-A' shown in Fig. 1. JMA is located on a hill covered by a thin layer of silty volcanic ash that overlies Tertiary rock, called Urahoro Group. ASH, SWI, and KBS are situated on a level Holocene sediment that overlies Tertiary rock. KMB and KHB are located on a Holocene layer underlain by a Pleistocene layer, called Kushiro Group. The depth to Urahoro and Kushiro Groups generally decreases from 80 m on the west and to about 20 on the east.

RESULTS OF MICROTREMOR MEASUREMENTS

Microtremor H/V Spectra

The microtremor H/V spectral ratio may be defined by one of the following:

$$H/V = (S_{NS}S_{EW})^{1/2} / S_{UD} \quad (1)$$

$$H/V = (S_{NS}^2 + S_{EW}^2)^{1/2} / S_{UD} \quad (2)$$

where S_{UD} is the Fourier amplitude of the microtremor vertical motion, and S_{NS} and S_{EW} are those of the two orthogonal horizontal motions. Equations (1) and (2) correspond to the H/V spectra of Rayleigh and surface (Rayleigh and Love) waves, respectively (Arai and Tokimatsu [7]).

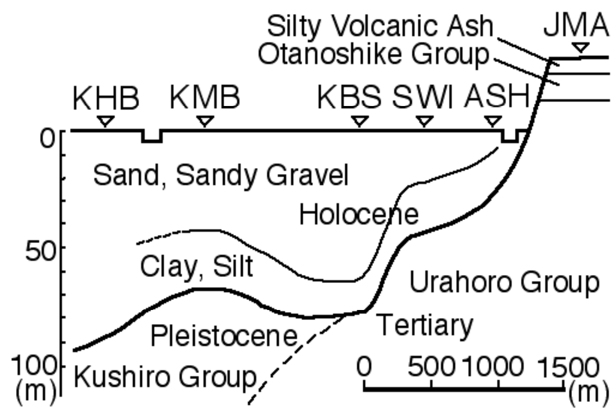

Fig. 2 Geologic cross section along Line A-A'

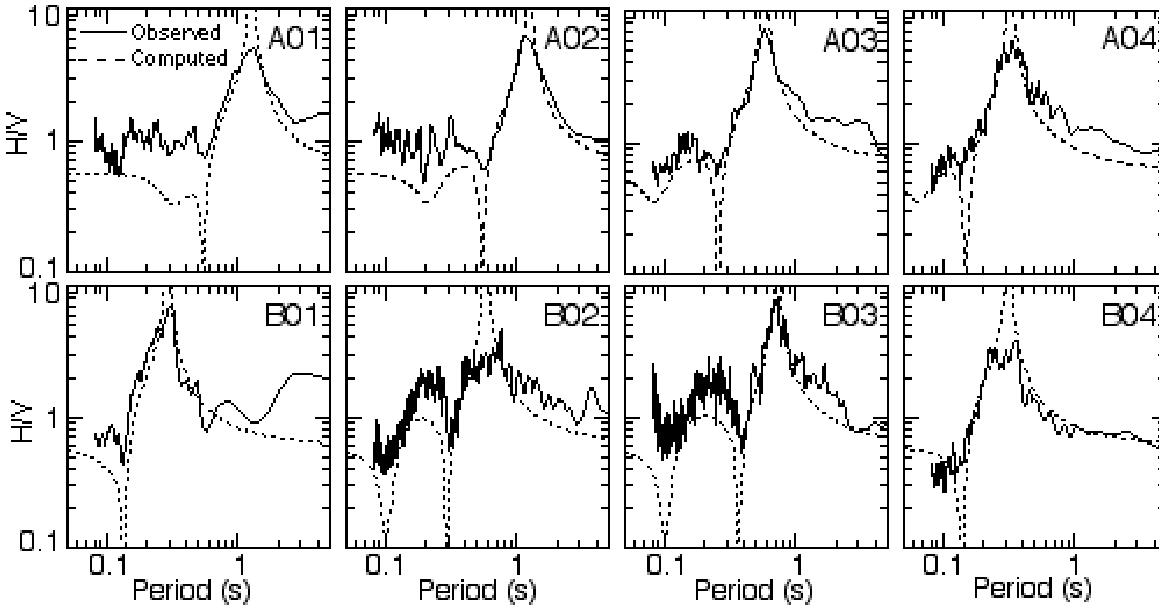

Fig. 3 Microtremor H/V spectra compared with those of Rayleigh waves at sites along Lines A-A' and B-B'

In this study, the microtremor H/V spectra are determined with Equation (1), since the following H/V inversion will be made assuming that microtremor H/V spectra reflect those of Rayleigh waves.

The solid lines in Fig. 3 show the microtremor H/V spectra defined by Equation (1) at several sites along Lines A-A' and B-B'. The peak period of H/V spectrum varies from place to place. Namely, it decreases from 1.2s at Station A01 on the west to 0.3 s at Station A04 on the west along Line A-A', but it increases from 0.3 s at Station B01 on the south to 0.7 s at Stations B02 and B03 and then decreases to 0.3 s at Station B04 on the north along Line B-B'. Of particular interest in the figure are the second prominent

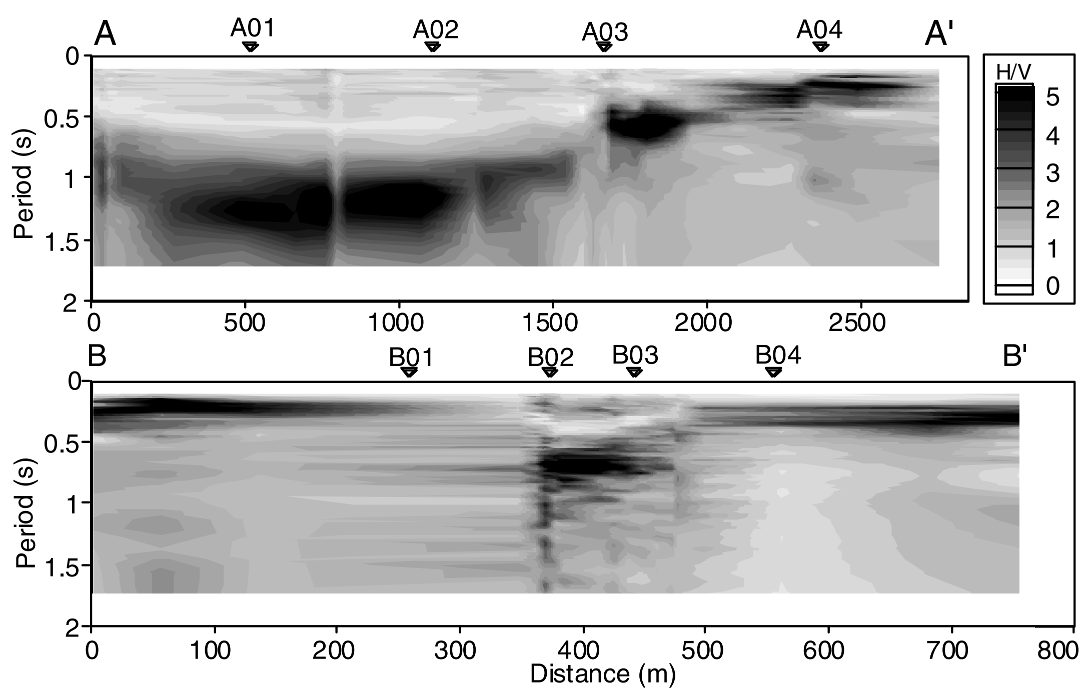

Fig. 4 Spatial variations of microtremor H/V spectra along Lines A-A' and B-B'

peaks that occur at B2 and B3 that cannot be clearly identified at other sites.

To investigate whether the above-mentioned trends exist within the region, variations of H/V spectra along the two lines are shown in Fig. 4. In the figure, the value of H/V is indicated by gradation as shown in the legend. The figure generally confirms the findings from Fig. 3. Namely, the H/V peak period decreases eastward from 1.3 to 0.2 s along Line A-A'. In contrast, it changes abruptly from about 0.25 to 0.8 s in the middle of Line B-B', with the appearance of the second prominent peak at 0.25 s. This creates discontinuity of the spatial variation of H/V spectra along Line B-B'.

Figure 5 shows a map indicating the contours of the H/V peak period. The figure confirms that the spectral peak generally decreases from 1.2 s on the west to 0.3 s on the east of the region, with contour lines generally running from north to south. The contour lines in the middle of the east side of the region, however, run almost orthogonal to those lines, i.e., from west to east, creating a narrow band having H/V peak period larger than those of the north and south side of this band.

Tokimatsu [6] indicated that (1) if the microtremor H/V spectrum of a site does not have a distinct peak, it may be a rock site or a soil site with a low impedance ratio between the bedrock and the overlying deposit, and (2) if the microtremor H/V spectrum of a site has a distinct peak, the impedance ratio of the site is moderate to high and the H/V peak period, T_p, could be equal to the natural site period, T_g. Considering that the Vs profile of the site controls the natural site period, the variation in H/V peak period suggests that the shear wave velocity profile could vary considerably along the region, even though no topographical variation exists except for the hill on the east end of the region.

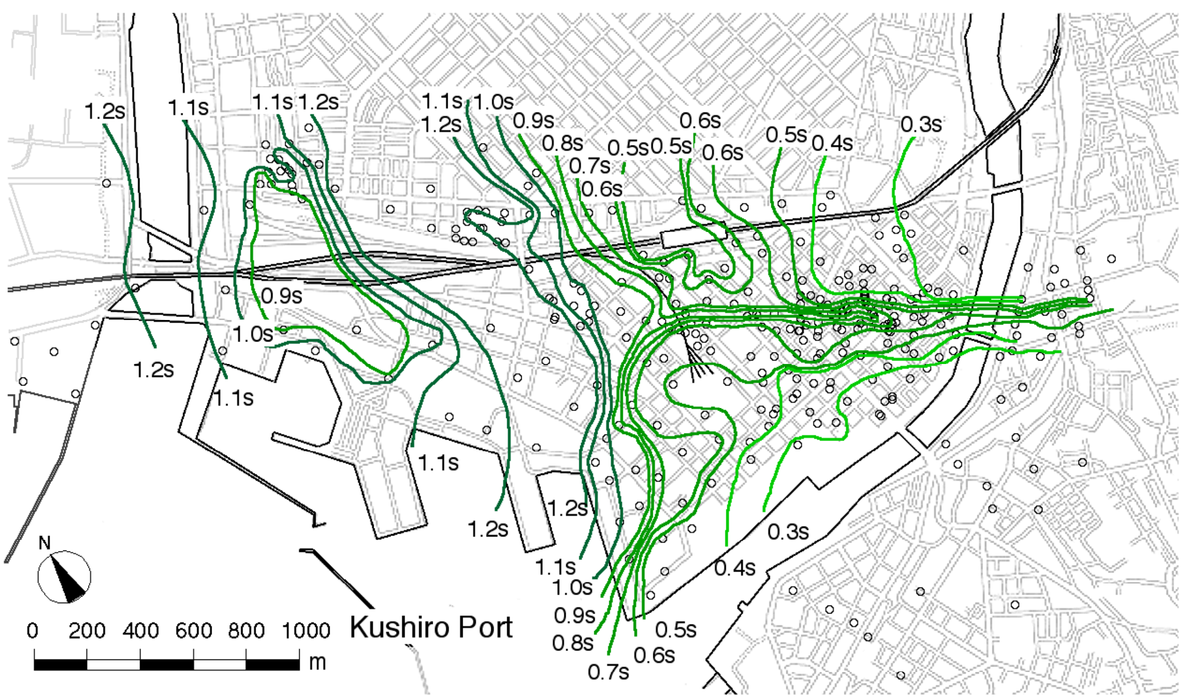

Fig. 5 Map showing contour lines of H/V peak period

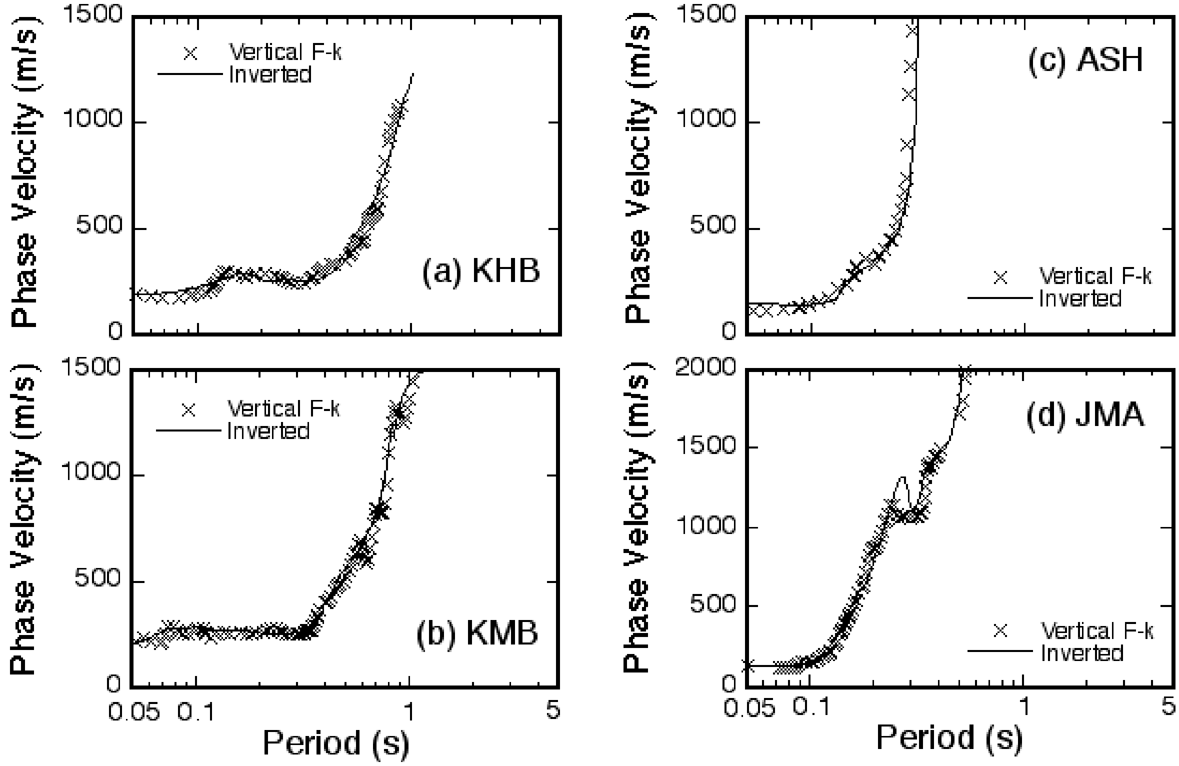

Fig. 6 Dispersion curves at selected sites

Dispersion Curves from Microtremor F-k Analysis

The high-resolution frequency-wave number (F-k) spectral analysis (Capon [8]) is used to determine dispersion curves of microtremor vertical motions recorded with arrays of sensors at the six sites. Open symbols in Fig. 6 show dispersion characteristics of microtremors at selected sites. The phase velocities at KBS and KHB, being almost constant at about 250 m/s below 0.4 s, begin to increase and become greater than 1.0 km/s at 1.0s, suggesting a soft thick layer overlies a stiff soil. In contrast, the phase velocities at JMA and ASH increase rapidly at periods greater than 0.15 s and become equal to or greater than 1.0 km/s at 0.3 s, suggesting that a stiff layer exists from a shallow depth. Considering that the peak H/V period generally increases with increasing thickness of the soft surface layer, these characteristics of dispersion curves are consistent with those of the microtremor H/V spectra and characteristics shown in Figs. 3 to 5.

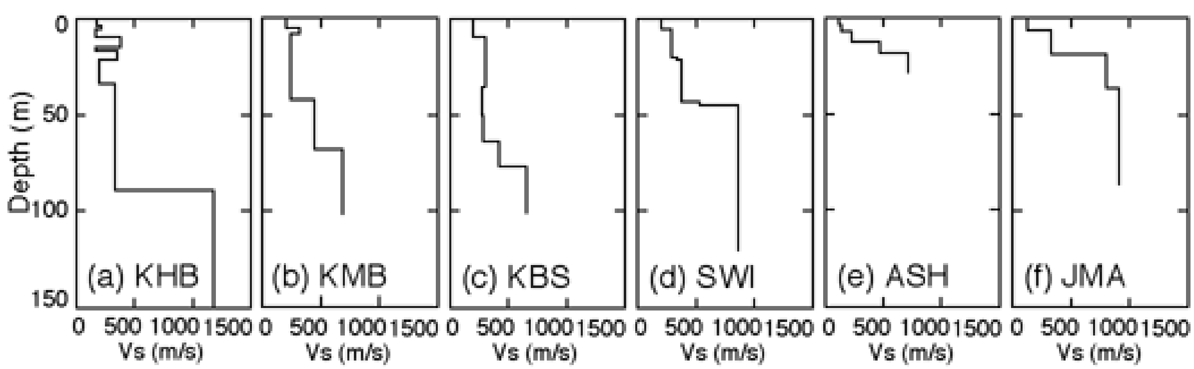

Fig. 7 Shear wave velocity profiles estimated from array observation of microtremors

Vs profiles estimated form Inversion of Microtremor Dispersion Data

An inverse analysis using the microtremor dispersion data can yield a shear wave velocity profile at each site. In the analysis, it is assumed that the observed dispersion data are those of Rayleigh waves and that the soil deposit consists of 4 to 10 horizontally stratified layers overlying an elastic half- space. The details of the analytical procedures have been described elsewhere (e.g. Tokimatsu et al. [3]).

Fig. 7 shows the shear wave velocity profiles at the six sites estimated from the inverse analysis. Comparison of Fig. 7 with Fig. 2 suggests that the layer with V_s over 650 m/s at KHB and KMB corresponds to the Pleistocene deposit and to Tertiary rock at the other sites. The depth at which the rock occurs generally decreases eastward from 80 m at KHB and less than 20 m at ASH and JMA. The shear wave velocities of the near-surface Holocene deposit are about 200-300 m/s for sand and sandy gravel layers, about 380-440 m/s for clay and silty clay layers, and less than 150 m/s for silty volcanic ash on the hill. The estimated structures appear consistent with the available geologic information shown in Fig. 2.

MULTI-DIMENSIONALVS-PROFLIES

Theoretical Background of H/V Spectrum Inversion

Arai and Tokimatsu [7] proposed theoretical formulas for computing the H/V spectrum of Rayleigh and surface (Rayleigh and Love) waves propagating on a layered half-space in which the effects of the fundamental and higher modes are taken into account, as given by the following equations.

$$(H/V)_R = (P_{HR}/P_{VR})^{1/2} \quad (3)$$

$$(H/V)_S = ((P_{HR} + P_{HL})/P_{VR})^{1/2} \quad (4)$$

in which subscripts R, L and S indicate Rayleigh, Love and surface waves, and P_H and P_V are their relative

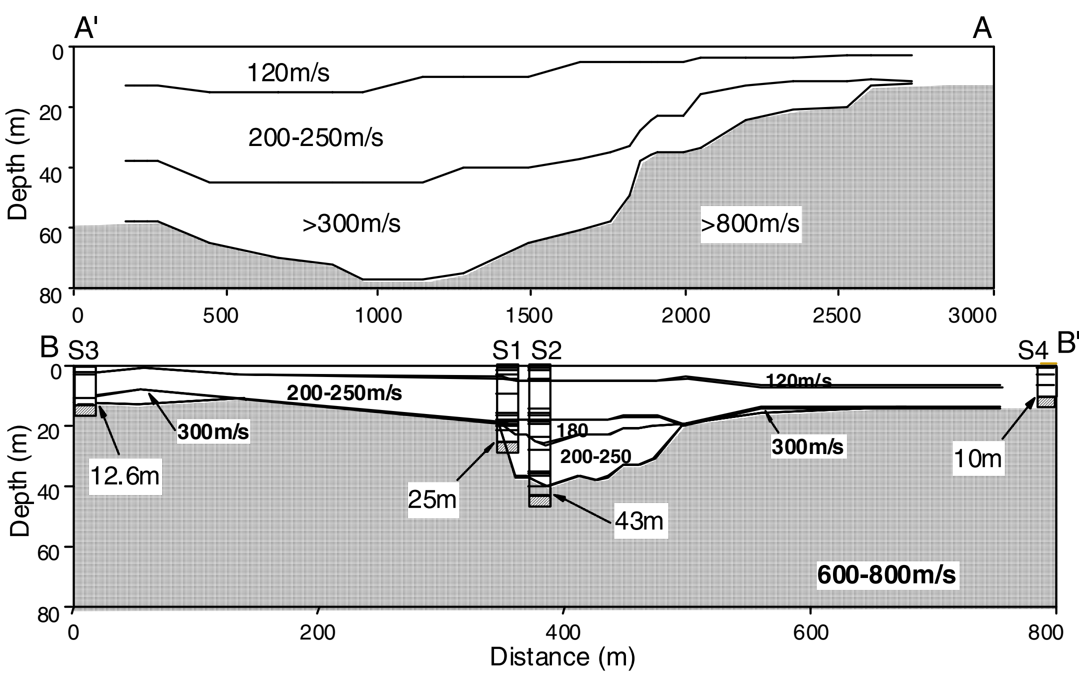

Fig. 8 Vs sections along Lines A-A' and B-B'

powers of vertical and horizontal components, respectively. P_H and P_V have been theoretically derived, provided that Fourier-time-transformed vertical and horizontal point forces having a frequency f are randomly distributed on the ground surface at distances greater than one wavelength from the observation point. It is conceivable that the theoretical H/V spectrum of Rayleigh waves given by Equation (3) corresponds to the observed microtremor H/V spectrum given by Equation (1) and that of surface waves given by Equation (4) corresponds to that given by Equation (2).

Arai and Tokimatsu [7] also proposed a method for estimating the S-wave velocity (V_S) profile of subsurface soils, based on inversion of the H/V spectrum of microtremors observed with a three-component sensor. In this study, this inverse analysis is adopted and performed so that misfits between observed and theoretical H/V spectra defined by Equations (1) and (3) are minimized, provided that the microtremor H/V ratios reflect those of the fundamental-mode Rayleigh waves. The shear wave velocities of all layers are predetermined from the results of array observation as shown in Fig. 7, and only their thicknesses are sought.

Fig. 8 shows the two-dimensional shear wave velocity structures thus determined for Lines A-A' and B-B' and Fig. 9 shows a bird-eye view of the bedrock with Vs greater than 500 m/s. Broken lines in Fig. 3 are the H/V spectra of Rayleigh waves for the inverted shear wave profiles. Good agreements in spectral shape and peak period suggest that the inverted structures could be reasonably reliable. It seems that the appearance of the second peaks at B2 and B3 is due probably to the presence of the stiff layer with V_s over 250 m/s that overlies the softer layer with V_s of about 180 m/s. The figures suggest that the depth to the bedrock on the west side of the region is about 80 m and that on the east side is generally about 20 m, except for a narrow unknown hidden valley crosses from east to west, of which depth is estimated to be about 40 m. The thick sedimentary deposit of the hidden valley contrasts well with the thin surface layer on the north and south sides of the hidden valley.

The results shown in Figs. 8 and 9 are consistent with those in Figs. 4 and 5, claiming the presence of the hidden valley. Probably, the valley that were formed by stream erosion during ice ages when the sea level was much lower than that of today, has been buried by stream deposition in the recent epoch. Since neither boring log nor geologic map confirming this estimate was available, borings are planed at two sites, labelled S1, S2, and S3 along Lone B-B' as shown in Fig. 8.

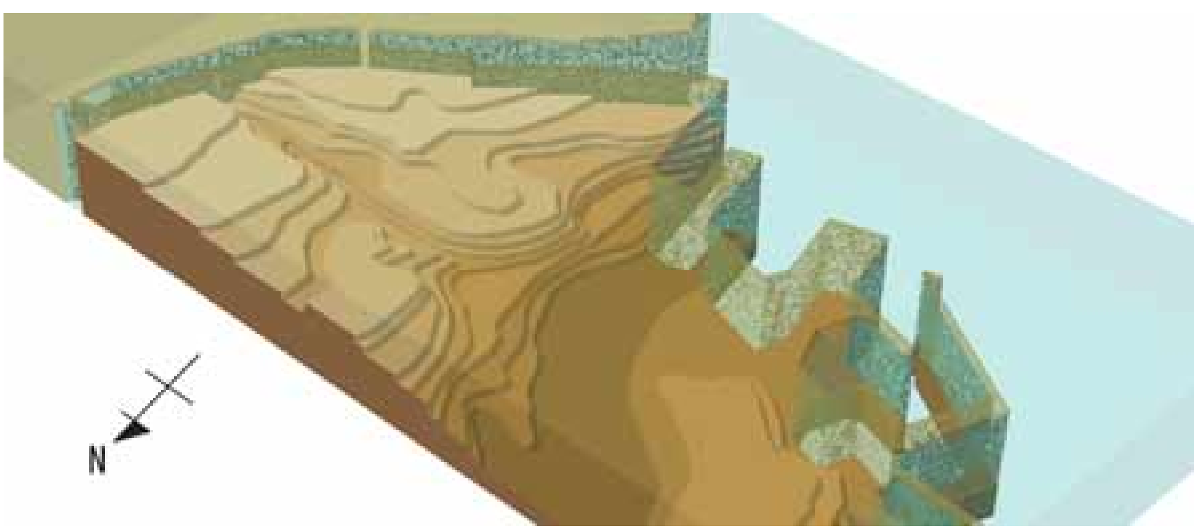

Fig. 9 Bird-eye view of estimated bedrock observed from the northwest of the city

The results of these borings are superimposed in Fig. 8. The rock occurs at depths of about 13 m at S3, 25 m at S1, and 43 m at S2, which appears to confirm the existence of the hidden valley. The confirmation of the hidden valley indicates that the proposed method may be an economical and yet reliable means of estimating multi-dimensional shear wave velocity profile.

CONCLUSIONS

A simple method for determining three-dimensional shear wave velocity profiles has been presented in which microtremor horizontal-to-vertical (H/V) spectral ratio techniques are used together with frequency-wave number (F-k) spectral analyses of microtremor array records or several available geophysical data within the region. To demonstrate the effectiveness of the proposed method, conventional microtremor measurements using a single station were conducted over Kushiro city together with microtremor measurements using array of sensors at several sites. Three-dimensional shear structures within the cities were estimated based on the microtremor dispersive characteristics and H/V spectra, assuming that they reflect those of Rayleigh waves. On the basis of the results and discussions, the following conclusions may be made:

(1) The proposed method has outlined a three-dimensional shear wave velocity structure down to the bedrock, which is consistent with the available geologic information.
(2) The proposed method has detected the presence of a hidden valley, which has been confirmed by the subsequent borings.
(3) The proposed method using microtremors could be an economical means of estimating two- or three-dimensional shear structures.

It was assumed in this study that microtremor H/V spectrum reflects that of the fundamental-mode Rayleigh waves. In reality, however, it may reflect those of surface (both Rayleigh and Love) waves, as the microtremor horizontal motions contain both. In addition, higher mode surface waves may dominate in microtremors as suggested by Arai and Tokimatsu [7]. Thus, it would be more appropriate that microtremor H/V spectrum is defined by Equation (2) and the H/V inversion be made using the theoretical H/V spectrum for surface waves defined by Equation (4) by taking into account the effects of their higher modes. Applicability and limitation of this approach to similar problem compared with the method described in this paper will be discussed elsewhere.

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