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# Three-dimensional $V_S$ profiling using microtremors in Kushiro, Japan

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## SUMMARY

A practical method is presented for determining three-dimensional S-wave velocity ($V_S$) profile from microtremor measurements. Frequency–wave number ($f$–$k$) spectral analyses of microtremor array records are combined, for this purpose, with microtremor horizontal-to-vertical ($H/V$) spectral ratio techniques. To demonstrate the effectiveness of the proposed method, microtremor measurements using arrays of sensors were conducted at six sites in the city of Kushiro, Japan. The spectral analyses of the array records yield dispersion characteristics of Rayleigh waves and $H/V$ spectra of surface waves, and joint inversion of these data results in $V_S$ profiles down to bedrock at the sites. Conventional microtremor measurements were performed at 230 stations within Kushiro city, resulting in the $H/V$ spectra within the city. Three-dimensional $V_S$ structure is then estimated from inversion of the $H/V$ spectra with the $V_S$ values determined from the microtremor array data. This reveals three-dimensional $V_S$ profile of Kushiro city, together with an unknown hidden valley that crosses the central part of the city. The estimated $V_S$ profile is consistent with available velocity logs and results of subsequent borings, indicating the effectiveness of the proposed method. Copyright © 2008 John Wiley & Sons, Ltd.

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KEY WORDS: three-dimensional $V_S$ structure; microtremor; dispersion curve; $H/V$ spectrum; surface wave; inversion

## INTRODUCTION

The S-wave velocity ($V_S$) profile is one of the key parameters for evaluating dynamic response characteristics of soil deposits. It is, however, difficult to estimate deep soil profiles using conventional geophysical methods, particularly when two- or three-dimensional soil profiles are required,

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as most of the conventional geophysical methods need boreholes and may not always be performed conveniently and economically.

The frequency–wave number ($f$–$k$) spectral analysis [1] of microtremors measured with arrays of sensors, an extended version of spectral-analysis-of-surface-wave (SASW) methods, is a cost-effective alternative, considering its potential to explore deep soils without any borehole. Previous studies [2–5], in fact, have shown the following: (1) surface (both Rayleigh and Love) waves dominate in microtremors; (2) the $f$–$k$ spectral analysis of microtremor vertical components yields dispersion characteristics of Rayleigh waves; and (3) the inverse analysis of dispersion data results in $V_S$ structure at a sedimentary site.

It has also been shown that the horizontal-to-vertical ($H/V$) spectral ratio of microtremors [6], which can be determined with a three-component sensor, corresponds to that of Rayleigh and/or surface waves and thus reflects $V_S$ structure at a site [5, 7–9]. The inversion of $H/V$ spectra can, however, result in a $V_S$ profile of the site, only if either layer thickness or S-wave velocity is known [9].

Based on the results of the microtremor studies, Arai and Tokimatsu [10] have indicated that the reliability of $V_S$ structure down to bedrock improves significantly with the joint inversion of both microtremor dispersion and $H/V$ data compared to the dispersion curve inversion. It is, however, still inconvenient and time consuming to perform the array measurement for determining dispersion curve, compared to the conventional measurement that can be easily conducted with only one station to obtain $H/V$ spectrum. Thus, each of the array and conventional microtremor methods has its merits and demerits.

These findings stated previously indicate a possibility that combined use of both array and conventional microtremor measurements could compensate for the defects and highlight the merits of the two methods, permitting evaluation of two- or three-dimensional $V_S$ structure down to bedrock in an economical manner. Several studies, e.g. [11–14] have also made a similar suggestion. The objective of this article is to explore the possibility of three-dimensional $V_S$ profiling using microtremors based on the field investigation conducted in the city of Kushiro, Japan.

## METHODOLOGY OF THREE-DIMENSIONAL $V_S$ PROFILING

### *Microtremor measurements and spectral analyses*

The proposed microtremor technique consists of a single-station measurement using a three-component sensor and simultaneous observation using array of sensors, hereafter called conventional and array measurements, respectively. The former is performed at a large number of stations within a target area to be investigated, whereas the latter is made at several sites within the area as a complement.

The data acquisition system and sensors used for both types of measurements are the same as those employed in the previous studies [5, 9, 10]. For the conventional observations, three-component microtremors are measured at each station for 5–15 min and digitized at a sampling rate of either 100 or 200 Hz. For the array observations, the sensor array configuration is close to a circular one with five or six stations, and several arrays with different radii are used at each site. For each array, microtremor vertical motions are measured simultaneously at all stations with two horizontal motions at the center for 5–50 min and digitized at an appropriate sampling frequency between 50 and 500 Hz. About 10–20 sets of data comprising 2048, 4096, or 8192 points each are made from the recorded motions and used for the following spectral analyses.



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The $H/V$ spectral ratio of microtremors at a period $T$, $(H/V)_m(T)$, is defined as

$$(H/V)_m(T) = \sqrt{\frac{P_{NS}(T) + P_{EW}(T)}{P_{UD}(T)}} \tag{1}$$

where $P_{UD}(T)$ is the Fourier power spectrum of vertical motion, and $P_{NS}(T)$ and $P_{EW}(T)$ are those of two orthogonal horizontal motions. The power spectra are determined by using the direct segment method [1] without any smoothing window. The microtremor $H/V$ spectra are determined for all the stations in the conventional measurements and only the central stations in the array measurements. The high-resolution frequency–wave number ($f$–$k$) spectral analysis [1] is used to determine dispersion curves of microtremor vertical motions recorded with each array.

### *Inversion analyses for $V_S$ profiling*

For the inversion analysis at the microtremor observation sites, the soil layer model of each site is assumed to be a semi-infinite elastic medium consisting of $J$ parallel, solid, homogeneous, isotropic layers. Each layer is characterized by its thickness, $H$, density, $\rho$, P-wave velocity, $V_P$, and S-wave velocity, $V_S$. Sensitivity analyses have revealed that $V_S$ and $H$ have stronger influence than $V_P$ and $\rho$ on Rayleigh-wave dispersion curves and surface-wave $H/V$ spectra [2, 9, 15]. The inversion of microtremor dispersion curve and/or $H/V$ spectrum can therefore be performed only with the $V_S$ and/or $H$ of the deposit, with $V_P$ and $\rho$ being dependent on $V_S$. The value of $V_P$ in each layer is assigned from that of $V_S$, provided the value of Poisson's ratio, $\nu$, ranges from 0.25 to 0.5 depending on $V_S$ as $\nu = \max(0.25, 0.5–0.1V_S$ (in km/s)).

The joint inverse analysis using both microtremor dispersion curve and $H/V$ spectrum [10] at each array observation site is performed for estimating the $V_S$ profile down to bedrock at the site. At the conventional observation sites, subsequently, the microtremor $H/V$ spectrum inversion [9] is conducted to determine the thicknesses of all sedimentary layers, given the $V_S$ values of the corresponding layers at the array sites. Compiling the inversion results at all the observation sites, finally, the three-dimensional $V_S$ structure of the target area may be determined.

In both inversions for conventional and array observations [9, 10], the generalized (non-linear) least-squares method (e.g. [16, 17]) is used because of the highly non-linear nature of the problem. In the governing equation of the problem, the weighting factors for dispersion curve and $H/V$ spectrum are set as 1 and 0.5, respectively [10], and those for frequencies are determined by the adaptive bi-weight estimation method [18]. To solve the governing equation, the modified Marquardt's technique [19, 20] is combined with the singular value decomposition method [21].

In the inversion, about 10–20 or more initial soil layer models are randomly generated, and the iteration analyses are performed using the initial models. For each initial model, the iteration procedure is repeated until the error ratio criterion, which is the root mean of the sum of the squares of the normalized misfit between observed and computed phase velocities and/or $H/V$ values, converges to an acceptably small value. Among the resulting solutions, the best one that gives the minimum value of the error ratio criterion, empirically less than 0.1 for dispersion curves and 0.2 for $H/V$ spectra, is selected for the final soil layer model.

To compute the theoretical $H/V$ spectrum of surface waves for the inversion, the value of Rayleigh-to-Love wave amplitude ratio of horizontal motion is assigned to 0.7 at any period



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[9, 10], which is based on the results of studies by Matsushima and Okada [22] and Arai and Tokimatsu [23].

Details of the methodologies and conditions of the inversions used can be found in the recent articles by Arai and Tokimatsu [9, 10].

## THREE-DIMENSIONAL $V_S$ PROFILING IN KUSHIRO

### *Microtremor observation sites and geological setting*

Figure 1 shows a map of Kushiro city, indicating six sites where array observations of microtremors were made [24]. These sites are hereafter labeled as KHB, KMB, KBS, SWI, ASH, and JMA. Sites KHB and JMA are those used in the previous studies on the joint inversion [10]. The minimum array radius used was 1 m at all the sites, and the maximum radii were 25, 120, 180, 50, 75, and 5 m at sites KHB, KMB, KBS, SWI, ASH, and JMA, respectively. The largest aperture arrays used at sites KMB, KBS, SWI, and ASH are shown in Figure 1. Conventional microtremor measurements were conducted at 230 stations over the city as shown in Figure 1 (open circles). The distance between two adjacent stations ranged from about 10 to 300 m, depending on the variation of microtremor $H/V$ spectra with distance.

Figure 2 illustrates a schematic diagram of geologic cross section along Line A–A′ in Figure 1 [25]. Site JMA is located on a hill covered by a thin layer of silty volcanic ash that overlies Tertiary rock, called Urahoro group. Sites ASH, SWI, and KBS are situated on a Holocene layer that overlies Tertiary rock. Sites KMB and KHB lie on a Holocene layer underlain by a Pleistocene layer, called Kushiro group. The depth to Urahoro and Kushiro groups generally increases westward from about 20 to 80 m.

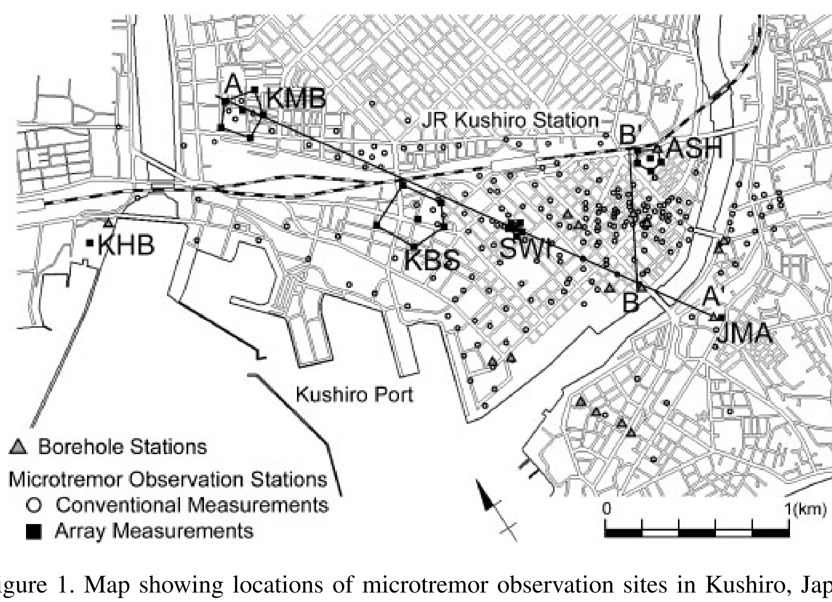


Figure 1. Map showing locations of microtremor observation sites in Kushiro, Japan.



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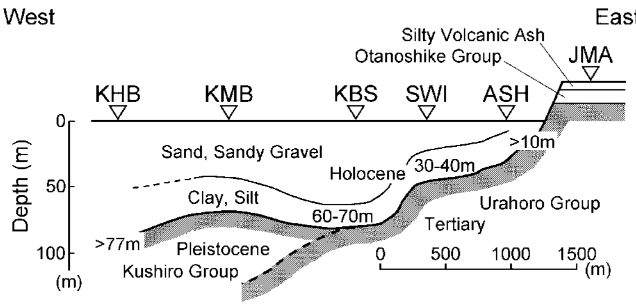


Figure 2. Schematic diagram showing geologic cross section along Line A–A′ in Kushiro [25].

*$V_S$ profiles from microtremor array data*

The dispersion curves and $H/V$ spectra determined for the six array observation sites are shown in Figures 3 and 4, respectively, as open circles. In Figure 4, the standard deviations of $H/V$ values, which are evaluated from those of $P_{UD}$, $P_{NS}$, and $P_{EW}$ in Equation (1), are also shown as vertical error bars. At each site, the observed $H/V$ spectrum has a distinct peak at a period of 0.2–1.2 s and the dispersion curve is detected in a period range shorter than the $H/V$ peak period. Based on the $H/V$ peak periods and Figure 2, there seems to be a good correlation between the $H/V$ peak period and the depth to Urahoro or Kushiro group. From the minimum and maximum phase velocities and shapes of the detected dispersion curves, it is also supposed that these dispersion data are sensitive to $V_S$ profiles above engineering bedrock with $V_S = 0.4$–$0.7$ km/s or higher. These indicate that the observed dispersion curves and $H/V$ spectra could reflect the characteristics of shallow $V_S$ structures above Urahoro or Kushiro group, which is considered as engineering bedrock.

A joint inverse analysis is conducted using the microtremor dispersion and $H/V$ data shown in Figures 3 and 4. In the inversion, the following assumptions are made: (1) the soil profile down to seismic bedrock at each site consists of a five- to seven-layered half-space, and (2) the deep soil layers below the boundary between Holocene and engineering bedrock are interpolated between the velocity structures listed in Tables I and II, which are based on available geological and geophysical information at sites KHB and JMA, respectively [25, 26]. This leaves unknown thicknesses and S-wave velocities of three to five layers above the engineering bedrock to be sought in the inversion. The variation ranges of the inversion parameters (thickness and S-wave velocity) and the inferred densities and P-wave velocities of the shallow soil layers in the initial models generated at the sites are shown in Tables III–V.

Solid black lines in Figure 5(a)–(f) show the S-wave velocity profiles estimated from the joint inverse analyses at the six sites. Solid lines in Figures 3 and 4 are the dispersion curve of Rayleigh waves and the $H/V$ spectrum of surface waves, respectively, computed for the soil profile estimated at each site. In the figures, the computed theoretical values show fairly good agreement with the observed ones at all the sites. In Figure 5, the standard errors $\sigma_j$ of the parameters $p_j$ at the $j$th layer evaluated in the inversion [2, 9, 27, 28] are shown as chained light gray lines. The standard error ratios of the estimated parameters $\sigma_j/p_j$ are generally less than 0.1 in any soil layer at all the sites. PS logging data available down to depths of 77 m at site KHB and 20 m at site JMA [29, 30] are shown as broken black lines in Figures 5(a) and (f), respectively.



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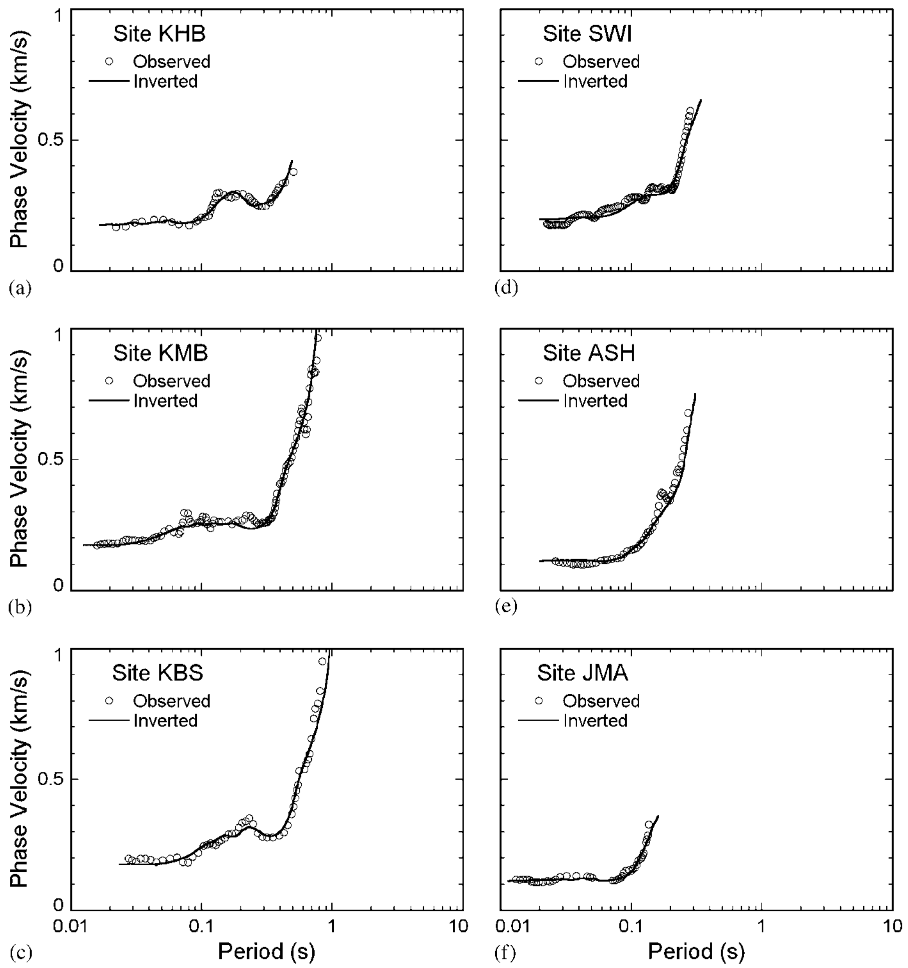


Figure 3. Dispersion curves of microtremor vertical motions (open circles) compared with those of theoretical Rayleigh waves (solid lines) for soil profiles inferred by joint inversion using both dispersion and $H/V$ data at array observation sites in Kushiro.

The estimated $V_S$ profiles at both sites are roughly consistent with the available PS logs. The differences between $V_S$ profiles from the microtremor and borehole methods at each site could be permissible for evaluating local site effects during earthquakes, as discussed in the previous article [10].

A comparison of Figures 2 and 5 suggests that the layers with $V_S$ over about 600 m/s at sites KHB and KMB on the west side of the city correspond to the Pleistocene deposit (Kushiro group), whereas those at the other sites on the east correspond to the Tertiary rock (Urahoro group). The depth at which the rock formation starts to appear generally increases westward. The $V_S$ values of the overlying Holocene deposit are about 250–350 m/s for clay and silt layers, about 200–300 m/s for sand and sandy gravel layers, and about 100–200 m/s for top thin layers including silty volcanic ash on the hill.



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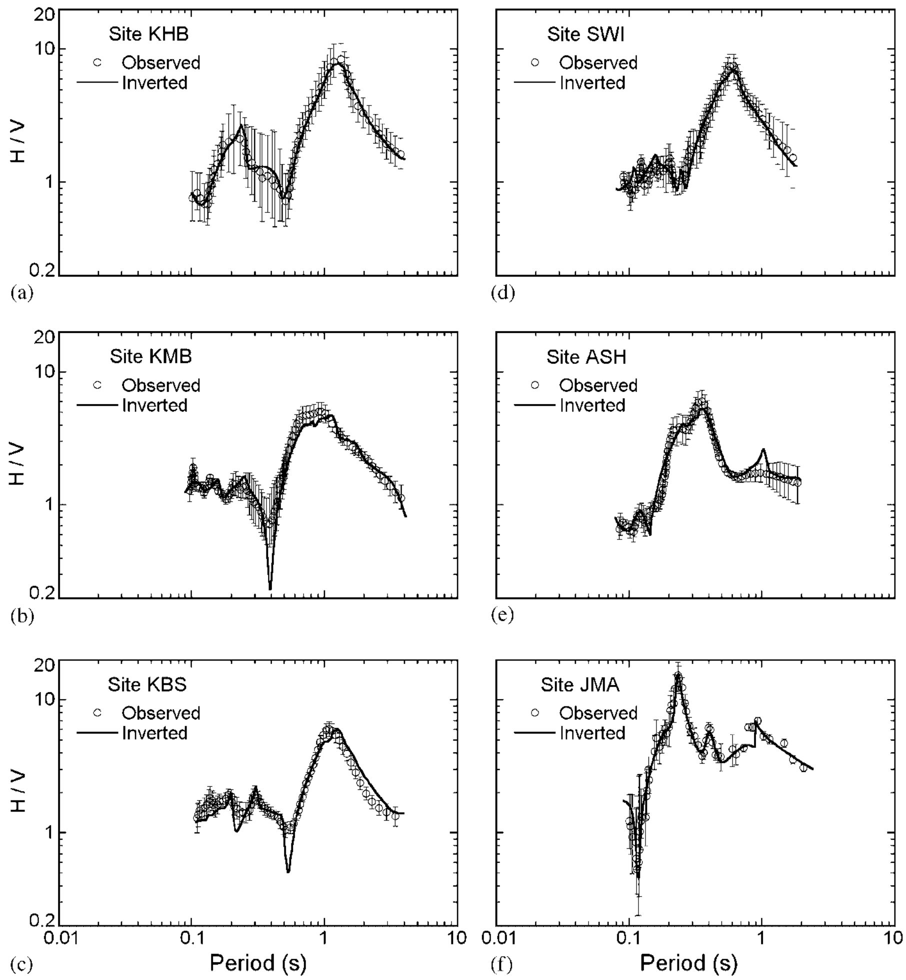


Figure 4. $H/V$ spectra of microtremors (open circles) compared with those of theoretical surface waves (solid lines) for soil profiles inferred by joint inversion using both dispersion and $H/V$ data at array observation sites in Kushiro. Vertical error bars indicate standard deviations of microtremor $H/V$ values.

Table I. Deep ground structure at site KHB in Kushiro, inferred from geological information and results of microtremor array observations [25, 26] (refer to Arai and Tokimatsu [10]).

| Depth (m) | $\rho$ (t/m$^3$) | $V_P$ (km/s) | $V_S$ (km/s) |
|---|---|---|---|
| 100–200 | 1.9–2.0 | 1.7–2.4 | 0.6–1.0 |
| 200–3000 | 2.1 | 3.6 | 1.9 |
| >3000 | 2.3 | 5.6 | 3.2 |



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Table II. Deep ground structure at site JMA in Kushiro, inferred from geological information and results of microtremor array observations [25, 26] (refer to Arai and Tokimatsu [10]).

| Depth (m) | $\rho$ (t/m$^3$) | $V_P$ (km/s) | $V_S$ (km/s) |
|---|---|---|---|
| 25–150 | 1.9–2.0 | 1.7–2.4 | 0.6–1.0 |
| 150–650 | 2.1 | 3.6 | 1.9 |
| >650 | 2.3 | 5.0 | 2.9 |

Table III. Variation ranges of thickness and S-wave velocity and inferred densities and P-wave velocities of shallow soil layers in initial models for joint inversions at site KHB (refer to Arai and Tokimatsu [10]).

| Thickness (m) | $\rho$ (t/m$^3$) | $V_P$ (km/s) | $V_S$ (km/s) |
|---|---|---|---|
| 0.5–20 | 1.6 | 0.5–1.7 | 0.05–0.5 |
| 0.5–20 | 1.7 | 0.5–1.7 | 0.05–0.5 |
| 1–50 | 1.8 | 0.5–1.7 | 0.05–0.5 |
| 2–100 | 1.8 | 0.7–2.2 | 0.1–0.8 |
| * | 2.0 | 1.5–2.7 | 0.4–1.2 |

*The bottom of this layer connects to the top of the deep soil layers.

Table IV. Variation ranges of thickness and S-wave velocity and inferred densities and P-wave velocities of shallow soil layers in initial models for joint inversions at sites KMB, KBS, and SWI.

| Thickness (m) | $\rho$ (t/m$^3$) | $V_P$ (km/s) | $V_S$ (km/s) |
|---|---|---|---|
| 0.5–20 | 1.6 | 0.5–1.7 | 0.05–0.5 |
| 1–50 | 1.7 | 0.5–1.7 | 0.05–0.5 |
| 2–100 | 1.8 | 0.7–2.2 | 0.1–0.8 |
| * | 2.0 | 1.5–2.7 | 0.4–1.2 |

*The bottom of this layer connects to the top of the deep soil layers.

Table V. Variation ranges of thickness and S-wave velocity and inferred densities and P-wave velocities of shallow soil layers in initial models for joint inversions at sites ASH and JMA (refer to Arai and Tokimatsu [10]).

| Thickness (m) | $\rho$ (t/m$^3$) | $V_P$ (km/s) | $V_S$ (km/s) |
|---|---|---|---|
| 0.5–10 | 1.6 | 0.5–1.3 | 0.05–0.3 |
| 1–30 | 1.7 | 0.7–1.7 | 0.1–0.5 |
| * | 1.9 | 1.5–2.7 | 0.4–1.2 |

*The bottom of this layer connects to the top of the deep soil layers.

### *Microtremor $H/V$ spectra*

Open circles in Figure 6 show the $H/V$ spectra at eight stations along Lines A–A′ and B–B′. Also shown as vertical bars in the figure are the standard deviations of the $H/V$ values observed at each station. The peak period of $H/V$ spectrum varies from place to place, namely, it increases



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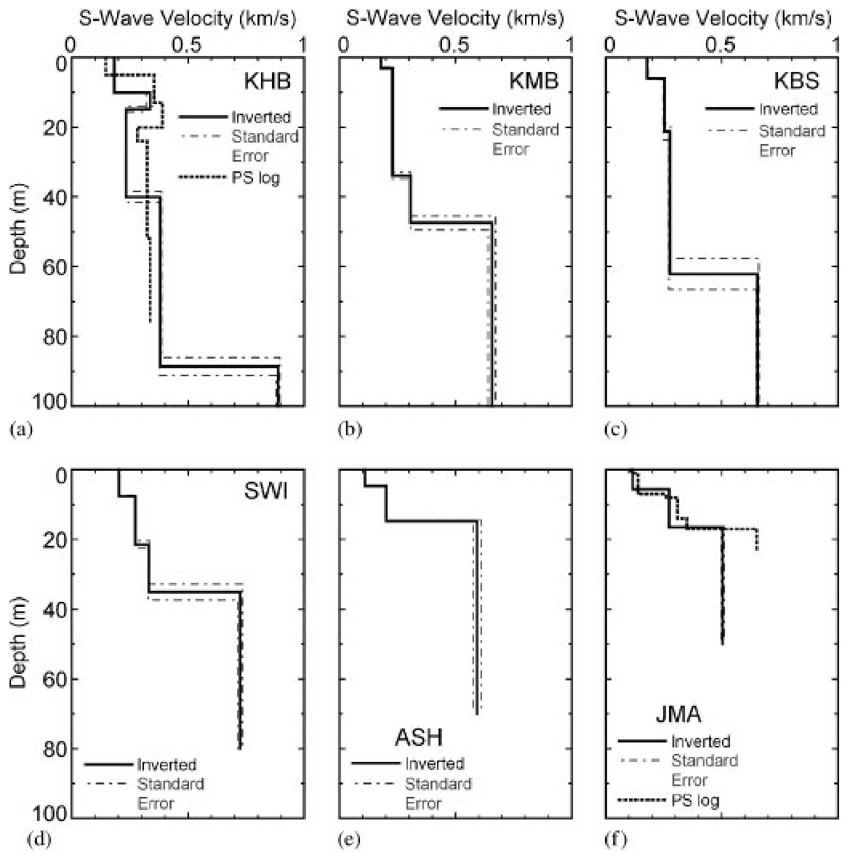


Figure 5. S-wave velocity profiles estimated by joint inversion using both dispersion curve and $H/V$ spectrum of microtremors at array observation sites in Kushiro (solid black lines). Also shown as chained light gray lines are standard errors of soil layer models evaluated by joint inversion. Broken black lines in panels (a) and (f) indicate S-wave velocity profiles from borehole logs at sites KHB and JMA, respectively [29, 30].

westward from 0.3 to 1 s along Line A–A′, but it is always about 0.3 s along Line B–B′ except for the middle of the line where it increases up to 0.7 s. These trends suggest that the $V_S$ structure could vary considerably along both lines, although no topographical variation exists except for the hill on the eastern end of Line A–A′. Of particular interest in the figure are the second prominent peaks occurring at stations B2 and B3 that cannot be identified at other stations.

To investigate whether the trends indicated previously exist within the area, the spatial variations of the $H/V$ spectra along the two lines are shown in Figure 7 using gradations as shown in the legend. In the figure, the $H/V$ values between two adjacent stations are inferred by linear interpolation of those at the stations. The figure generally confirms the findings from Figure 6, in which the $H/V$ peak period increases westward from 0.2 to 1.2 s along Line A–A′. In contrast, it changes abruptly from about 0.3 to 0.8 s in the middle of Line B–B′, accompanied by the second prominent peak at 0.2–0.3 s.



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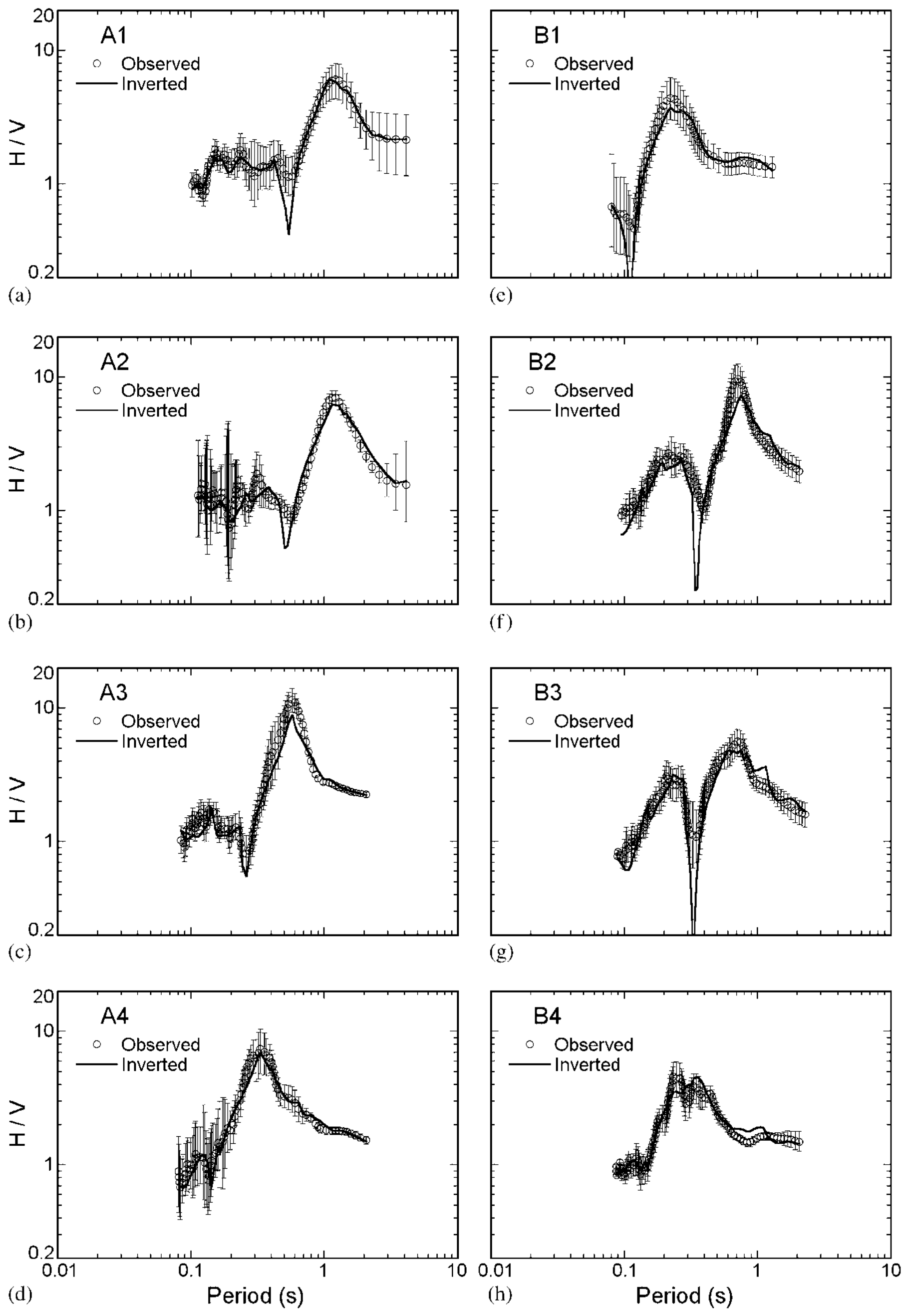


Figure 6. $H/V$ spectra of microtremors (open circles) compared with those of theoretical surface waves (solid lines) for soil profiles inferred by $H/V$ inversion at eight stations along Lines A–A′ and B–B′ in Kushiro. Vertical error bars indicate standard deviations of microtremor $H/V$ values.

*Three-dimensional $V_S$ profile*

The inverse analyses of microtremor $H/V$ spectra are performed to determine the $V_S$ structures for the 230 stations where the conventional microtremor measurements were made. The $V_S$ values of all the soil layers at each station are assigned to those of the corresponding layers estimated from the array observations as stated previously, which leaves only the thicknesses of top two or three layers above the engineering bedrock (Kushiro or Urahoro group) unknown in the inversion.

On the eastern side of the target area, borehole data down to Urahoro group with a maximum depth of 50 m are available at 15 sites shown as open triangles in Figure 1, where the shallow $V_S$ profiles are estimated from the microtremor $H/V$ inversion. Figure 8 shows a comparison of

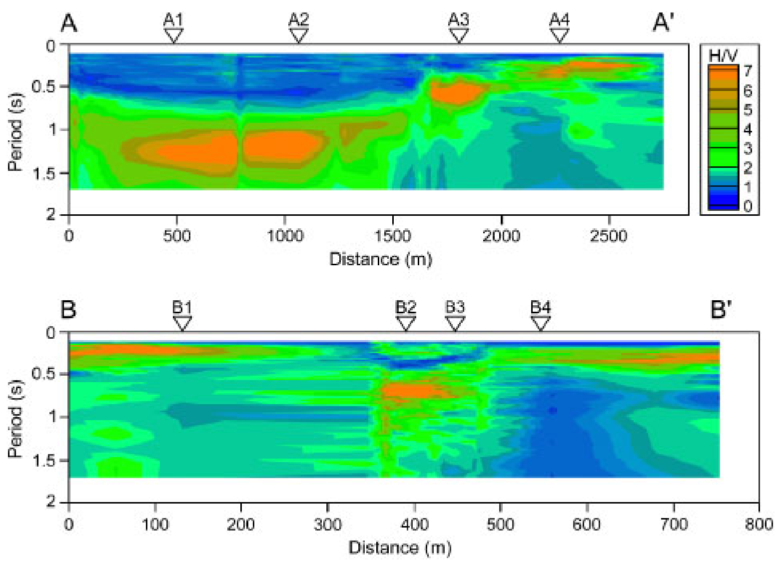


Figure 7. Spatial variations of microtremor $H/V$ spectra along Lines A–A′ and B–B′ in Kushiro.

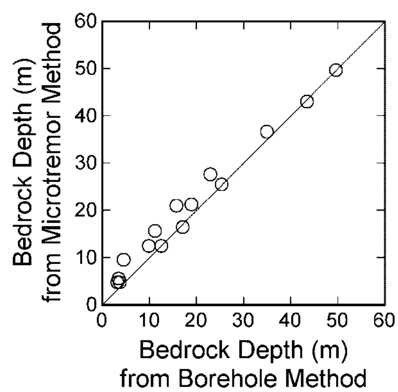


Figure 8. Comparison of depths to engineering bedrock (Urahoro or Kushiro group) estimated from proposed microtremor method with those from available borehole data at 15 sites shown in Figure 1.



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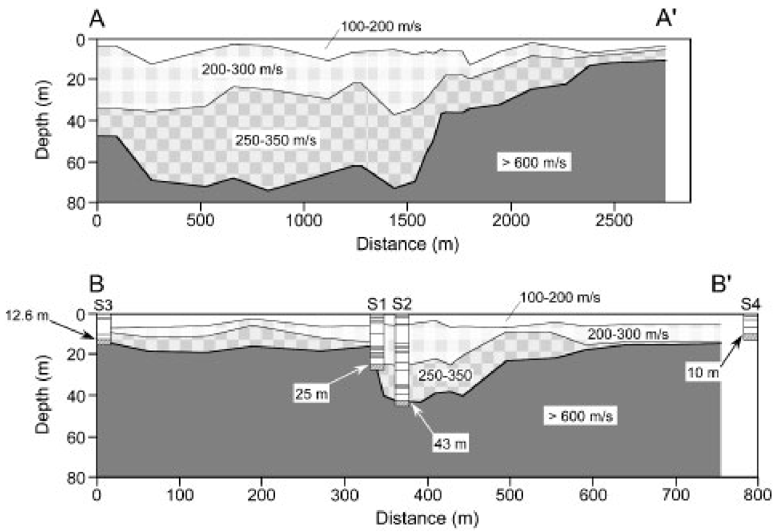


Figure 9. Two-dimensional shallow S-wave velocity structures estimated from proposed microtremor method along Lines A–A′ and B–B′ in Kushiro. Results of boring investigation at sites S1–S4 along Line B–B′ are also shown in lower figure.

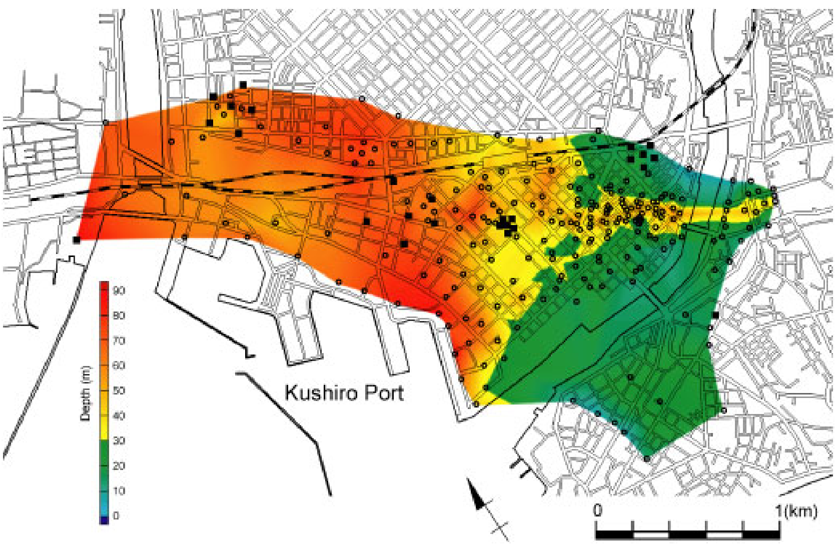


Figure 10. Map showing spatial variation of depth to engineering bedrock in Kushiro (Urahoro or Kushiro group) estimated from proposed microtremor method.

the bedrock depths from the estimated $V_S$ structures with those from the borehole data at the 15 sites. The engineering bedrock depths estimated from microtremors are consistent with those from borehole method, indicating that the proposed microtremor method is promising.



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Figure 9 shows two-dimensional $V_S$ structures thus determined for Lines A–A′ and B–B′. Solid lines in Figure 6 are the $H/V$ spectra of surface waves for the inverted $V_S$ profiles. Good agreements between the observed and theoretical spectra indicate that the inverted structures are reasonably reliable. Figure 10 shows a map indicating the spatial variation of the depth to the engineering bedrock estimated from the inversion analyses. The figure suggests that, in addition to a wide hidden valley with a maximum depth of 70–80 m that runs from the north to the south in the central part of the city, a narrow unknown hidden valley with a depth of 40–50 m also runs from the southeast to the northwest. Probably, the valley 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 the presence of the narrow hidden valley was available, borings were planned at two sites, labeled as S1 and S2 along Line B–B′ in Figure 9. The results of these borings are superimposed on the figure. The rock occurs at depths of 25 m at site S1 and 43 m at site S2, which appears to confirm the presence of the hidden valley. This confirms again that the proposed method is an economical and yet reliable means of estimating three-dimensional $V_S$ structure including hidden valley.

## CONCLUSIONS

A simple method for determining three-dimensional S-wave velocity profiles has been presented in which frequency–wave number ($f$–$k$) spectral analyses of microtremor array records are combined with microtremor horizontal-to-vertical ($H/V$) spectral ratio techniques. To demonstrate the effectiveness of the proposed method, microtremor measurements were conducted in Kushiro city using single station and with arrays of sensors. Three-dimensional $V_S$ structure within the city is then estimated based on the microtremor dispersive characteristics and $H/V$ spectra, assuming that they reflect those of Rayleigh and surface waves. On the basis of the results and discussions, the following conclusions are made:

1. The proposed method has outlined a three-dimensional $V_S$ structure down to 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 is an economical means of estimating three-dimensional $V_S$ structure.

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