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**Paper No. 1485. (quote when citing this article)**
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

# COMPARISON OF LOCAL AMPLIFICATIONS ESTIMATED FROM MICROTREMOR F-K SPECTRUM ANALYSIS WITH EARTHQUAKE RECORDS

HIROSHI ARAI*, KOHJI TOKIMATSU*, and AKIO ABE**

* Tokyo Institute of Technology, 2-12-1 O-okayama, Meguro-ku, Tokyo 152, Japan
** Tokyo Soil Research Co. Ltd., 2-1-12 Umezono, Tsukuba-shi, Ibaraki 305, Japan

## ABSTRACT

Possible use of short-period microtremors is explored for estimating the effects of subsurface soil conditions on the ground motion characteristics. For this purpose, microtremor measurements are conducted using arrays of sensors at six sites that are located on different soils in Kushiro city. Based on the F-k spectrum analysis of microtremors, dispersion curves of Rayleigh waves for the sites are determined. The inverse analyses of these dispersion curves result in shear wave velocity profiles down to a depth of the bedrock with $V_s$ greater than 650 m/s, called Kushiro or Urahoro group. With these profiles, the S-wave transfer functions between surface and down-hole stations at two sites as well as those between surface stations are computed, and compared with those of the observed strong motion records. The computed and observed transfer functions show a fairly good agreement, indicating that the array observations of microtremors are economical and yet reliable means for estimating local site conditions.

## KEYWORDS

microtremors, shear wave structure, array observation, F-k spectrum analysis, Rayleigh waves, microtremor H/V spectrum, natural site period, transfer function, site effects

## INTRODUCTION

Recent studies have shown that microtremor measurements at a site using an array of sensors can successfully extract Rayleigh-wave dispersion characteristics. The inversion using these dispersion data can provide a shear wave velocity($V_s$) profile at the site(e.g., Horike, 1985; Okada and Matsushima, 1986; Tokimatsu *et al.*, 1992). This method is attractive, since it can readily be made on the ground surface without drilling any boreholes, and provides shear wave velocity profiles that control local site conditions during earthquakes. Thus, the method could be an economical mean of estimating local site conditions, if shear wave velocity profiles down to bedrock can be determined with a reasonable degree of accuracy.

To explore such a possibility, field tests were conducted at six sites (Kushiro Japan Meteorological Agency, Kushiro Harbor, Asahi, Kotobuki, and Komaba elementary school, and Saiwaityo-kouen, hereby abbreviated as JMA, KHB, ASH, KBS, KMB and SWI) in Kushiro city, Hokkaido, Japan. These sites, located on different soils, have been shaken in a completely different manner during past earthquakes. In the Hokkaido Toho-oki earthquake of October 4, 1994, for example, the peak ground accelerations were 0.40 G at JMA, 0.33 G at ASH, and 0.18 G at KMB(e.g., Association for Earthquake Disaster Prevention, 1995).

The F-k spectrum analysis of microtremors and the inverse analysis of the resulting dispersion data successfully provided the $V_s$ profiles from the ground surface to the bedrock at the sites. This enables one to examine the total performance of the present method, by comparing the observed transfer functions with those computed for the $V_s$ profiles obtained from microtremor measurements. This paper outlines the field test procedures and in-house analysis involved, then discusses the effectiveness of the present method.

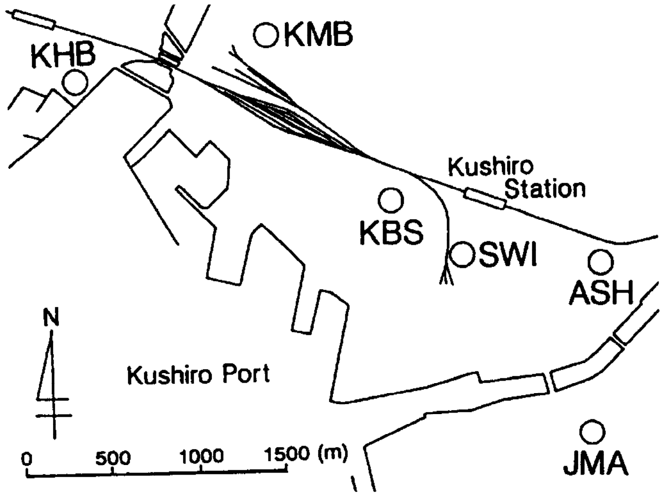


Fig. 1 Map showing observation sites

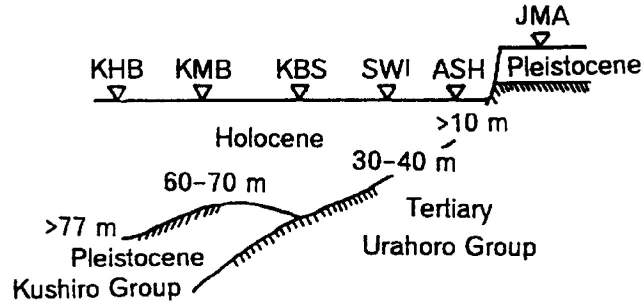


Fig. 2 Schematic diagram showing geologic cross section

## ARRAY OBSERVATION OF MICROTREMORS

Array observations of microtremors were conducted at KHB, KMB, KBS, SWI, ASH, and JMA, of which locations are shown in Fig. 1. Fig. 2 shows a schematic diagram showing geologic cross section along the line passing through KHB and JMA. JMA is located on a hill covered by a thin volcanic deposit that overlies Tertiary rock. ASH, SWI, and KBS are situated on Holocene deposit that overlie Tertiary rock, and KMB and KHB lie on Holocene deposit underlain by Pleistocene deposit. At ASH and SWI, the depths to the Tertiary rock are more than 10 m and 30–40 m, respectively. At KMB and KHB, the depths to the Pleistocene are 60–70 m and more than 77 m, respectively.

The test equipment used in this study consists of amplifiers, A/D converters, and a note–size personal computer, all built in a portable case; and of three–component sensors. This system has a maximum sensitivity of 26 $\mu$kine/V (2.6 nm/s/V). The natural period of the sensors is either 1 s or 5 s. The computer is a model PC9801–NS/R from NEC, and the A/D converter has a resolution of 16 bits.

Five or six three–component sensors were placed on the ground surface to form a circular observation 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. The minimum array radius was 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.

With each array, the ground surface motions of microtremors were measured simultaneously. The analog motions measured with the sensors were amplified, converted into digitized form at a sampling frequency of 50–500 Hz, and stored in the hard disk of the computer. Generally, 16–24 sets of digitized records with 2048 or 4096 data points each were obtained for each array, and used in the subsequent analysis. In the short wavelength range in which microtremor amplitudes get low, the Spectrum Analysis of Surface Waves (SASW) method (e.g., Stokoe and Nazarian, 1984) was adopted in which several sensors were placed on the ground in a line with a source. This measurement covers the characteristics near the ground surface, while microtremor measurements those of deeper depths.

## $V_s$ PROFILING USING F–k SPECTRUM ANALYSIS

Fig. 3(a)–(d) show high resolution frequency–wavenumber spectra at KMB on a two–dimensional wavenumber space at several frequencies for the vertical motions of microtremors. The details of the F–k spectrum analysis have been described elsewhere(e.g., Capon, 1973). The maximum of the spectral power is indicated by an asterisk and the contours of the spectral power are drawn from 0 to 12 dB in steps of 2 dB. In the figure, the spectrum has a clear–pointed peak on the north to north–west, indicating that the microtremors propagated mainly from that direction where a paper mill is located.

Open circles in Fig. 4(a)–(d) are the dispersion data resulting from the F–k spectrum analyses of the microtremor records at KHB, KMB, ASH, and JMA. Fig. 4(c) shows that the data at ASH show a normally dispersive trend in which the phase velocity increases with increasing wavelength. At KHB, KMB, and JMA, on the other hand, the data show inversely dispersive trends at wavelength of 50 m, 50 m, and 300 m, respectively.

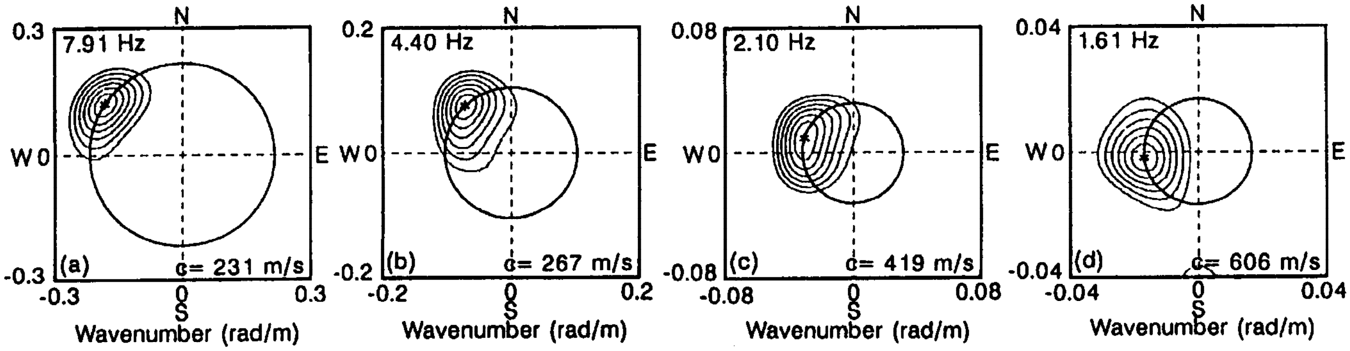


Fig. 3 F–k spectra at selected frequencies for microtremors at KMB

Using the dispersion data shown in Fig. 4 and assuming a 4– to 6–layer model, the inverse analysis was conducted for each site in which the effects of higher Rayleigh modes were considered(e.g., Tokimatsu et al., 1992). Fig. 5(a)–(d) show the $V_s$ profiles at KHB, KMB, ASH, and JMA estimated from the inversion. At each site of the figure, the soft layers overlie the stiff layer with $V_s$ over 650 m/s. The depths to the stiff layer vary from place to place, and are 89 m, 68 m, 77 m, 45 m, 18 m, and 18 m at KHB, KMB, KBS, SWI, ASH, and JMA, respectively. The Rayleigh–waves dispersion curves for the inverted soil profiles at each site are shown in Fig. 4 in solid lines, which are compatible with the observed data. A comparison of Figs. 4 and 5 indicates that at KHB and KMB, the presence of the stiff layers at depths 10–25 m within the soft soils is the primary factor for the inversely dispersive trends at wavelengths less than 50 m.

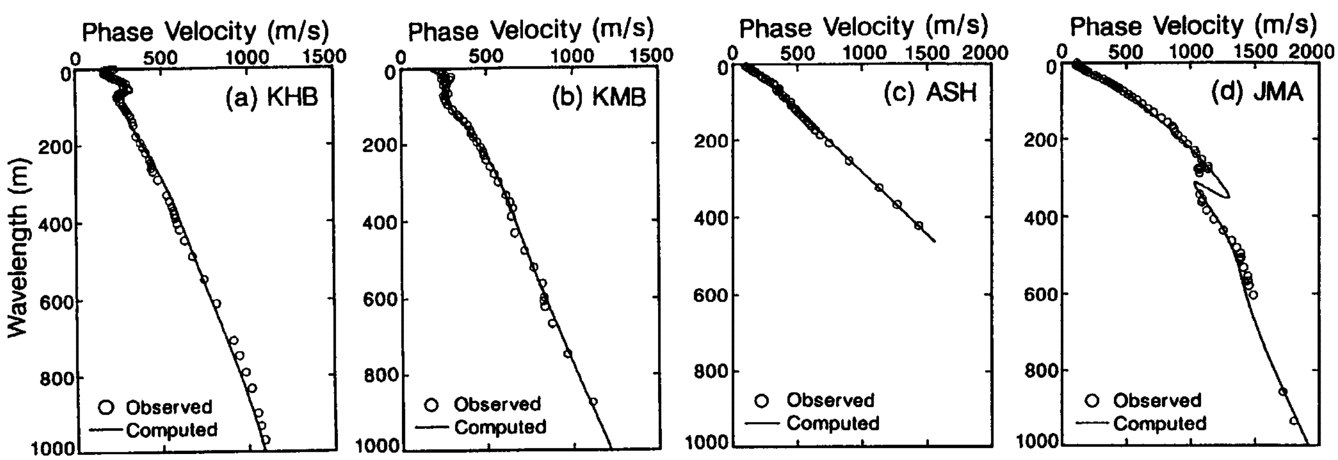


Fig. 4 Observed and computed dispersion curves at KHB, KMB, ASH, and JMA

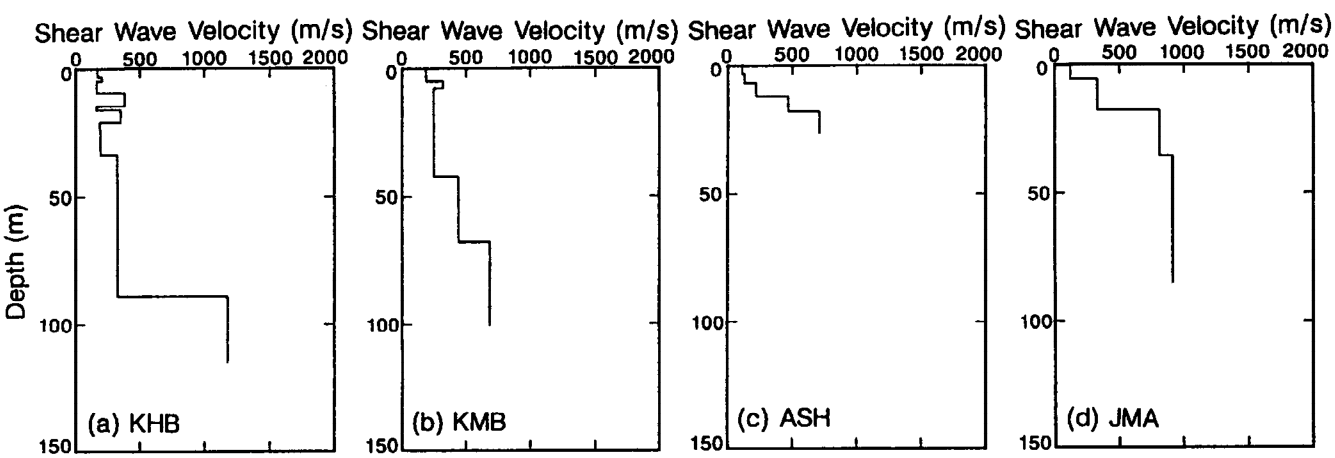


Fig. 5 $V_s$ profiles estimated from microtremor analyses at KHB, KMB, ASH, and JMA

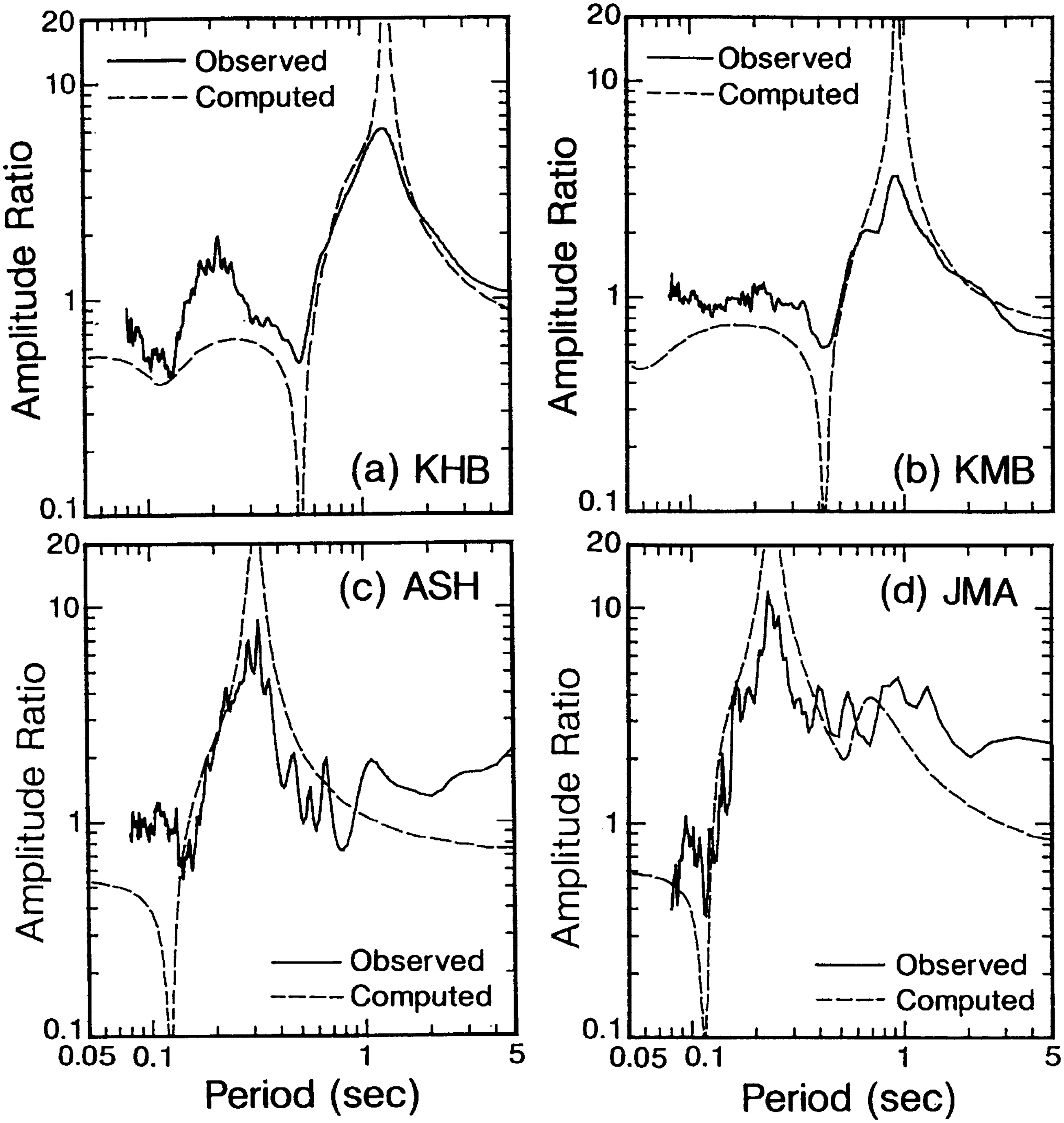


Fig. 6 Microtremor H/V spectra compared with those of theoretical Rayleigh waves at KHB, KMB, ASH, and JMA

The solid lines in Fig. 6(a)–(d) show the variation with frequency of horizontal–vertical amplitude ratio(H/V spectrum) of microtremors(e.g., Nakamura and Ueno, 1986, Tokimatsu and Miyadera, 1992) at the array centers of KHB, KMB, ASH, and JMA, respectively. At each site, the microtremor H/V spectrum has a clear peak. The broken lines in the Figure are the amplitude ratios of Rayleigh waves, computed for the estimated soil profiles. The Rayleigh–wave amplitude ratios, as well as the periods of their peaks and minimums, are in good agreement with the observed H/V spectra. This indicates that the microtremor H/V spectrum reflects that of Rayleigh waves(Tokimatsu and Miyadera, 1992), and that the inferred soil profiles are reasonable.

## RELATION AMONG SHEAR WAVE STRUCTURE, NATURAL SITE PERIOD AND MICROTREMOR H/V RATIO

The estimated shear wave velocity profiles shown in Fig. 5 are consistent with the available geologic information as shown in Fig. 2. Based on these results and information, the geophysical and geological cross sections along the line passing through KHB and JMA are shown in Fig. 7. The layer with $V_s$ over 650 m/s, at KHB and KMB, corresponds to the Pleistocene deposit called Kushiro group, and at the other sites, it corresponds to the Tertiary rock called Urahoro group. The shear wave velocities of the overlying Holocene deposits are about 200 to 330 m/s in sandy or sandy gravel layer, and about 380 to 440 m/s in clay or silty layer.; however, they are less than 150 m/s at JMA on the hill.

Fig. 8(a) shows the correlation of the H/V peak period of microtremors with the natural site period of the vertically incident S-waves computed for the inferred soil profiles, and Fig. 8(b) shows the relation between the H/V peak period and depth to the Pleistocene or Tertiary rock. The microtremor H/V peak period shows a good agreement with the natural site period. Thus, microtremors reflect geophysical and geological profiles, in such a way that the larger the H/V peak period(the natural site period), the deeper the top of the layer with $V_s$ over 650 m/s becomes. These results indicate that the microtremor H/V spectrum could be an effectiveness and economical means for estimating natural site periods, on the condition that the impedance ratio between surface layer and bedrock is moderate to high.

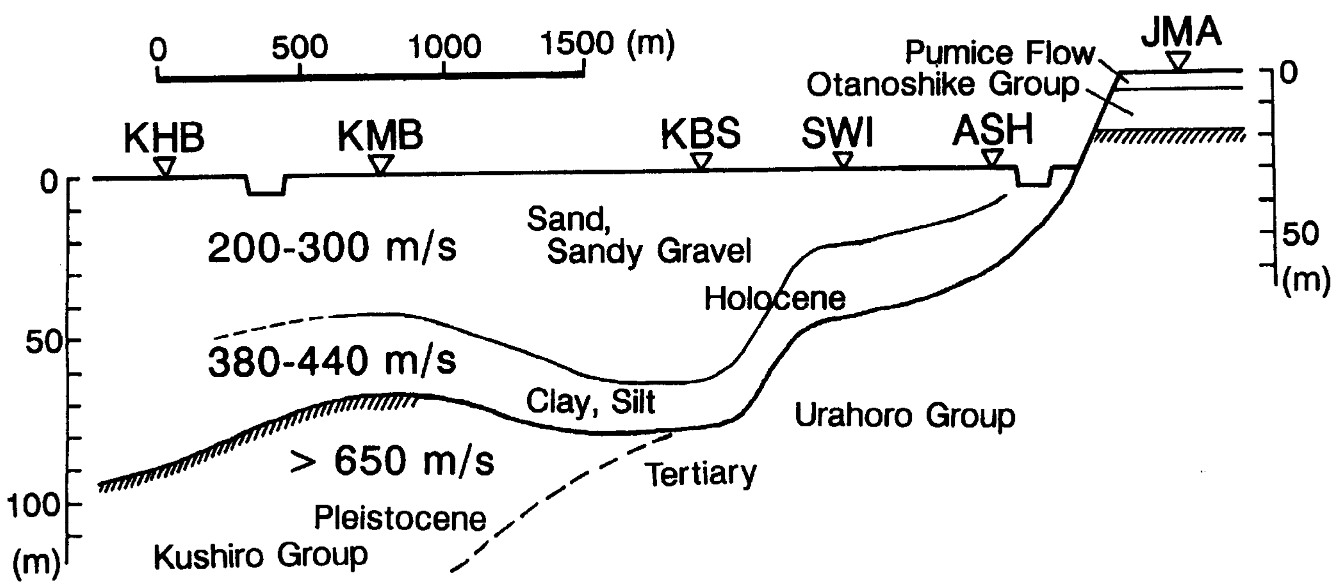


Fig. 7 Geophysical and geological cross sections along the line passing through KHB and JMA

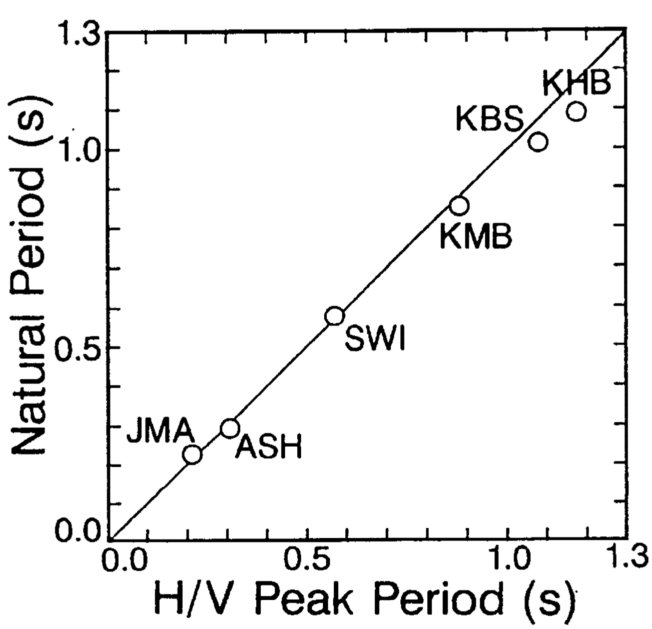


Fig. 8(a) Correlation of the H/V peak period with the natural site period

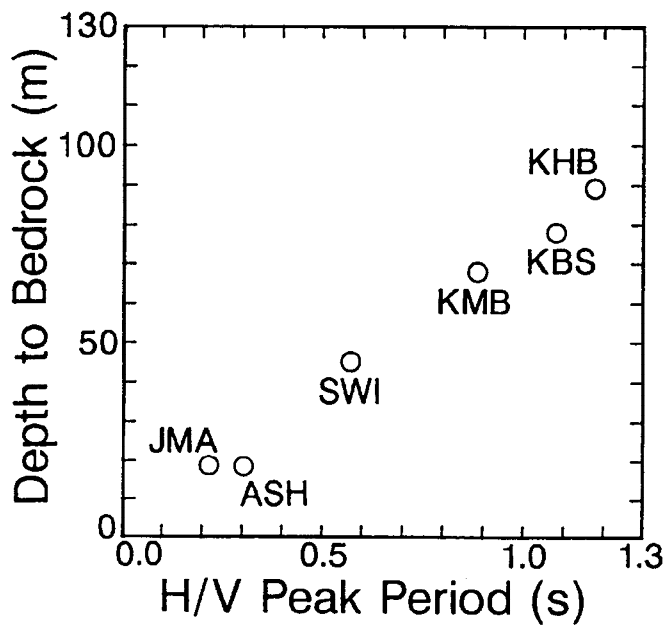


Fig. 8(b) Correlation of the H/V peak period with the depth to the Pleistocene or Tertiary rock

In Fig. 7, the upper surface of Urahoro group dips sharply in between SWI and KBS, only 400 m apart. This suggests that site effects could be considerably different within the area.

## OBSERVED AND ESTIMATED S–WAVE TRANSFER FUNCTIONS

### *S–Wave Transfer Functions at KHB and JMA*

KHB and JMA sites were instrumented with arrays of down–hole and surface accelerograms. In addition to the accelerograms on the ground surface, down–hole accelerograms were installed at a depth of 77 m slightly above the top Pleistocene deposit at KHB and at a depth of 20 m in the Tertiary rock at JMA. These down–hole arrays successfully recorded the strong motions during the earthquakes of February 4, 1993 at KHB, and of January 26, 1994 at JMA(e.g., Matsunaga *et al.*, 1994; Kashima *et al.*, 1994).

Since the epicenters of both events were located in the south of Kushiro city, only the E–W component motions are considered hereafter. The solid lines in Figs. 9(a) and (b) show the observed transfer functions between surface and down–hole stations at KHB and JMA, $(A_G/A_{-77m})_{KHB,obs}$ and $(A_G/A_{-20m})_{JMA,obs}$, respectively, in which A is the Fourier spectrum. The spectral peaks occurring 1.0–1.2 s at KHB and 0.2–0.3 s at JMA, correspond to the natural site periods of these sites.

The broken lines in Figs. 9(a) and (b) are the transfer functions for vertically incident S–waves, $(A_G/A_{-77m})_{KHB,cmp}$ and $(A_G/A_{-20m})_{JMA,cmp}$, computed for the inferred profiles shown in Fig. 5. In each Figs. 9(a) and (b), the estimated transfer function shows a fairly good agreement with the observed one. This indicates that the inferred soil profiles at both sites are reasonable and that the array observation of microtremors is a reliable means for estimating the effect of local site conditions.

### *S–Wave Transfer Functions between Sites*

At KMB, ASH, and JMA, the digitized strong motion records for the 1994 Hokkaido Toho–oki earthquake are available. The peak ground accelerations at the sites during this earthquake are listed in Table 1(e.g.,

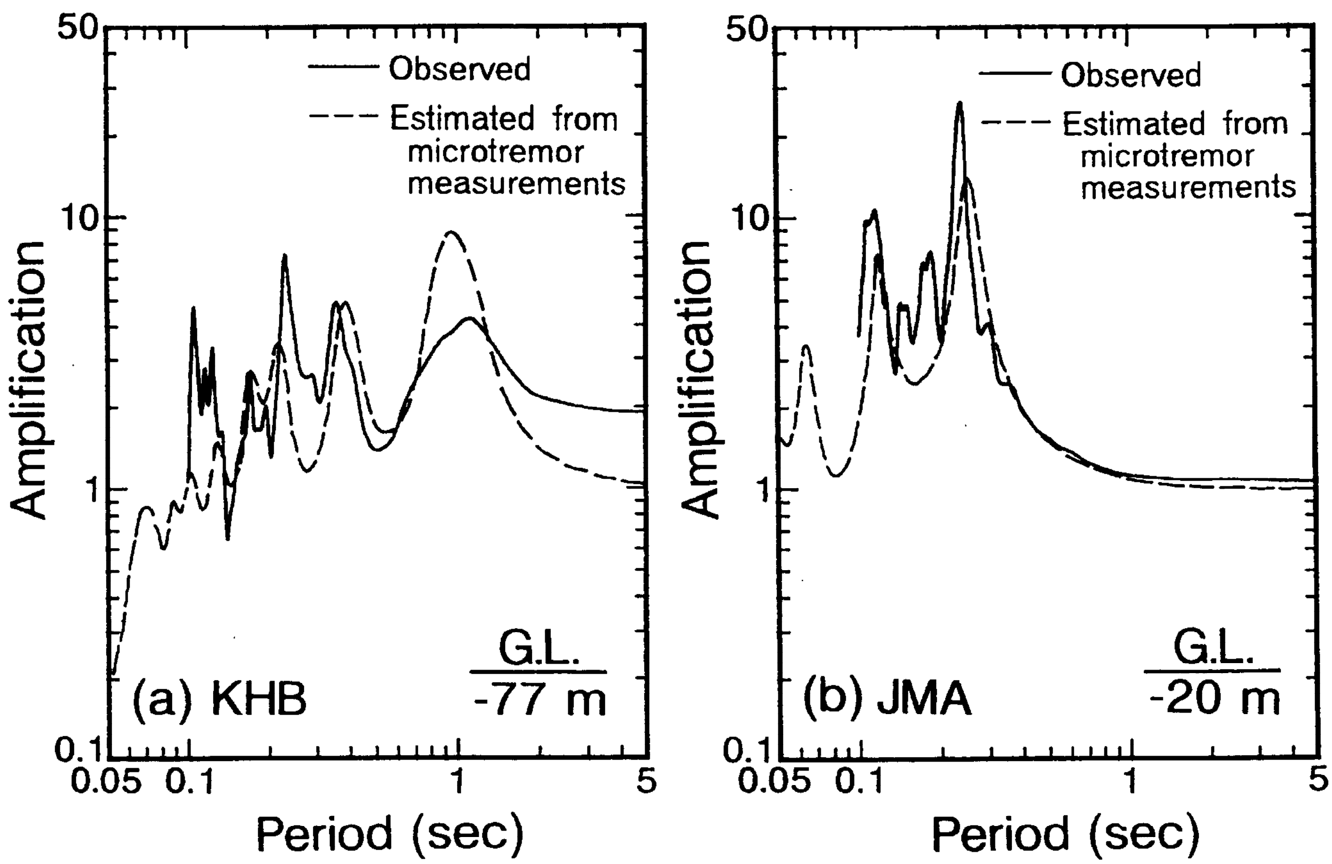


Fig. 9 Observed and estimated transfer functions at KHB and JMA

Table 1 Peak ground accelerations at KMB, ASH, and JMA (in $cm/s^2$)

| | KMB | | ASH | | JMA | |
|---|---|---|---|---|---|---|
| | NS | EW | NS | EW | N063E | N153E |
| 10/04/94 | 152.5 | 176.2 | 250.7 | 320.2 | 313.9 | 392.4 |

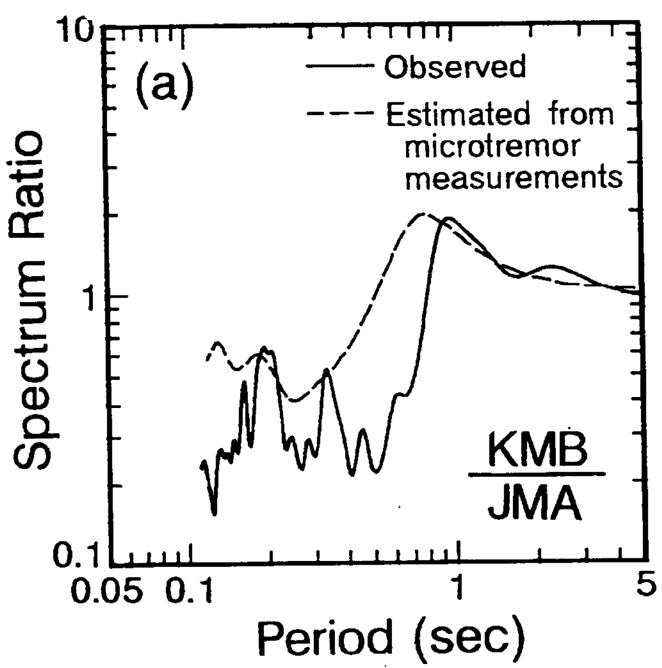


Fig. 10 Observed and estimated transfer functions between surface stations

Association for Earthquake Disaster Prevention *et al.*, 1995). The peak accelerations at JMA and ASH are greater than that at KMB by a factor of 2–3.

Since the epicenter of the 1994 event was located about 300 km east of Kushiro city, only the N–S component motions are considered hereafter. The solid lines in Figs. 10(a) and (b) show the transfer functions of ground surface motions between KMB and JMA$(A_{KMB}/A_{JMA})_{obs}$ and between ASH and JMA$(A_{ASH}/A_{JMA})_{obs}$, in the 1994 event. $A_{KMB}$, $A_{ASH}$, and $A_{JMA}$ are the Fourier spectra of the ground accelerations at the three sites. In Fig. 10(a) the spectral peak occurring 0.9 s appear to reflect the natural site period at KMB. In Fig. 10(b), on the other hand, the spectrum does not have a prominent peak in periods over 0.1 s.

Assuming that the layers with $V_s$ over 650 m/s, i.e., the surface of Kushiro or Urahoro group, are the common bedrock for these sites, the transfer functions of ground surface motions between sites, were computed and are shown in Figs. 10(a) and (b) in broken lines. The computed spectra show a fairy good agreement with the observed ones. This again indicates that the array observation of microtremors is promising for estimating the effect of subsurface soil conditions on the ground motion characteristics.

## CONCLUSIONS

Array observations of microtremors were conducted at six sites in Kushiro city. Based on the F–k spectrum analysis, dispersion curves of Rayleigh waves for the sites were determined. From the inversion analyses of the dispersion curves, $V_s$ profiles down to the bedrock with $V_s$ over 650 m/s have been estimated. With these profiles, the S–wave transfer functions between surface and down–hole stations at two sites as well as those between surface stations are computed, and compared with those of the observed strong motion records. The computed and observed transfer functions show a fairly good agreement, indicating that the array observations of microtremors are economical and yet reliable means for estimating local site conditions.

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