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THREE-DIMENSIONAL SOIL PROFILING IN KOBE AREA USING MICROTREMORS

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ABSTRACT

Microtremor measurements are conducted at two sites in Kobe using arrays of sensors. The F-k spectral analysis of microtremor array records provides dispersion curves of Rayleigh waves, and the inversion of these data results in shear wave velocity profiles down to the bedrock. Conventional microtremor measurements with only one station are also performed at over 100 locations, and the horizontal to vertical amplitude ratio (H/V) of microtremors are determined. The shear structures within the Kobe area are then estimated based on the H/V spectrum of microtremors, assuming that it reflects that of Rayleigh waves. These results enable one to outline three-dimensional soil profiles down to the bedrock which might have had significant effects on the damage distribution in the 1995 Hyogoken Nanbu earthquake. It is shown that: (1) On the south of the foot of the Rokko mountain, a deep sedimentary deposit overlies the bedrock, while rock outcrops are found on the north; (2) The thickness of the sedimentary deposit is estimated to be on the order of 1 km, and gradually increases toward the sea; (3) The use of H/V spectra of microtremors, combined with the array observation of microtremors may be an economical means of estimating two- or three-dimensional shear structure in an economical and yet reliable manner.

KEYWORDS

Hyogoken Nanbu earthquake, microtremors, shear wave velocity profile, Rayleigh wave, dispersion curve, inverse analysis, microtremor H/V spectrum, geophysical exploration, surface wave, array observation

INTRODUCTION

The Hyogoken Nanbu earthquake of January 17, 1995, with its causative fault near Kobe city, destroyed over 100 thousand wooden houses, and residential and office buildings, claiming a high death toll over 5,500. The damage to building in the Kobe area was concentrated in the 1-km wide belt parallel to the coastline. The concentration of damage is considered to be due partly to the "focusing phenomena" of seismic waves and partly to "local site effects."

In order to evaluate those effects qualitatively, two- or three-dimensional shear wave velocity profiles down to the bedrock should be properly identified. It is, however, difficult to estimate deep soil profiles using conventional geophysical methods, particularly when two- or three-dimensional soil stratification is to be required. One of the convenient methods for this purpose is to make use of the dispersive nature of Rayleigh waves in microtremors that can readily be observed on the ground surface. Recent studies, for example, have shown that (1) array observation of microtremors could yield a shear structure at the site (e.g., Horike, 1985; Okada and Matsushima, 1986) and (2) the variation with period of the horizontal to vertical amplitude ratio (H/V) of microtremors at a site correspond to that of Rayleigh waves and thus could reflect the shear structure of the site (e.g., Tokimatsu and Miyadera, 1992; Tokimatsu, 1995). This indicates a possibility that the H/V spectrum method combined with the array observation enables one to outline two- or three dimensional shear wave velocity profiles in an economical manner. The object of this paper is to study such a possibility, in the hope of quantifying the effects of soil conditions on the damage distribution in the Kobe area during the 1995 Hyogoken Nanbu earthquake. For this purpose, array observations as well as conventional microtremor measurements with only one station were performed in the area.

THEORETICAL BACKGROUND OF MICROTREMOR MEASUREMENTS

After the pioneer work by Kanai and Tanaka (1961), microtremor measurements with one station have been used for determining dynamic characteristics of sites as well as natural site periods. They assumed that the microtremor horizontal motions at periods less than 1 s consist mainly of shear waves, and that the spectra of the horizontal motions reflect the incident S–wave transfer function of a site. However, many researchers, e.g., Udwadia and Trifunac (1978), indicated that microtremor spectrum method often tell the exciting function rather than the transfer function of the site.

Nakamura and Ueno (1986) proposed a revised spectrum method in which the effect of source function is minimized by normalizing the horizontal spectral amplitude in terms of the vertical one. Assuming that S–waves dominate in microtremors, they indicated that the horizontal–to–vertical (H/V) spectral ratio of microtremors roughly equals the transfer function of incident S–waves. This method has the potential to make site periods more reliable, but it rests on tenuous assumptions (Finn, 1991).

Phase velocity methods using arrays of sensors have also been conducted to characterize soil profiles. The working principle of this method lies in the fact that the F–k spectral analysis of microtremor vertical motions at a site could provide Rayleigh wave dispersion characteristics that reflect the shear structure of the site. The inversion using such dispersion data can yield a shear structure of the site (e.g., Horike, 1985; Okada and Matsushima, 1986; Tokimatsu et al., 1992).

Tokimatsu and Miyadera (1992) and Tokimatsu (1995) conducted both of the above method at sites with known shear structures and concluded that the microtremor H/V spectrum does not reflect the incident S–wave transfer function but corresponds to the Rayleigh–wave amplitude ratio computed for the known soil profile. They also indicated that (1) if the microtremor H/V spectrum of a site does not have a distinct peak, it may be rock site or soil site with a low impedance ratio, 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 could be equal to the natural period of the site and thus could reflect the thickness of sedimentary deposits overlying bedrock.

The above findings suggest that when the H/V spectrum techniques are combined with the phase velocity method, two– or three–dimensional soil profiling may be estimated in an economical manner. Described in the following is such a case study conducted in the Kobe area.

MICROTREMOR MEASUREMENTS

Microtremor measurements conducted in the Kobe area include array observations and conventional measurements. The equipment used for these measurements consists of amplifiers, lowpass–filters, 16–bit A/D converter, and a 32–bit computer, all built–in a portable case; and three–component velocity sensors. The sensors with a natural period of 5 s were used.

Array observations were made at sites S and R, as shown in Fig. 1. Site S is located in the heavily damaged zone, while site R is on Rokko Island where heavy damage to structures was rarely seen, despite extensive soil liquefaction. Five or six sensors were placed on the ground to form a circular array with a sensor in the center. Microtremors were then measured simultaneously for several to 30 minutes. The analog motions measured with the sensors were amplified, lowpass–filtered, converted into digitized form. The sampling rate varied from 50 to 500 Hz, depending on site geological conditions and array radius used. Eight – 16 sets of data consisting 8192 points each were produced from the recorded motions, and are used for the following analysis. The test was started with an array radius of 5 m, and repeated after expanding the array radius by a factor of 2–3, e.g., 10, 20, 50,100, 200, and 500 m. The maximum array radii used were about 0.7 km at site S and about 1.0 km at site R.

Conventional microtremor measurements were conducted at 101 sites along lines A – F as shown in Fig. 1. The distances between adjacent two observation points were about 50 m – 500 m, depending on the variation of microtremor H/V spectrum with distance. At each location, microtremor ground motions were observed for about 15 minutes, and digitized at equal intervals of 0.01 s. Eight – 16 sets of data consisting 8192 points each were made from the recorded motions, and used for the following spectral analysis.

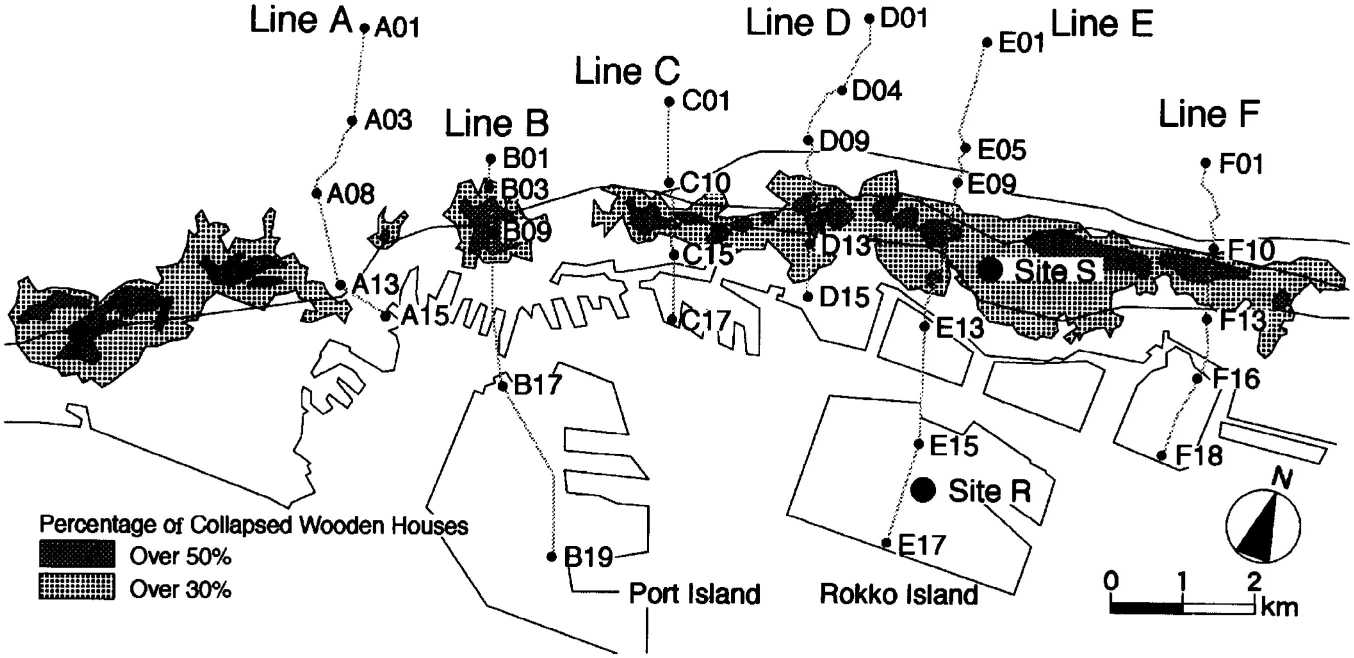


Fig. 1 Map showing observation lines and sites for microtremor measurements and areas with heavily structural damage

SHEAR STRUCTURE FROM F–K SPECTRUM ANALYSES OF MICROTREMORS

The high–resolution frequency–wavenumber spectrum analysis is used to determine dispersion characteristics of microtremor vertical motions measured with each array. The details of the F–k spectrum analysis have been described elsewhere (Capon, 1969). Figure 2 shows high resolution F–k spectra on a two–dimensional wavenumber space at several periods for the microtremors at sites S and R. At both sites, microtremors are found to have propagated from various directions, depending on period, and phase velocities up to about 1.5 km have been determined.

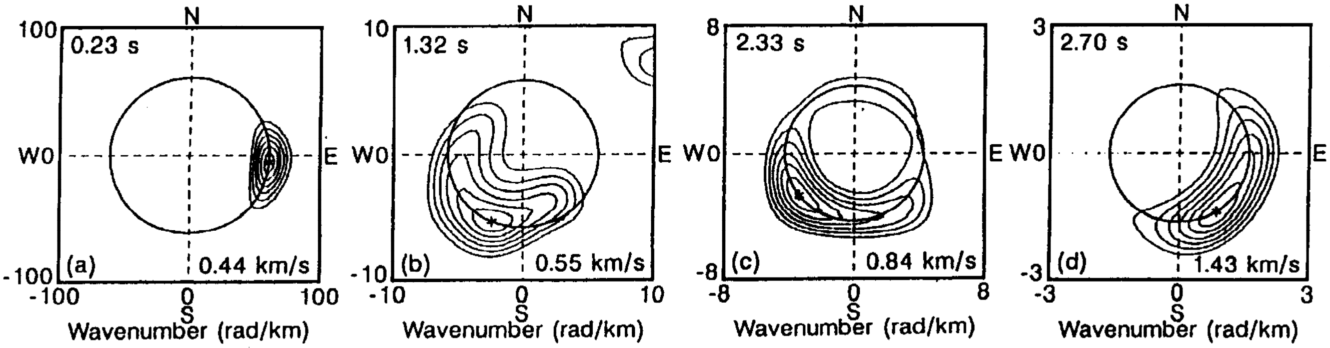


Fig. 2(a) F–k spectra of microtremors at site S

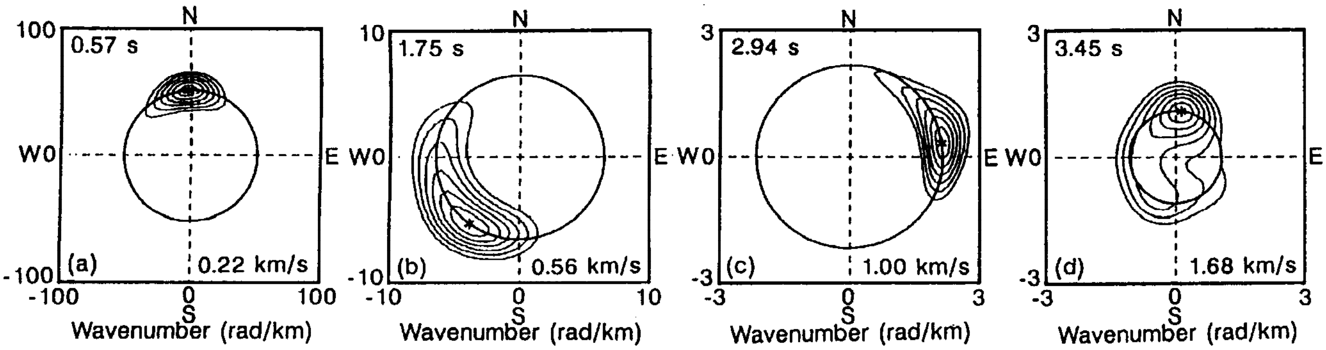


Fig. 2(b) F–k spectra of microtremors at site R

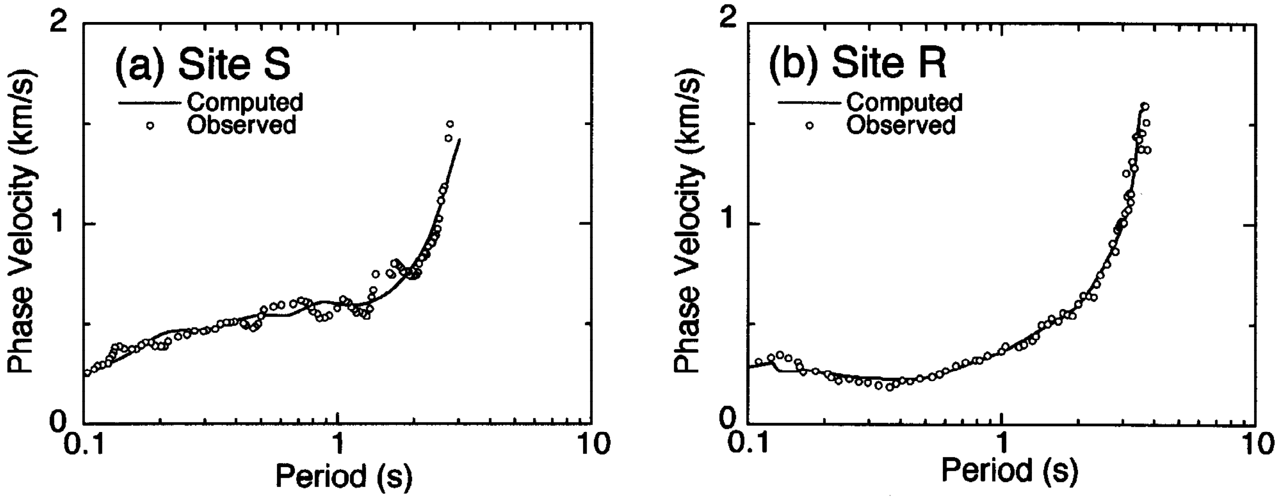


Fig. 3 Dispersion curves estimated from F–k spectral analysis of microtremors compared with those computed for inverted soil profiles at sites S and R

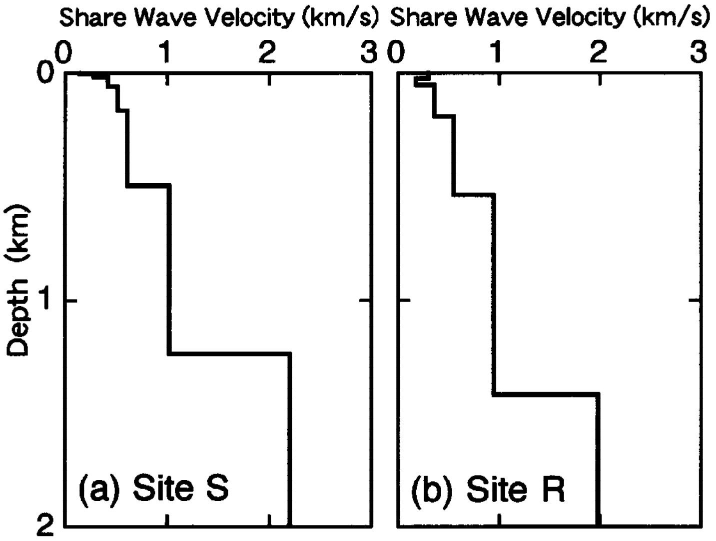


Fig. 4 Shear wave velocity profiles inferred from inverse analysis of observed dispersion curves for sites S and R

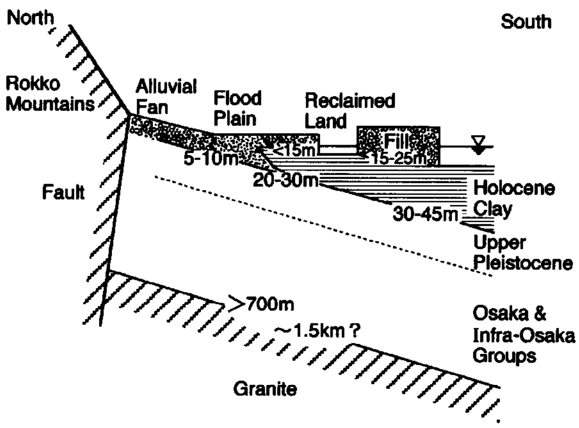


Fig. 5 Schematic diagram showing geologic cross section

The resulting dispersion curves are shown in Fig. 3 in open circles. The data at site S show a normally dispersive trend in which the phase velocity tends to increase with increasing period. The data at site R, by contrast, show an inversely dispersive trend at periods less than 0.2 s, indicating that a stiff surface layer could overlie a soft layer.

Figure 4 shows the shear wave velocity profiles inferred from the inverse analysis of the dispersion data, and Fig. 5 shows a schematic diagram showing an N–S cross section across the area. A comparison of Fig. 4 with Fig. 5 indicates that the layer with V_s less than 400 m/s could correspond to either the Holocene or upper Pleistocene deposit, while the layer with V_s from 500 m/s to 1.2 km/s corresponds to either Osaka and Infra–Osaka Groups. At both sites, bedrock with V_s greater than 2 km/s could occur at depths greater than 1 km. The dispersion curve for the inverted soil layer model is shown in Fig. 3 in a solid line, which is compatible with the observed data.

MICROTREMOR H/V SPECTRAL RATIO

The microtremor H/V spectral ratio used in this paper is defined as

$$H/V = \sqrt{S_{NS}S_{EW}}/S_{UD} \tag{1}$$

in which S_{UD} is the Fourier amplitude of microtremor vertical motions, and S_{NS} and S_{EW} are the Fourier amplitudes of the two orthogonal horizontal motions.

Solid lines in Fig. 6 show the H/V spectra at several sites along lines B and E as well as those as at sites S and R near line E. At site E01 located in the Rokko mountains, the H/V spectrum does not have a prominent peak, indicating that it is rock site. At other sites, the H/V spectra have prominent peaks, indicating that they are soil sites. In addition, at the soil sites on both lines, the period of H/V peak increases towards the sea from less than 1 s to over 5 s. To investigate whether such a trend exists within the area, the variations of H/V spectrum along all lines are shown in Fig. 7. In the figure, the value of H/V is indicated by gradation as shown in the legend. Figure 7 confirms that the same trend exists on all lines.

Broken lines in Figs. 6 (h) and (i) show the amplitude ratios of the fundamental-mode Rayleigh waves computed based on the transfer matrix method (Haskell, 1953) for the inverted soil models shown in Fig. 4. The Rayleigh wave amplitude ratios are consistent with those of microtremors. This suggests that the inverted soil models are reasonable and confirms that the microtremor H/V spectrum could reflect that of Rayleigh waves.

A comparison of Fig. 4(a) with Fig. 4(b) suggests that, despite a significant difference in the shear structure near the surface, the shear wave profiles below the upper Pleistocene layer may be considered to be almost

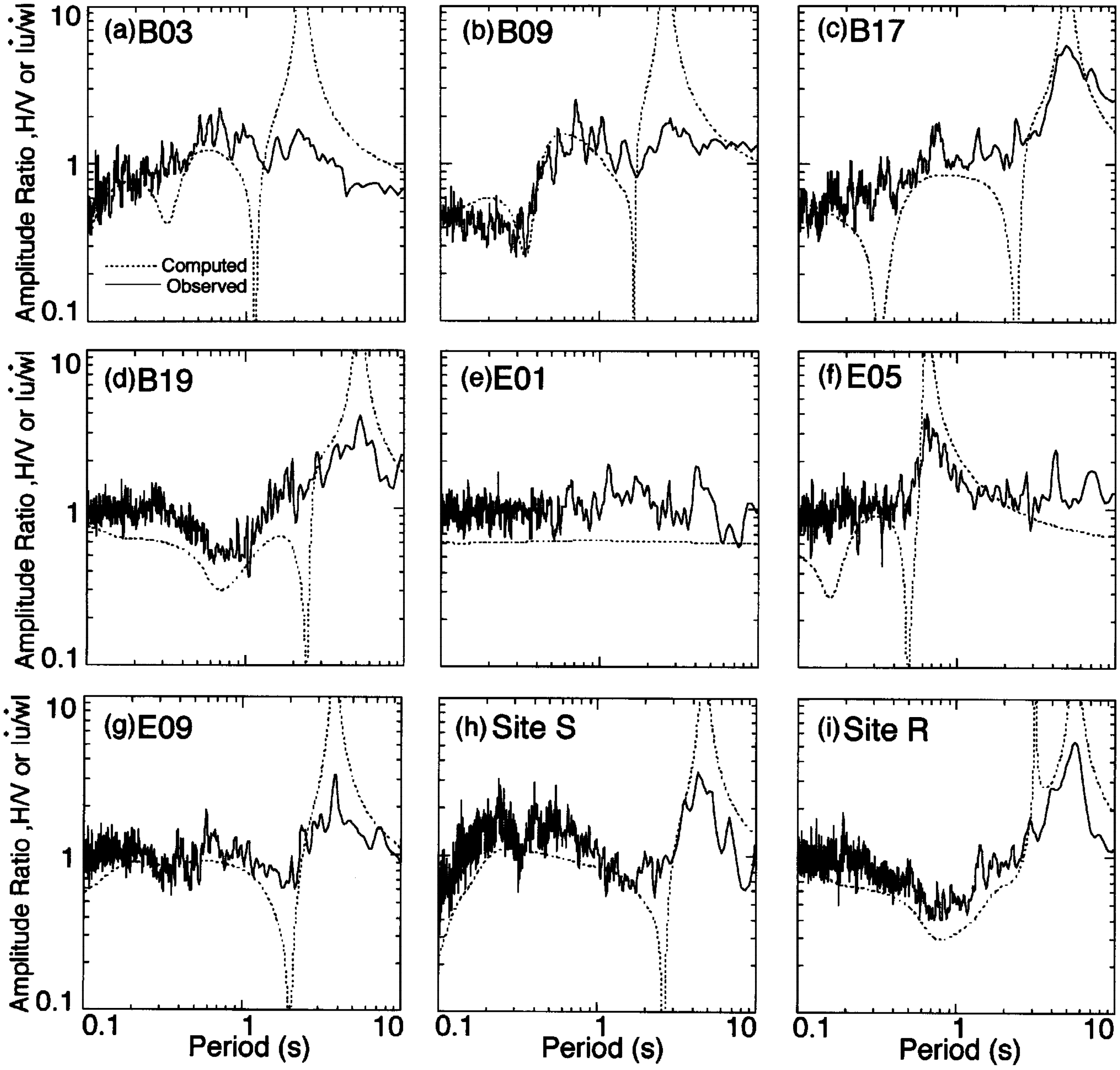
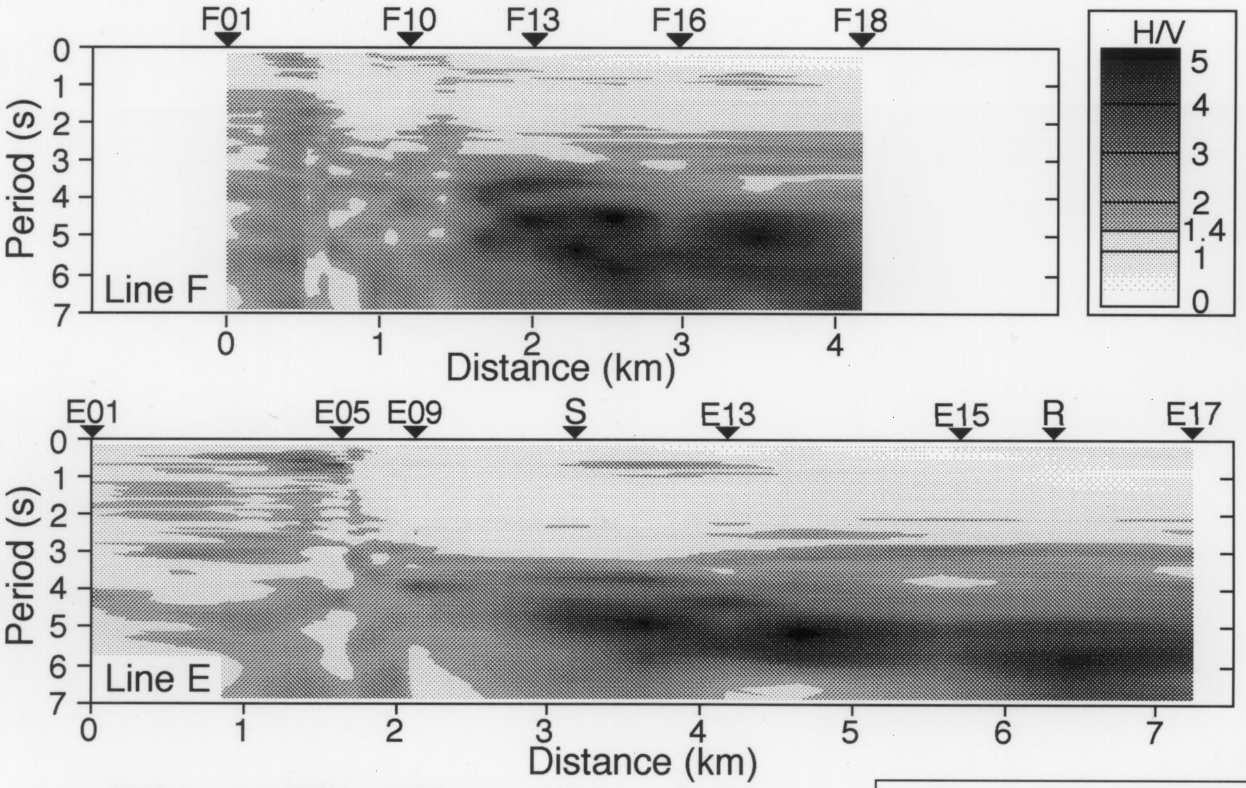
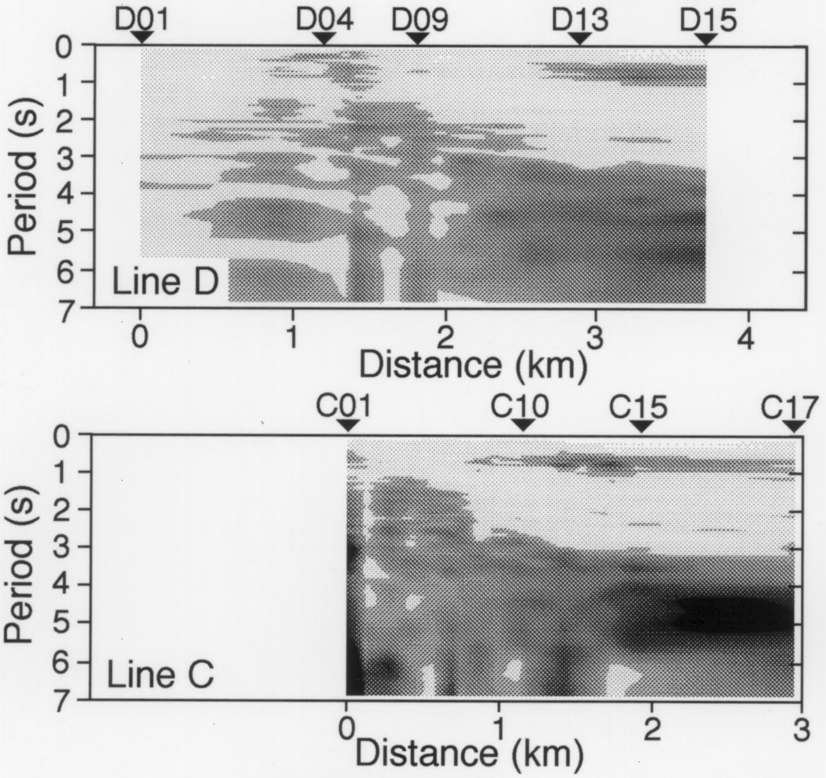


Fig. 6 H/V spectrum of microtremors compared with that of theoretical Rayleigh waves at sites along lines B and E





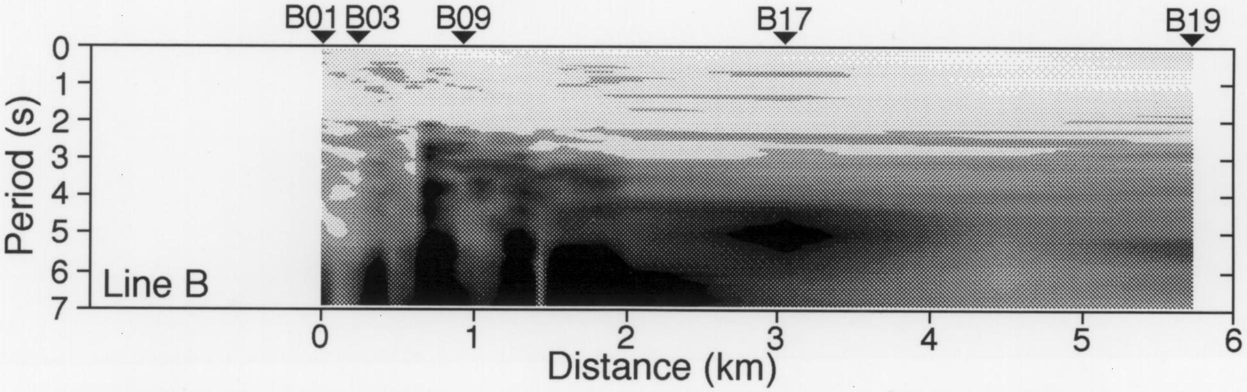


Fig. 7 Variation of microtremor H/V spectra along observation lines

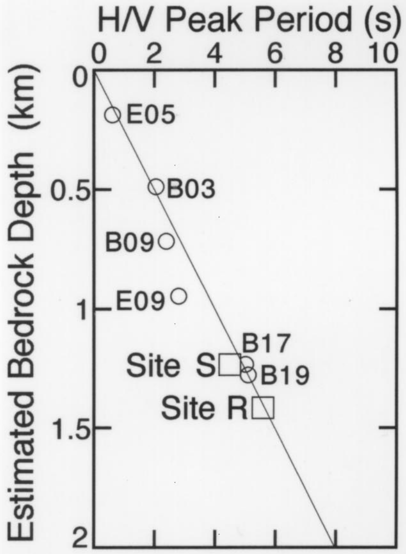


Fig. 8 Relation between H/V peak period and estimated bedrock depth

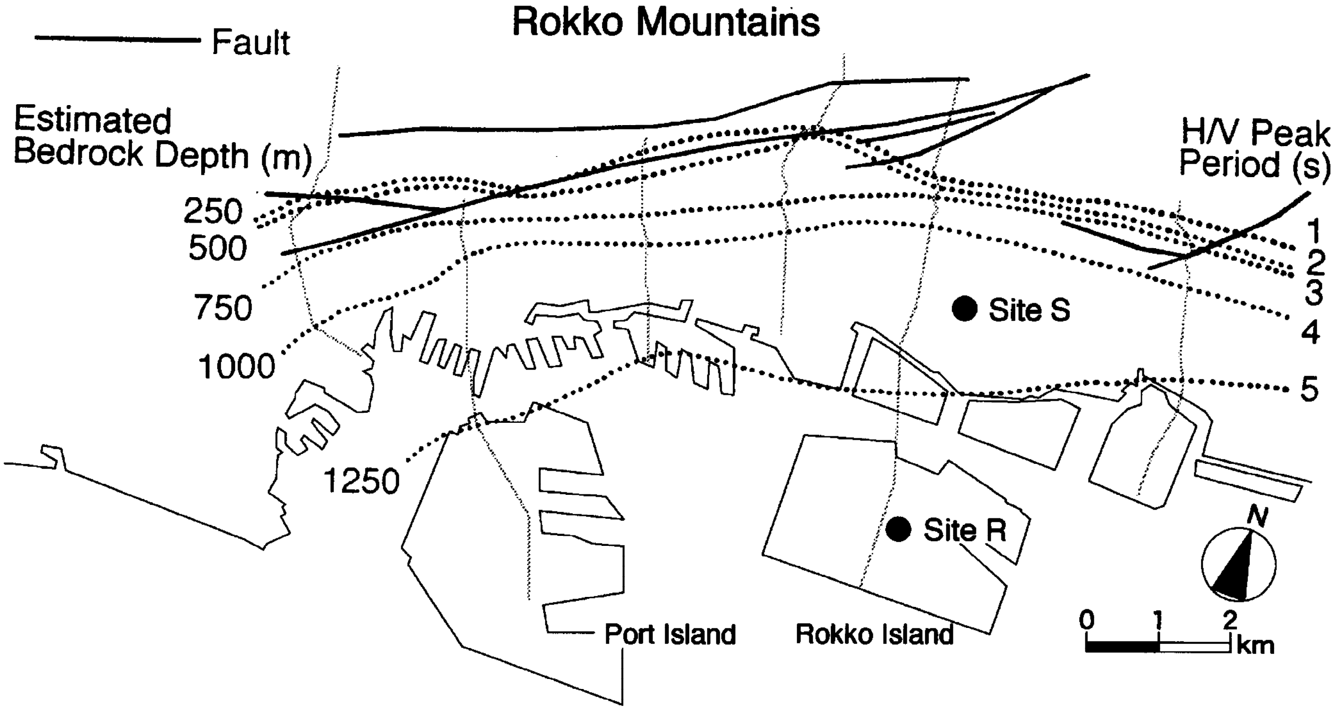


Fig. 9 Map showing contour lines of H/V peak period and estimated depth to bedrock with V_s greater than 2 km/s

the same, except for their thicknesses.

Based on the above findings, the shear structures along the observation lines were estimated so that the Rayleigh wave amplitude ratios computed for the structures are compatible with the observed H/V spectra shown in Fig. 6. In the analysis, the shear structure down to the upper Pleistocene layer was predetermined, based on a correlation between SPT N-value and shear wave velocity, and the shear wave velocities below the upper Pleistocene layer were also fixed. Thus, only the thicknesses of the deep layers were unknown variables. The depths to the bedrock with V_s greater than 2 km/s determined from the shear wave velocity profiles thus estimated, D (km), are shown in Fig. 8 against H/V peak periods, T_p, and the corresponding amplitude ratios of the fundamental-mode Rayleigh waves are shown in Fig. 6 in broken lines. Relatively good agreements between observed and computed amplitude ratios indicate that the estimated depths of bedrock are reasonable. Figure 8 shows that there is a fairly good correlation between the two, which is defined as

$$D = 0.25T_p \tag{2}$$

Thus, the depth to the bedrock with V_s greater than 2 km/s in other Kobe area could be estimated approximately using Eq. (2).

Figure 9 shows a map indicating the contours of both H/V peak period and approximate bedrock depth thus estimated within the Kobe area. Also shown in the figure in broken lines are known faults. Bedrock almost outcrops on the north of the fault zone, but dips sharply on the immediate south of the fault zone and then dips gently to the sea. The thickness of the sedimentary deposit overlying bedrock is on the order of 1 km in the 1-km wide damaged zone. The estimated shear structure is consistent with that estimated from seismic prospecting using reflection method (Irikura, 1995). This indicates that microtremor measurements are promising and yet economical means of estimating three dimensional shear structures down to bedrock.

CONCLUSIONS

Microtremor measurements were conducted at two sites in Kobe using arrays of sensors as well as conventional measuring techniques with only one station. The F-k spectral analysis of microtremor array records provides dispersion curves of Rayleigh waves, and the inversion of these data results in shear wave velocity profiles down to the bedrock. The shear structures within the Kobe area are then estimated based on the horizontal to vertical amplitude ratio (H/V) of microtremors at over 100 locations, assuming that the microtremor H/V spectral ratio reflects that of Rayleigh waves. These results enable one to outline three-dimensional soil profiles down to the bedrock which might have had significant effects on the damage distribution in the 1995 Hyogoken Nanbu earthquake. It is shown that: (1) On the south of the foot of the Rokko mountain, a deep sedimentary deposit overlies bedrock, while rock outcrops are found on the north; (2) The thickness of the sedimentary deposit is estimated to be on the order of 1 km, and increases abruptly on the immediately north of the fault zone and then gradually increases toward the sea; (3) these findings are consistent with the results of other field investigation, and thus (4) The use of H/V spectra of microtremors, combined with the array observation of microtremors may be an economical means of estimating two- or three-dimensional shear structure in a economical and yet reliable manner.

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