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Proceedings: Third International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, April 2–7, 1995, Volume II, St. Louis, Missouri

Estimation of Local Site Conditions in Kushiro City Based on Array Observation of Microtremors

Paper No. 7.22

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SYNOPSIS : 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 two strong motion stations (Kushiro Japan Meteorological Agency and Kushiro Harbor, Hokkaido, Japan), which are located nearby but on different soils. Based on the F-k spectrum analysis of microtremors, dispersion curves of Rayleigh waves for the sites are determined. The inverse analysis of these dispersion curves results in shear wave velocity profiles down to a depth of 300 m. With these profiles, the spectrum ratio of ground surface motions between the two sites is computed, and compared with that of the observed records. The computed and observed spectrum ratios show a fairly good agreement, indicating that the array observation of microtremors is an economical and yet reliable means of estimating local site conditions.

INTRODUCTION

Recent studies have shown that microtremor measurements at a site using an array of sensors can successfully extract Rayleigh-wave dispersion characteristics in a short period range (e.g., Tokimatsu et al., 1992). The inversion using these dispersion data can provide a shallow shear-wave velocity (V_S) profile at the site. This method is attractive, since it can readily be made on the ground surface without drilling any boreholes, and provides dynamic soil properties that control local site conditions during earthquakes. Thus, the method could be an economical means of estimating local site conditions, if shear wave velocity profiles down to the bedrock can be determined with a reasonable degree of accuracy.

To explore much deeper depths compared with the previous system, field test equipment had been remodeled, and field tests were conducted at two strong motion stations (Kushiro Japan Meteorological Agency and Kushiro Harbor, hereby call sites J and H) in Kushiro city, Hokkaido, Japan. These two sites, located nearby but on different soils, have been shaken in a completely different manner during past earthquakes. In the Kushiro-oki earthquake of January 15, 1993, for example, the peak ground acceleration at site J was 0.73 G, while that at site H was 0.48 G (e.g., Kashima, 1993, and Iai et al., 1994).

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 both sites. This enables us to examine the total performance of the present method, by comparing the spectral ratio of the recorded ground surface motions between the sites with that computed for the V_S profiles inferred from the microtremor analysis. This paper outlines the field test procedures and in-house analysis involved, and then discuss the effectiveness of the present method.

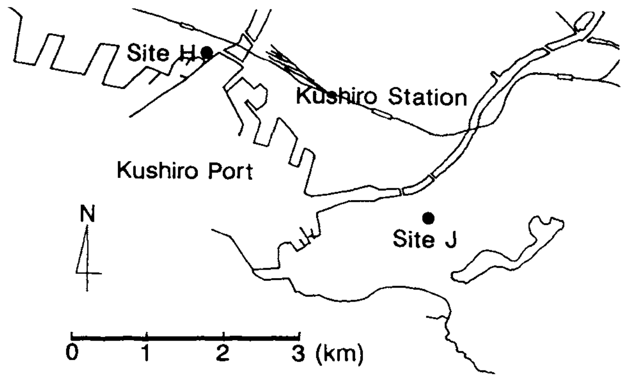

Fig. 1 Map showing observation sites

ARRAY OBSERVATION OF MICROTREMORS

Array observation of microtremors was conducted at sites H and J, of which locations are shown in Fig. 1. The site H is situated on a deep Holocene deposit that overlies Tertiary Rock at a depth more than 77 m. The site J, on the other hand, is located on a hill covered by a thin volcanic deposit that is underlain by Tertiary Rock.

The test equipment used in this study, consists of three-component velocity sensors, amplifiers, A/D converters, and a note-size personal computer. The last three parts are all built in a portable case. This system has a maximum sensitivity of 26 µkine/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 to six three-component sensors were placed on the ground surface to form an observation array. Because the effective wavelength is 2-6 times the average sensor spacing in the array, several arrays with different sensor spacing

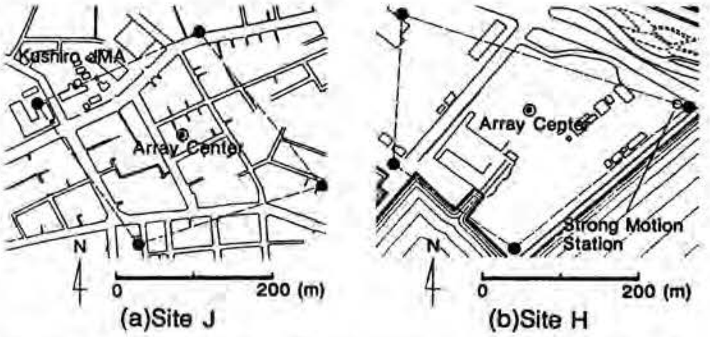

Fig. 2 Maximum aperture arrays used at site J and H

were used. The minimum and maximum sensor spacings were 3 and 160 m at site J, and 3 and 200 m at site H. Figs. 2(a) and (b) show the array centers and the maximum aperture arrays used at the sites.

With each array, the ground surface motions of microtremors were measured simultaneously. The analog motions measured with all the sensors are amplified, converted into digitized form at a sampling frequency of 100-500 Hz, and stored in the hard disk of the computer. Generally, 16 sets of digitized records with 2048 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.

DETERMINATION OF V_s PROFILES BASED ON THE F-k SPECTRUM ANALYSIS

Result at Site J

The solid line in Fig. 3 shows the variation with frequency of horizontal-vertical spectral ratio of microtremors (e.g., Nakamura and Ueno, 1986, Tokimatsu and Miyadera, 1992) at the array center. A sharp peak occurs at 0.26 s, which appears to correspond to the natural site period.

Fig. 4 shows high resolution F-k spectra on a two-dimensional wavenumber space at several frequencies for the vertical motions of microtremors (Fig. 4(a)-(f)). The details of the analysis have been described elsewhere (e.g., Capon, 1973, Tokimatsu et al., 1992). The spectra, $P(f,\mathbf{k})$, are drawn as contours of $-10\log[P(f,\mathbf{k})/P_{max}(f)]$ in which $P_{max}(f)$ is the maximum value of $P(f,\mathbf{k})$, $\mathbf{k}$ is vector wave number, and f is frequency. 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. It is considered that the vertical motions in microtremors, i.e., mainly Rayleigh waves, are characterized by the vector wavenumber having the maximum spectrum peak, $\mathbf{k}_p$. Namely, the waves are propagated with a phase velocity, $c = 2\pi f/|\mathbf{k}_p|$, from the azimuth at which the peak occurs.

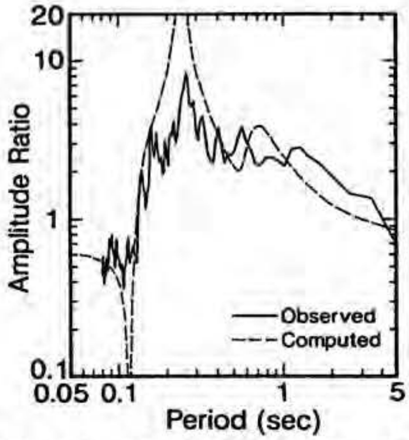

Fig. 3 Variation with frequency of amplitude ratio of microtremors at site J compared with that of Rayleigh waves

In Fig. 4, the spectrum does not have a sharp-pointed peak, and the azimuth of the peak varies with frequency. This indicates that microtremor sources exist at various places around the site.

Open circles in Fig. 5(a) are the dispersion data resulting from the F-k spectrum analysis of the microtremor records. Except for the wavelength of around 300 m, the data show a normally dispersive trend in which the phase velocity increases with increasing wavelength.

Using the dispersion data shown in Fig. 5(a), the inverse analysis was conducted in which the effects of higher Rayleigh modes were considered (e.g., Tokimatsu et al., 1992). Fig. 5(b) shows the V_s profile estimated from the inversion. The shear wave velocity of the top 17 m-thick layer varies from 100 to 330 m/s. Underlying this layer is stiff layers with V_s over 800 m/s. These profiles are consistent with the geological conditions of the site. The theoretical dispersion curve for the inverted soil profile is shown in Fig. 5(a) in a solid line, which is compatible with the observed data.

The variation with frequency of the horizontal-vertical amplitude ratio of Rayleigh waves was theoretically determined for the computed soil

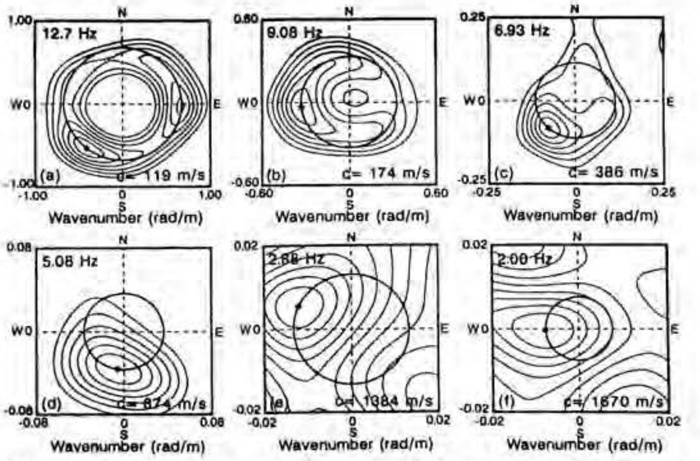

Fig. 4 F-k spectra at selected frequencies for microtremors at site J

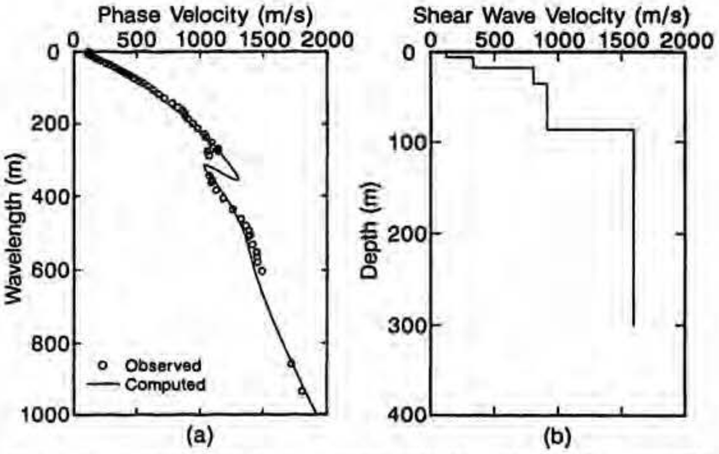

Fig. 5 Measured and computed dispersion curves and resulting V_S profile at site J

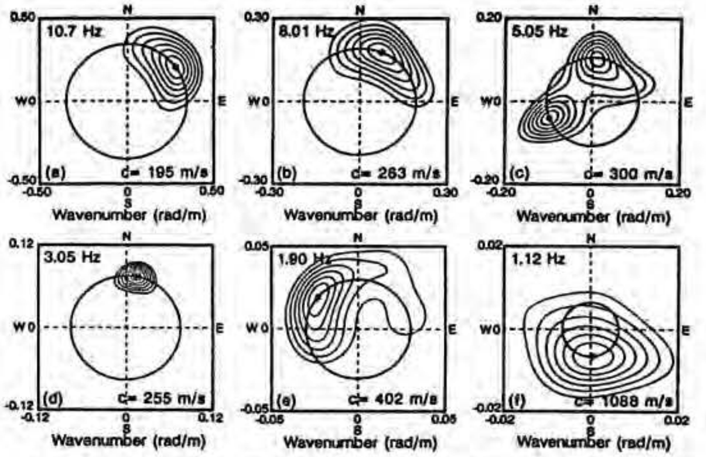

Fig. 7 F-k spectra at selected frequencies for microtremors at site H

profile, and is shown in Fig. 3 in a broken line. The theoretical amplitude ratio, as well as the period of its peak, is in good agreement with the observed one. This indicates that the horizontal-vertical amplitude ratio of microtremors reflects those of Rayleigh waves (Tokimatsu and Miyadera, 1992), and that the inferred soil profile is reasonable. The natural site period for the vertically propagating shear waves computed for the same profile is 0.29 s, which is compatible with the period of peak amplitude ratio of Rayleigh waves.

Result at Site H

Fig. 6 shows the variation with frequency of the amplitude ratio of microtremors at the array center of site H. A sharp peak occurs at 1.2 s, which appears compatible with the site natural period.

Fig. 7 shows F-k spectra at several frequencies for the observed microtremors. The microtremors in the frequency range over 2 Hz are propagated mainly from the north, while microtremors less than 2 Hz from the south. This indicates that the heavy traffic on the north is the major source of microtremors above 2 Hz at this site.

Fig. 8(a) shows the dispersion data from the F-K spectrum analysis of the microtremor records. The data show an inversely dispersive trend at a wavelength about 50 m, suggesting that a stiff layer exists within the deep Holocene deposit.

The inverse analysis was conducted assuming a twelve-layer model. Fig. 8(b) shows the V_S profile estimated from the inversion. The shear wave velocity varies from 160 to 380 m/s from the ground surface to a depth of 90 m. Underlying are stiff layers with V_S over 1000 m/s. These soil conditions are consistent with the available information. The dispersion curve for the inverted soil profile is shown in Fig. 8(a) in a solid line. Comparison of Figs. 8(a) and (b) indicates that the presence of the stiff layers at depths 20-30 m within the soft soils is the primary factor for the inversely dispersive trend at the wavelength about 50 m.

The variation with frequency of the theoretical amplitude ratio of Rayleigh waves for the inferred soil profile is also shown in Fig. 6, in a broken line. The theoretical amplitude ratio is in good agreement with the observed one. The

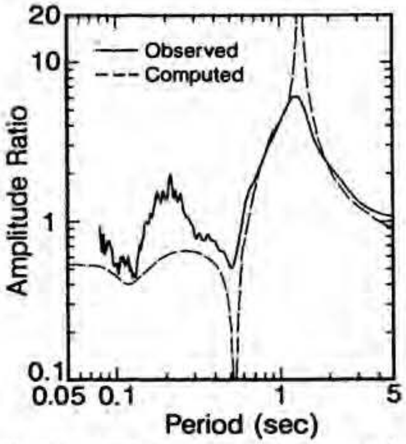

Fig. 6 Variation with frequency of amplitude ratio of microtremors at site H compared with that of Rayleigh waves

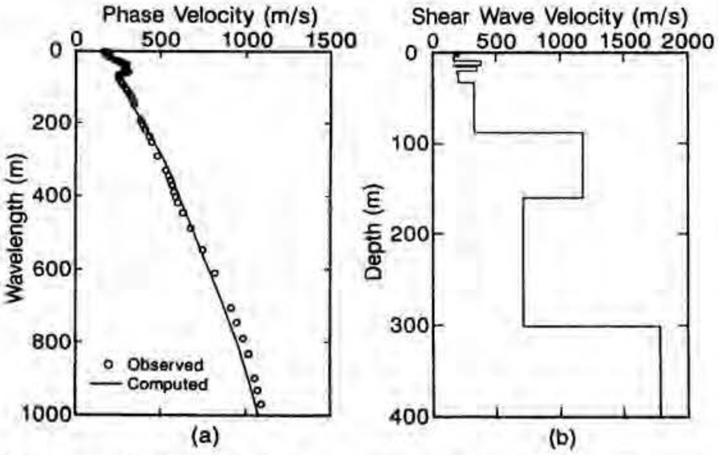

Fig. 8 Measured and computed dispersion curves and resulting V_S profile at site H

period of the computed peak amplitude ratio of 1.38 s is also compatible with the observed one. The natural period of the vertically propagating shear waves for the inferred soil profile is 1.57 s, which, in this case, is slightly longer than the above value.

COMPARISON OF OBSERVED AND ESTIMATED SPECTRUM RATIOS

Since the digitized strong motion records for the 1993 event are unavailable, the records during the earthquake of October 10, 1988, are used in this study. The peak ground accelerations at the sites during this earthquake are listed in Table 1, together with those of the 1993 Kushiro-oki earthquake and its aftershock (e.g., Kashima, 1993, and Iai et al., 1994). In any case, the peak acceleration at site J is greater than that at site H by a factor of 2-4.

Since the epicenter of the 1988 event was located to the south of the city, only the E-W component motions are considered hereafter. The solid line in Fig. 9 shows the observed spectrum ratio between the two sites $(A_{HG}/A_{JG})_{obs}$, in which A_{HG} and A_{JG} are the Fourier spectra of the ground accelerations at the two sites. The spectrum peak and minimum occurring 1.0-1.5 s and 0.3 s, appear to reflect the natural site periods at sites H and J, respectively.

Assuming that the layers at a depth of 90 m of site J and at a depth of 300 m of site H are the common bedrock, the ground surface amplifications relative to the bedrock of vertically propagating S-wave, A_{HG}/A_B and A_{JG}/A_B, were computed for the two sites, in which A_B is the Fourier spectrum at the bedrock. This resulted in the amplification ratio between the two sites $(A_{HG}/A_{JG})_{cmp}$, as shown in a broken line in Fig. 9. The computed spectrum shape, including the periods of its minimum and maximum, shows a fairly good agreement with the observed one.

Table 1 Peak ground accelerations at Kushiro JMA and Kushiro Harbor (in cm/s^2)

	Kushiro JMA		Kushiro Harbor	
	N63E	N153E	NS	EW
10/10/88	174.4	168.1	45.4*	60.0*
1/15/93	711.4	637.2	469.3	344.2
2/04/93	53.6	74.2	16.4	18.3

* uncorrected

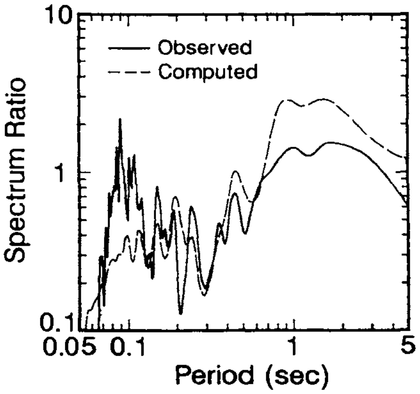

Fig. 9 Observed and Estimated spectrum ratios

This indicates that the array observation of microtremors is simple and yet reliable means of estimating the effects of subsurface soil conditions on the ground motion characteristics.

CONCLUSIONS

Array observations of microtremors were conducted at two sites, where strong motion accelerograms are available. Based on the F-k spectrum analysis, dispersion curves of Rayleigh waves for the sites were determined. From the inversion analysis of the dispersion curves, V_s profiles down to a depth over 300 m have been estimated. The shear wave amplification ratio between the two sites computed for the V_s profile shows a good agreement with that observed during an earthquake. This indicates that the array observation of microtremors is promising for estimating the effects of subsurface soil conditions on the ground motion characteristics.

ACKNOWLEDGEMENTS

The authors are grateful to Dr. Iai, Port and Harbor Research Institute, for this support of the field tests. The strong motion records at the sites J and H used in this study were recorded by Building Research Institute, Japanese Ministry of Construction and Port and Harbor Research Institute, Japanese Ministry of Transportation, respectively.

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