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SPECTRAL CHARACTERISTICS AND NONLINEAR EFFECTS DURING RECENT LARGE EARTHQUAKES OBSERVED AT KUSHIRO CITY, JAPAN

I.SUETOMI and S.NAKAMURA

Engineering Research Institute, Sato Kogyo Co., Ltd.
Nihonbashi-honcho 4-12-20, Chuo-ku, Tokyo 103, JAPAN

ABSTRACT

Strong ground motions with JMA seismic intensity 6 were recently observed twice at the Kushiro city: the 1993 Kushiro-oki earthquake and the 1994 Hokkaido-toho-oki earthquake. Many strong motion records were recorded during the Hokkaido-toho-oki earthquake by a cooperative measurement. Several interesting features were observed related to site effects at the cooperative measurement. For example, PGA was larger on a hill than at lowland. In this study, S-wave velocity structure of alluvial deposits is estimated by short period microtremors measurement using arrays. Then, incident wave spectra at bedrock are calculated by the deconvolution method using one dimensional equivalent linear analysis with the proposed ground model for the earthquake records observed at four sites at lowland during five earthquakes including the Hokkaido-toho-oki earthquake. The difference of spectra between earthquakes is shown to be larger than the difference between observation sites.

KEYWORDS

Earthquake; site effect; microtremors; incident wave spectra at basement; phase velocity of Rayleigh wave; S-wave velocity structure; equivalent linear analysis; nonlinear behavior

INTRODUCTION

The Kushiro city is an interesting site to research site effects; strong ground motions with JMA seismic intensity 6 were observed during the 1993 Kushiro-oki earthquake of January 15 and the 1994 Hokkaido-toho-oki earthquake of October 4. At the time of Kushiro-oki earthquake, PGA at the Kushiro Japan Meteological Agency (JMA) office was more than 900 cm/s^2 whereas that at the Kushiro harbor (PHRI) was about a half of JMA record, although they are located within 4 km distance. A cooperative strong motion measurement was conducted at 23 sites, which were located within 10 km to each other, by the research group of strong motion observations, Japanese Working Group on Effects of Surface Geology (JWGESG) after the Kushiro-oki earthquake. This project succeeded to measure strong motion records during the Hokkaido-toho-oki earthquake, which are compiled by Kudo and Kataoka (1996). PGA was larger on the hill than at lowland against, which fact was common knowledge that the amplification factor is smaller at hillside than at lowland. Same kind of records were observed during the Kushiro-oki earthquake. Moreover, damage pattern at Kushiro city during the Hokkaido-toho-oki earthquake was similar to the one during the Kushiro-oki earthquake (Wakamatsu *et al.*, 1995). These facts indicated the importance of the quantitative estimation of the effect of geological condition to the ground motion amplification. In this paper, we estimate S-wave velocity structure at lowland and make the ground motion distribution at Kushiro city clear by using strong motion records, especially focusing on the spectral characteristics and nonlinear effect during the Hokkaido-toho-oki earthquake.

SPECTRAL CHARACTERISTICS OF OBSERVED RECORDS

Figure 1 shows peak ground accelerations (PGA), peak ground velocities (PGV), peak ground displacements (PGD) and spectrum intensities at 5% damping (SI) of strong motion records observed by JWGESG during the 1994 Hokkaido-toho-oki earthquake. They are computed as two-dimensional peak values in the horizontal plane. Heights of bars are normalized by the values at KMB site where we had charge of the observation in the cooperative measurement. Vector power spectra of observed records are also shown in Fig. 1 in order to clarify the relationships between peak parameters and frequency characteristics. The vector spectrum is obtained by modifying the mean energy spectrum considering vector time series to represent the maximum amplitude of the earthquake ground motion in the horizontal plane (Nakamura, 1995). Most of observation sites that are located on the east of the old Kushiro river are on the hill. On the

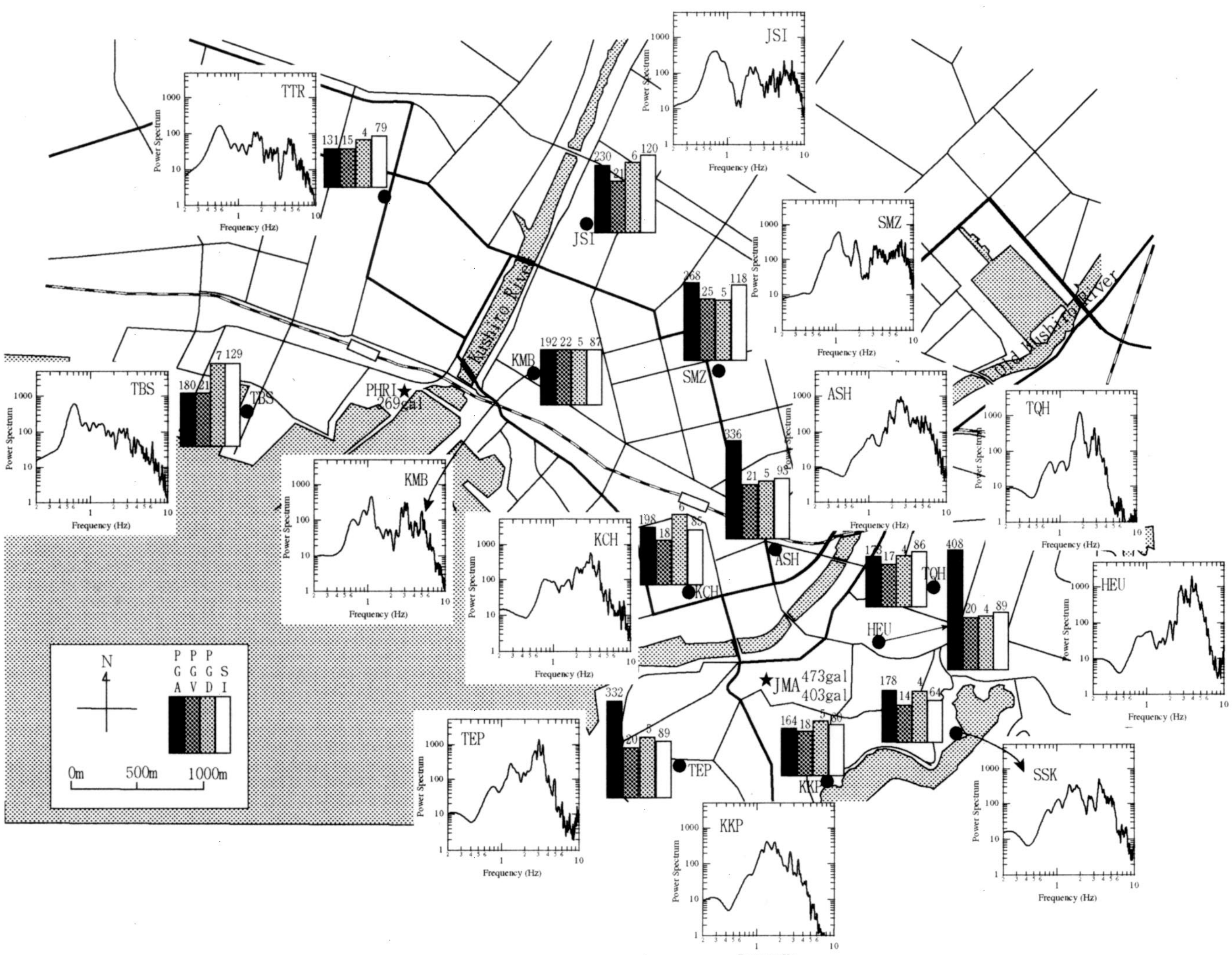


Fig. 1. PGA, PGV, PGD, SI and vector power spectra of strong motion records observed by the JWGESG during the 1994 Hokkaido-toho-oki earthquake.

other hand, sites located on the west of the old Kushiro river are at lowland; the farther a site leaves from it, the thicker alluvial deposit at the site becomes.

PGA is larger at HEU, TEP, ASH, etc. They are located on the hill or at the lowland where thickness of the alluvial deposit is thin. The maximum PGA was 473 cm/s^2 which was observed at JMA. PGA during the 1993 Kushiro-oki earthquake was also large at the site. The value of 919 cm/s^2 was about twice as large as PGA at PHRI (469 cm/s^2). Considering that the Kushiro city is located about 270 km away from the epicenter and observation sites are located in the regions within a radius of 3 km, incident waves at bedrock were almost identical. Therefore, spectral characteristics of each observation site reflects site effects and effects by adjacent buildings. As mentioned above, against the common knowledge that the amplification factor is smaller at hillside than at lowland, PGA is larger at the eastern sites (on a hill) than at the western sites (on thick soft soil deposits). However, the same tendency is observed during the other recent earthquakes. Records at Tarzana during the 1994 Northridge earthquake (CSMIP, 1994) and that at JMA at Kobe during the 1995 Hyogoken-Nanbu earthquake are good examples.

The difference of PGV between on a hill and at lowland is small. PGD and SI values at TBS where alluvial layer deposited thick are the largest. Frequency components higher than 3 Hz are small whereas those lower than 1 Hz are large at TBS resulting small PGA and large PGD. On the contrary, PGA is large and PGD is small at hill sites such as HEU and TEP. Here it is noted that it does not imply that hill is more dangerous than lowland for the structures because PGA is larger at hillside than at lowland. It depends on vibration characteristics of an objective structure; PGA is a good index for rigid structures, whereas PGD for structures with long-period. Short period components are much amplified at sites such as JMA where soft surface layer exists because of the striking contrast of S-wave velocity between the surface deposit and basement. Nonlinear effects during strong motions may diminish short period components. Tobita and Sugimura (1994) showed, however, that the relatively short period components were amplified because of loam layer of several meters at JMA. On the other hand, those are not so amplified at sites such as SSK where soft surface layer does not exist because of the small contrast.

UNDERGROUND STRUCTURES ESTIMATED BY MICROTREMOR MEASUREMENTS

Ground models must be constructed in order to evaluate site effects. Especially, S-wave velocity is an important parameter. We estimate underground structures at lowland by microtremor measurements.

We measured phase velocities of Rayleigh waves included in short-period microtremors by the F-K spectral analysis (Horike, 1980). The microtremors measurements in the vertical direction were conducted at 8 sites shown in Fig.2. In each site, 7 seismometers were put in such a way that they form triangle array with diameters of about 30m as shown in Fig.3. The measurements were carried out in the early morning in order to avoid disturbances such as traffic noise.

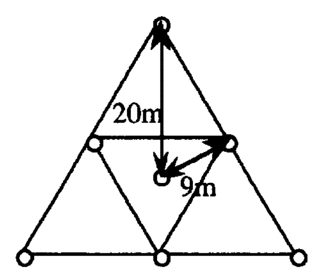


Fig.3. Arrangement of seismometers for microtremors measurement.

The measurements were conducted considering following earthquake damages: At the time of the 1993 Kushiro-oki earthquake, man holes floated up about 130 cm near NCH by soil liquefaction. They were reconstructed after the earthquake. The manholes again lifted up about 5 cm relative to the road surface during the Hokkaido-toho-oki earthquake. This area is located on the marshy lowland consisting of mainly peat (Wakamatsu *et al.*, 1995). KMB is the strong motion observation site where we had charge of the measurement among the observation sites in JWGESG.

Observed phase velocities are shown in Fig. 2. Average values of five trials, each of which was 20.48 sec long, and standard deviations are shown in the sub-figures. Since we used small arrays, phase velocities are reliable in the frequency range from 3 Hz to 8 Hz. Phase velocities in this range are inverted to S-wave velocity distribution in the vertical direction (Horike, 1985). Since it is difficult to evaluate all parameters by only the inversion analysis, parameters except S-wave velocities of alluvial deposits are decided by using following information:

Thickness of layers is decided based on JSSMFE report (1994) and the borehole data near by. The S-wave velocity of the Kushiro-group is assumed to be 500 m/sec and that of Urahoro-group 700 m/sec based on the PS logging data at SMZ site and the long-period microtremor measurements using large arrays (Miyakoshi *et al.*, 1994).

Estimated S-wave velocity structure is shown in the table of each sub-figure in Fig. 2, and theoretical phase velocities of the Rayleigh waves using the S-wave velocity structure are also shown as solid lines in the sub-figure. Calculated phase velocities show good agreement with observed values at all the sites except SKE. It is noted that reliability of observed phase velocities at SKE is low, since there were many traffic noises.

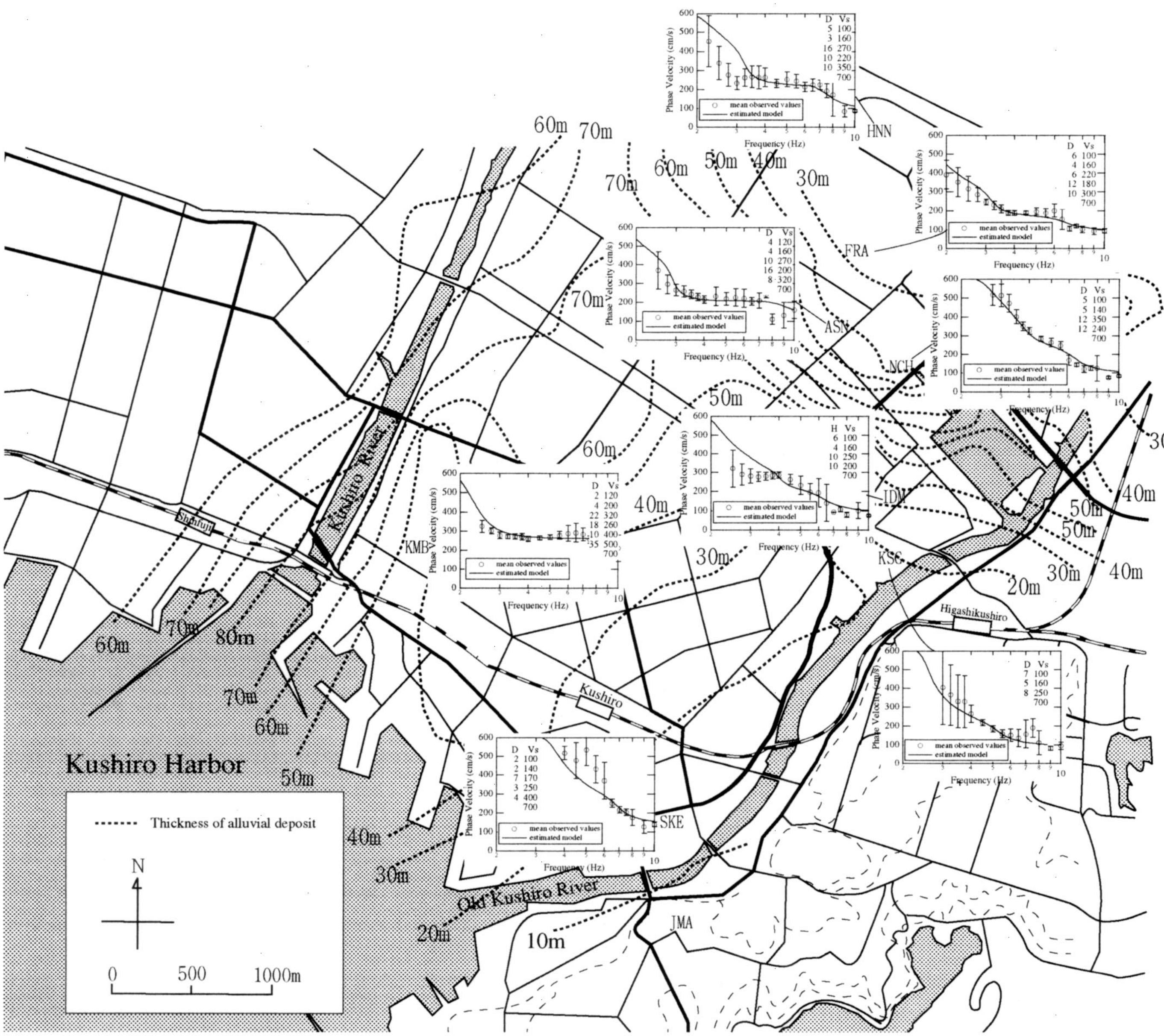


Fig. 2. Phase velocities estimated by microtremors measurement using arrays and S-wave velocity structure estimated by inversion analysis.

ESTIMATION OF INCIDENT WAVE SPECTRA AT BEDROCK

Spectra of the incident wave at the bedrock, that are calculated by deconvolution of earthquake records observed at several sites, are compared to each other in order to examine the accuracy of the evaluated S-wave structures and to evaluate the effect of the nonlinear behavior. Four sites, ASH, SMZ, JSI and KMB, are chosen to be as test sites. Ground motions during the 1994 Hokkaido-toho-oki earthquake are recorded at these sites. These sites are close to the sites whose soil profiles are evaluated by the microtremors measurement. In addition, PS logging was conducted at SMZ (Kudo and Kataoka, 1996).

One-dimensional equivalent linear analysis are employed in the analysis. Records observed at the ground surface during the five earthquakes shown in Table 1 and Fig. 4 are used in the analysis. The Urahoro-group is assumed to be the bedrock. Lower gravel layer and Kushiro-group are assumed to be elastic material. The equation proposed by Yasuda and Yamaguchi (1985) is used as the strain-dependent characteristics of soils in the surface deposit.

Calculated incident wave spectra at the bedrock are shown in Fig. 5. Fourier amplitude characteristics at each earthquake are similar regardless to the site. On the other hand, they seem different under different earthquakes. The larger the scale of earthquake becomes, the larger low frequency components of calculated spectra become. Therefore, calculated spectra are concluded to reflect characteristics of the source and path.

There is, however, a problem. The difference of the spectra between the observation sites is small in the frequency range lower than 5 Hz, but it is large in the frequency range higher than 5 Hz; the incident wave spectra are the largest at SMZ and those are the smallest at KMB under five earthquakes. It comes from various reasons such as 1) effect of the buildings where seismometers are put or buildings near by, 2) error included in evaluating the models (S-wave velocity, damping coefficient, strain-dependent characteristics of soils), 3) frequency dependent characteristics of damping coefficient due to scattering. The PGA of the calculated incident wave at KMB under EQ5 is 69 cm/s^2, which is smaller than observed PGA (119 cm/s^2) at JMA (GL-22m) (Sasaki *et al.*, 1995). The seismometers were set in the one-story building at the sites SMZ, JSI and ASH, whereas it were set in the two-story school building at KMB (Kudo and Kataoka, 1996). Therefore high frequency components of earthquake motions observed at KMB may be small because of interaction between the building and the ground. On the other hand, the calculated PGA at SMZ is larger than the observed PGA. It may be caused by the scattering damping which has frequency-dependent characteristics.

Table 1. Parameters of earthquakes.

Earthquake No.	Date	Epicenter Location		M_{JMA}	Depth (km)	Epicentral Distance (km)	PGA (cm/s^2)			
		Latitude	Longitude				ASH	SMZ	JSI	KMB
EQ1	1994.7.1	42.250	143.083	5.3	67	134	6	11	-	5
EQ2	1994.7.6	42.750	143.967	4.8	107	43	25	35	10	12
EQ3	1994.8.25	42.733	145.167	5.3	65	71	31	41	14	20
EQ4	1994.8.31	43.483	146.067	6.5	84	148	75	62	51	46
EQ5	1994.10.4	43.367	147.667	8.1	30	270	320	261	220	176

PGA is larger value of the horizontal components, and epicentral distance is calculated at KMB site.

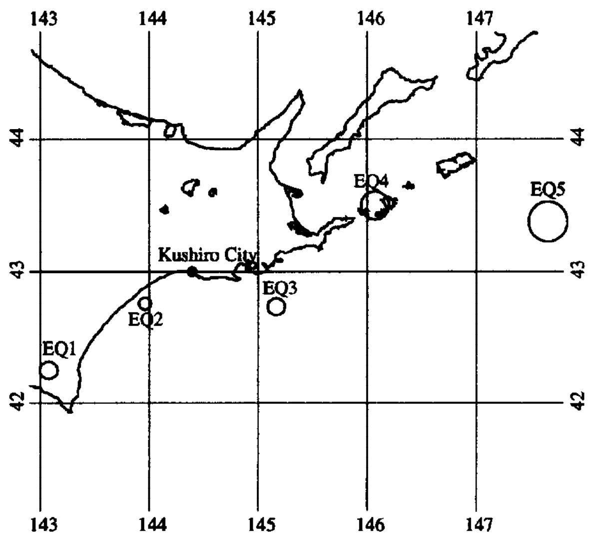
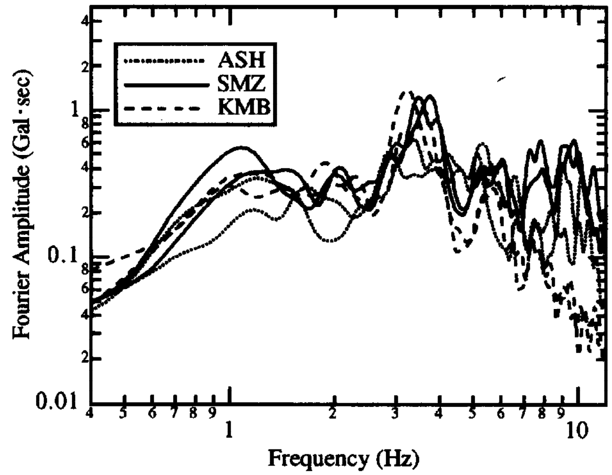
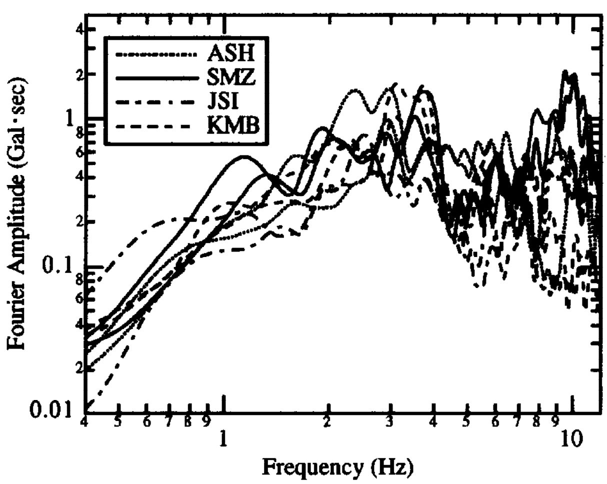


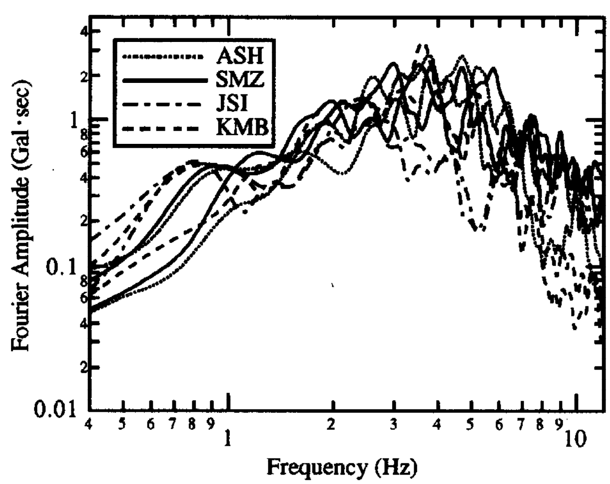
Fig. 4. Locations of epicenters of earthquakes shown in Table 1, where radius of circle indicates magnitude of the earthquake.



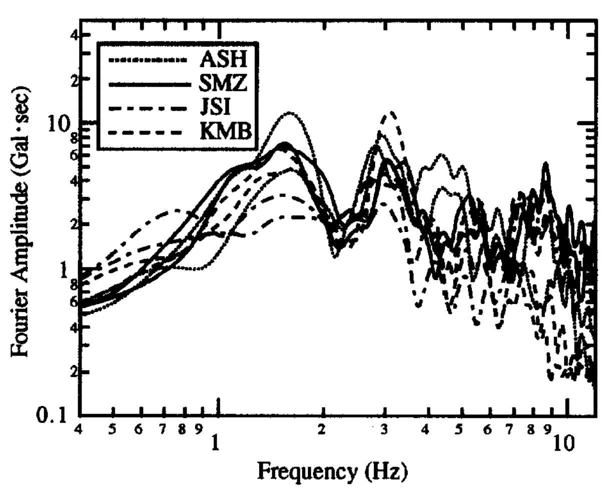
(a) EQ1



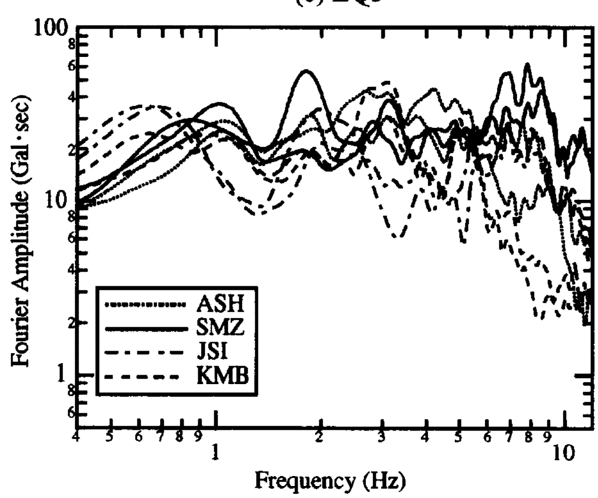
(b) EQ2



(c) EQ3



(d) EQ4



(e) EQ5

Fig. 5. Incident wave spectra at basement estimated by deconvolution of the ground motion records.

NONLINEAR BEHAVIOR

Spectral ratios of the horizontal component to the vertical component (H/V) at four observation sites are shown in Fig. 6. Since the difference of the predominant frequency between five earthquakes is not apparent, nonlinear behavior of the surface layer may not affect spectral characteristics of observed records very much. Figure 6 also includes both the effect of the building at KMB and the effect of frequency dependent characteristics of damping coefficient at SMZ. The ratio H/V are smaller than 1 in the frequency range higher than 8 Hz at KMB. On the other hand, H/V in the high frequency range are large at SMZ.

Figure 7 shows the calculated peak shear strain under EQ5. Since peak shear strain is less than 0.1%, shear modulus ratio G/Go is larger than 0.5. Actually, G/Go is about 0.8. In the case of the 1995 Hyogoken-nanbu earthquake, the nonlinear behavior affected the ground shaking very much (Yoshida *et al.*, 1996), but in this case the effect of nonlinear behavior may not be predominant factor.

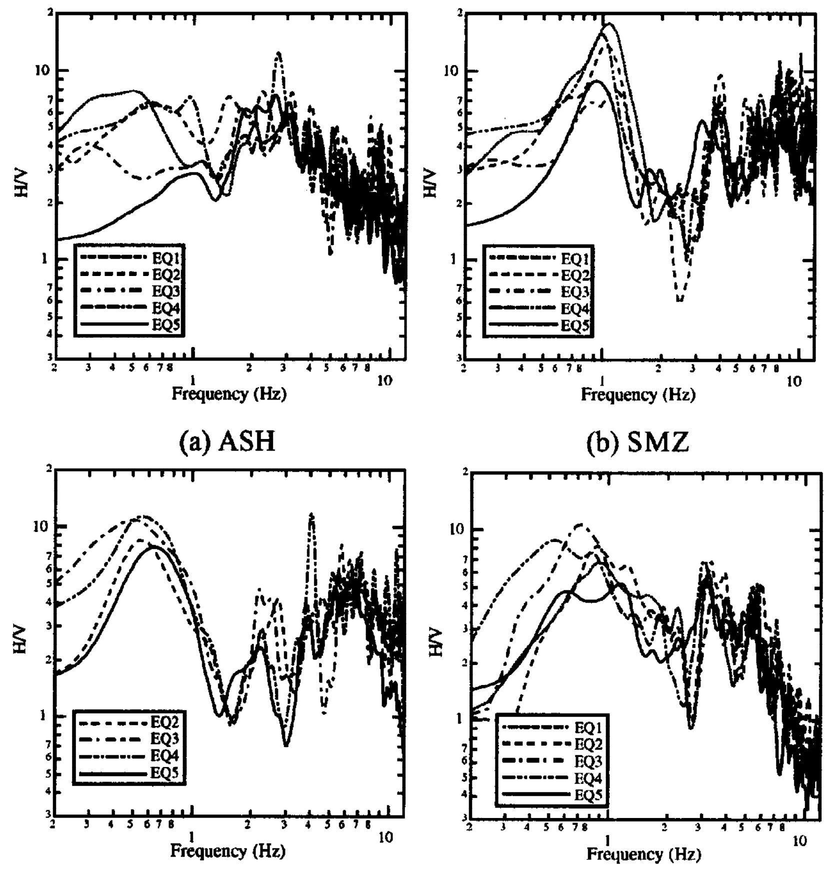


Fig. 6. Spectral ratios of the horizontal component to the vertical component at four observation sites.

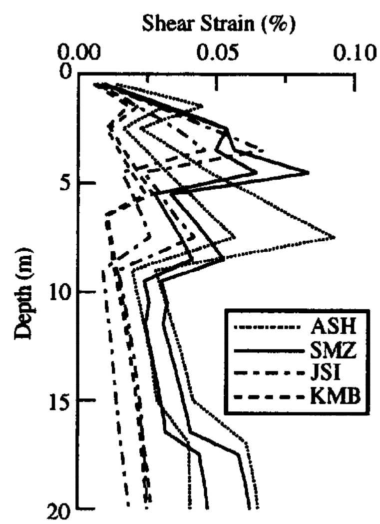


Fig.7. Peak shear strain calculated by equivalent linear analysis.

CONCLUDING REMARKS

We examined the strong motion records observed during the 1994 Hokkaido-toho-oki earthquake in order to clarify the relation between the earthquake records and ground conditions. The following conclusions are made:

1) S-wave velocity structure can be estimated by microtremors measurements using arrays.
2) Predominant frequencies lies in the range from 2 to 4 Hz at the hill, whereas those at lowland were between 0.6 and 1 Hz. This indicates that the thickness of the alluvial deposit strongly affected the frequency characteristics of the ground shaking. In addition, spectral amplitudes around predominant period is larger at the hill area than at the lowland. This caused the difference of peak accelerations. On the other hand, there is not much difference of peak velocity at these sites.
3) The predominant frequency for the Hokkaido-toho-oki earthquake is almost equal to those for other small earthquakes. The peak shear strain calculated by the analysis is smaller than 0.1 %, therefore the nonlinear effect to the ground motion is small in this earthquake.

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