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ESTIMATION OF AMPLIFICATION CHARACTERISTICS OF THE GROUND DURING MODERATE EARTHQUAKES USING SIMULATED MICROTREMORS

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SUMMARY

The characterization of ground amplification during moderate earthquakes has been task of several researches along last century. In most cases, characteristics of ground motion such as, predominant frequency, amplification factor, damping, etc. have been discussed using the SH waves propagation theory. However, the determination of appropriate depth of engineering base-layer for modeling soil profile has been a controversial point. Parameters such as, S wave velocity or impedance contrast, have been used to discuss the depth of engineering base-layer, but the relationship is not clear. Likewise, verifications about above-mentioned characteristics have been difficult because of lack of observed earthquake ground motion records at the surface and at a certain depth for the same location, as well as, the availability of detailed reliable bore-hole log.

This research shows some comparisons between the characteristics of observed horizontal transfer function of moderate earthquake motion and H/V spectral ratio of simulated microtremors at seismological observation sites in Kik-net Akita Prefecture. This seismological observation network possesses two accelerometers installed at the surface and at a depth of more than 100m for each site. Observed horizontal transfer functions of moderate earthquake motions have been obtained by dividing respective top and bottom horizontal Fourier amplitude spectra for each seismic event. The effect of the characteristics of wave input motion in observed transfer functions is supposed to be diminished. Likewise, physical parameters such as, thickness, P and S waves velocities and type of soil, at each site are also available for modeling purposes.

According to the results, the technique of simulated microtremors could be a useful tool for characterization of ground amplification during earthquakes. The possibility of identifying engineering base-layer, as well as, the estimation of amplification characteristics using simulated microtremors has been probed successfully.

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INTRODUCTION

The adequate modeling of the ground to evaluate its amplification characteristics during earthquakes has been a difficult task. Usually, parameters such as the impedance contrast and S wave velocity have been use for the determination of the appropriate depth for modeling of the ground. Ordinarily, after making the appropriate modeling of the ground, the fundamental resonance frequency of SH waves is usually calculated to estimate the predominant frequency of the ground during earthquakes. However, it is known that most part of earthquake ground motion responds to the effect of surface waves (Love and Rayleigh waves). As consequence, the value of the fundamental resonance frequency of SH wave does not always fit well with the value of the predominant frequency of observed horizontal transfer function.

In 1995, Wakamatsu [1] reported the possibility of estimate the amplification characteristics of soil deposits based on the ratio of horizontal and vertical spectra (H/V spectral ratio) of microtremors. Originally, the method of H/V spectral ratio of microtremor measurements was proposed by Nakamura [2] in 1989.

The present research attempts to clarify the possibility of estimate the amplification characteristics of the ground using H/V spectral ratio of simulated microtremors, as well as, to introduce this technique to discuss the appropriate depth for modeling of the ground. Discussion is performed through the observed horizontal transfer function of earthquake ground motion, the theoretical transfer function of SH waves and the H/V spectral ratio of simulated microtremors.

OBSERVED HORIZONTAL TRANSFER FUNCTION, THEORETICAL TRANSFER FUNCTION OF SH WAVES AND H/V SPECTRUM OF SIMULATED MICROTREMORS

Observed horizontal transfer function

Earthquake ground motion data from eight seismological observation sites of the digital strong motion seismograph network (Kik-net) in Akita Prefecture were analyzed. The Kik-net belongs to the National Research Institute for Earth Science and Disaster Prevention of Japan (NIED). Each seismological observation site consists of two digital strong motion seismographs; one installed at the surface and another at a depth greater than 100m. The Table 1 summarizes the physical parameters of soil profile at each site. The 12 available largest horizontal components of earthquake ground motion recorded during the period January 1997 – September 2002 at each observation site were selected. The largest horizontal component acceleration was 34.2 gals, which was recorded at AKTH04 in December 2nd, 2001. The top frame in each observation site of Fig. 1 and Fig. 2 shows the average observed horizontal transfer function of the 12 selected largest events (bold black line) and the variations with standard deviation (thin black lines). Each observed horizontal transfer function was obtained by dividing respective surface and deep horizontal Fourier amplitude spectrum. The horizontal Fourier amplitude spectrum was calculated from the root square of the sum of the squares of the two horizontal amplitude spectra (NS and EW components), respectively (Eq. 1).

$$F_H(\omega)=\sqrt{\left|F_{NS}(\omega)\right|^2+\left|F_{EW}(\omega)\right|^2} \tag{1}$$

A time length of 81.92 s from the beginning of the earthquake ground motion with a sampling frequency of 100 Hz was selected for FFT analysis. All surface and deep horizontal Fourier amplitude spectra were smoothed with Hanning filter, which number of iterations is defined in Eq. (2).

Number of iterations = Number of data * Predominant freq.(Hz) * Sampling freq.(Hz) / 25600 (2) where, the value of the predominant frequency is the lowest predominant frequency of observed horizontal transfer function. The low standard deviation in amplification factor indicates independence of the transfer function of the ground from input wave motion. The dynamic characteristics of the input wave motion are supposed to be cancelled by dividing surface/deep horizontal Fourier amplitude spectra. Slight variations in observed average horizontal transfer functions indicate quasi-elastic behavior of the ground during moderate earthquakes.

Likewise, the observed horizontal transfer function of the May 26th, 2003 earthquake (bold red line) is displayed for comparison purposes. The largest horizontal component acceleration was recorded due to this earthquake at each observation site, whose maximum acceleration is displayed in parenthesis (top frame of each site in Fig. 1 and Fig. 2). The amplification factor tends to decrease for large ground motions. The AKTH04 observation site did not record this event due to it was inactive at that moment.

Theoretical transfer function of SH waves

To discuss some relationships with the value of the predominant frequency of observed horizontal transfer function of earthquake ground motion and the value of the predominant frequency of the H/V spectral ratio of simulated microtremors, the fundamental frequency of SH waves for several systems of the ground was calculated at each site. The first system consisted of the upper first layer overlying the second layer (base layer), the second system consisted of the upper two layers overlying the third layer (base layer), and the other superior systems were defined analogously.

The third column from the right of Table 1 summarizes the fundamental resonance frequency of SH waves obtained for each system. The central frame of Fig. 1 and Fig. 2 shows the theoretical transfer function of SH waves for all systems obtained at each site. Lower fundamental frequencies are obtained as the number of layers increases.

H/V spectral ratio of simulated microtremors

The technique of simulated microtremors was previously developed and verified by Tokeshi [3], introducing the parameter R_F, which is the ratio between the horizontal point source and the vertical point source applied on surface of the ground (horizontally layered underlain by a half-space). These sources (pseudo-Dirac wave type) were randomly distributed around the observation site. Under these suppositions, Love wave is absent in horizontal components when $R_F = 0$, but that Love wave content increases as R_F varies from 0 to 1. As the Love wave content increases with R_F, a predominant peak in the H/V spectral ratio develops around the called "natural frequency of the ground". The simulated microtremors ($R_F = 1$) in the three components (two horizontal and one vertical components) for 81.92 s with sampling frequency of 100 Hz were calculated for all systems at each site using the same physical parameters of soil profile displayed in Table 1. The systems are the same defined in previous section. Simulated microtremors for the whole system (considering all layers) were calculated assuming an additional layer with same physical parameters of the upper deepest layer at each site.

The H/V spectral ratio was obtained using Eq. (3).

$$\frac{H(\omega)}{V(\omega)} = \frac{|F_H(\omega)|}{|F_V(\omega)|} \tag{3}$$

Before calculating the H/V spectral ratio, all Fourier amplitude spectra for all systems were smoothed for a predominant frequency of 1 Hz, i.e., 32 iterations (applying Eq. 2). The bottom frame at each site in Fig. 1 and Fig. 2 shows the H/V spectral ratio for all systems of the eight seismological observation sites.

Table 1. Summary of physical parameters constituting the soil profile at eight Kik-net seismological observatory sites in Akita Prefecture.

	Layer	Thick (m)	Type of soil	Dens.(1) (t/m3)	Vp (m/s)	Vs (m/s)	Qp & Qs	Freq. (2) (Hz)	Imp. Ratio	Corre. (3) Coef.
AKTH01 Nishiki-Kita	1	2.0	Gravel	1.62	750	200	20	25.2	2.8	0.48
	2	13.9	Gravel and andesite	2.10	2090	430	25	6.8	1.6	0.85
	3	34.1	Tuff breccia	2.10	2090	680	35	3.3	1.3	0.96
	4	36.0	Tuff	2.10	2090	850	45	2.3	1.4	1.00
	5	14.0	Mudstone	2.10	2090	1200	60	2.2	1.0	
AKTH02 Nishiki-Minami	1	5.2	Terrace deposits	1.50	550	250	20	12.1	5.1	0.99
	2	50.8	Mudstone	2.12	2180	900	45	4.0	1.2	1.00
	3	44.0	Tuff	2.17	2410	1080	55	2.6	1.0	
AKTH03 Yashima	1	1.0	Gravel, sand and volcanic ash	1.53	600	180	20	45.3	1.7	0.99
	2	3.0	Gravel, sand and volcanic ash	1.81	1150	260	20	16.7	1.1	0.46
	3	12.0	Gravel, sand and volcanic ash	1.98	1680	260	20	4.2	1.8	0.93
	4	38.0	Mudstone	1.98	1680	460	25	2.1	1.4	1.00
	5	49.0	Mudstone	1.98	1680	640	25	1.4	1.0	
AKTH04 Higashi-Naruse	1	2.0	Conglomerate	1.29	300	150	20	18.9	3.8	0.17
	2	18.0	Conglomerate	1.69	880	430	25	5.5	3.1	0.90
	3	12.0	Rudite and tuff breccia	2.29	3000	980	50	5.0	1.2	0.94
	4	38.0	Tuff breccia	2.29	3000	1150	50	3.8	1.3	1.00
	5	30.0	Tuff breccia	2.29	3000	1500	75	3.1	1.0	
AKTH05 Chokai	1	5.6	Gravel, sand and clay	1.74	1000	580	20	26.0	1.4	- 0.10
	2	8.4	Andesite	2.37	3420	580	30	11.3	2.3	0.81
	3	26.0	Andesite	2.37	3420	1330	70	7.6	1.4	0.92
	4	81.3	Andesite	2.37	3420	1880	100	3.8	1.3	0.99
	5	78.7	Altered andesite	2.48	4120	2530	120	2.7	1.0	
AKTH06 Ogachi	1	1.0	Volcanic ash	1.34	350	150	20	37.7	1.2	- 0.30
	2	3.0	Volcanic ash	1.65	810	150	20	9.9	2.3	0.23
	3	12.0	Tuff breccia	1.65	810	350	25	5.3	4.2	0.99
	4	84.0	Tuff breccia	2.21	2560	1100	50	2.7	1.0	
AKTH07 Kosaka	1	2.0	Gravel and sand	1.47	500	250	20	22.6	1.5	0.69
	2	12.0	Gravel and sand	1.60	710	340	25	4.7	1.2	0.85
	3	4.0	Gravel and sand	1.98	1660	340	25	3.8	1.1	0.99
	4	22.0	Lapilli tuff	1.98	1660	390	50	2.7	1.3	1.00
	5	65.0	Lapilli tuff	2.02	1800	490	50	1.5	1.0	
AKTH08 Fujisato	1	2.0	Gravel, sand and clay	1.34	350	120	20	15.1	6.5	0.37
	2	14.0	Sandstone	2.06	1960	510	25	7.9	1.4	0.97
	3	34.0	Sandstone	2.06	1960	720	25	3.6	1.3	1.00
	4	108.0	Sandstone	2.11	2140	900	50	1.4	1.1	1.00
	5	42.0	Sandstone and andesite	2.11	2140	1000	50	1.2	1.0	

(1) Density was estimated by $\rho = 0.31 V_P^{0.25}$, where ρ is in (t/m3) and V_P is in (m/s) [4]

(2) Fundamental resonance frequency of SH waves considering the next below layer as base-layer

(3) Correlation coefficient between the H/V spectra of i^{th} and $(i+1)^{th}$ systems

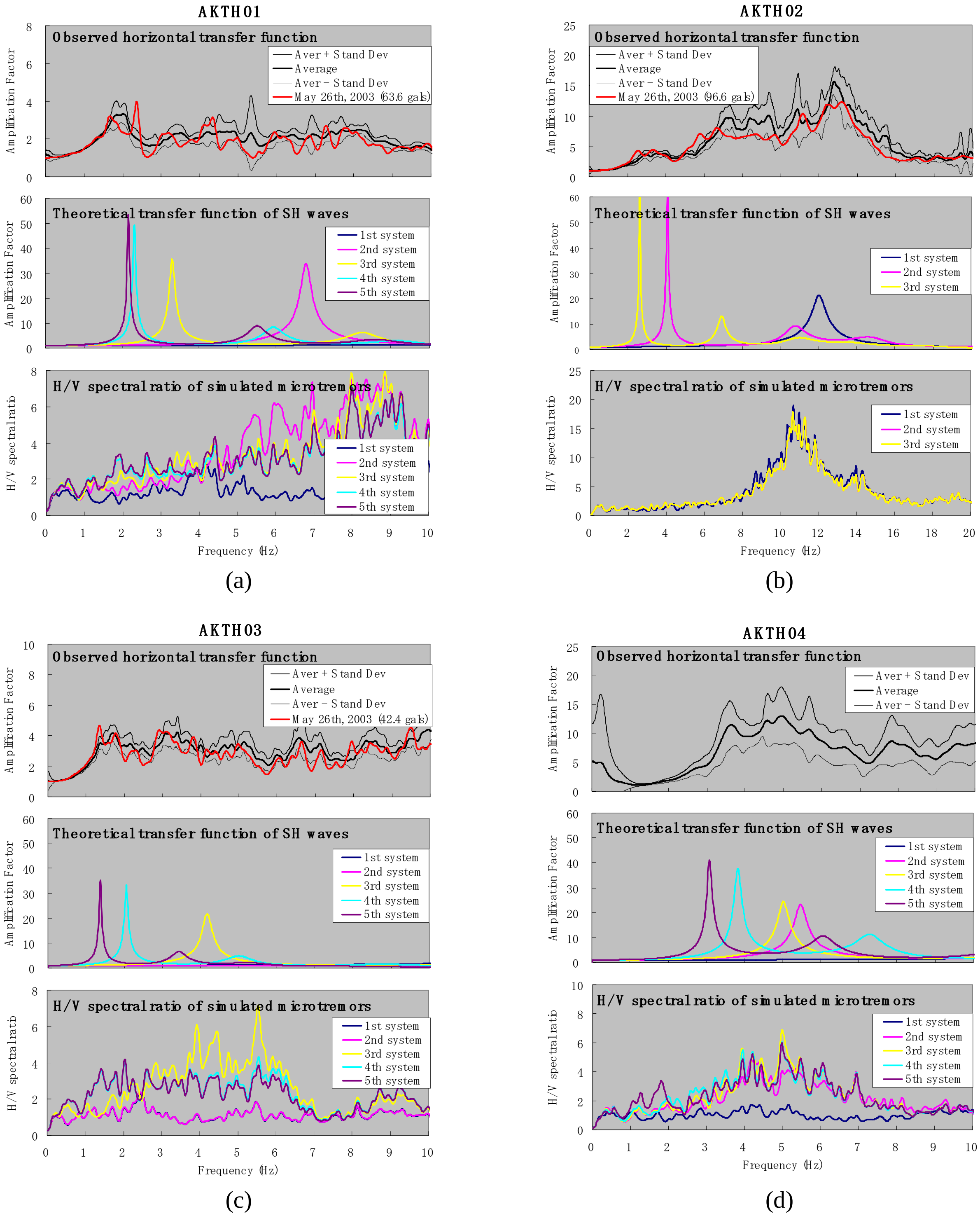

Figure 1. Comparison of spectra at (a) AKTH01, (b) AKTH02, (c) AKTH03 and (d) AKTH04 Kik-net seismological observation sites in Akita Prefecture. [TOP: average observed horizontal transfer function of moderate earthquake ground motions (bold line), variations with standard deviation (thin lines) and observed horizontal transfer function of May 26th 2003 earthquake ground motions (red line), which maximum acceleration is in parenthesis. CENTER: theoretical transfer function of SH waves for each system. BOTTOM: H/V spectral ratio of simulated microtremors for each system].

DISCUSSIONS ON RESULTS AT 8 SEISMOLOGICAL OBSERVATION SITES

AKTH01: Nishiki-Kita

The physical soil properties for this site shown at the top of Table 1, indicates that no clear engineering base-layer is distinguished. The average observed horizontal transfer function (Fig. 1.a) shows a predominant frequency at 1.9 Hz with amplification factor of 3.6. The fundamental resonance frequencies for the 4th and 5th systems are 2.3 and 2.2 Hz, respectively, which are close to the predominant frequency of the average observed transfer function of moderate earthquakes (Table 1 and Fig. 1.a). The H/V spectra of simulated microtremors for the five systems display changing shapes, but tend to stabilize for the 4th and 5th systems. The lowest predominant frequency is around 2 Hz with H/V spectral ratio of 3.3.

AKTH02: Nishiki-Minami

Clear shallow base-layer is distinguished from physical soil properties at this site (Table 1). High impedance contrast of 5.1 at 1st interface, would suggests strong effect of this interface, which fundamental frequency is 12.1 Hz. The average observed horizontal transfer function (Fig. 1.b) shows a predominant frequency at 12.8 Hz with amplification factor of 15.4. The H/V spectral ratios of simulated microtremors (R_F =1) for the three models display similar shapes and predominant frequency at about 10.7 Hz with spectral ratio of 17.7, indicating that the amplification produced in the 1st layer is predominant. The predominant frequencies (12.8 Hz and 10.7 Hz) and the relationship between the H/V spectral ratio and the amplification factor of average observed horizontal transfer function for moderate earthquake motions (15.4 and 17.7) show acceptable correlation.

AKTH03: Yashima

Analogously to site AKTH01, low impedance contrasts (Table 1) make difficult to decide the appropriate depth for modeling the ground. The average observed horizontal transfer function (Fig. 1.c) shows a predominant frequency at 1.7 Hz with amplification factor of 4.1. The H/V spectra of simulated microtremors for the 4th and 5th systems display similar shapes and the predominant frequency is around 2 Hz with H/V spectral ratio of 4.1. The high correlation coefficient of 0.93 between the 4th and 5th systems (Table 1) would suggests that the 4th system (4 layers/5th layer) would be predominant. Same value of 4.1 was obtained for the H/V spectral ratio and the amplification factor of the average observed horizontal transfer function of moderate ground motions.

AKTH04: Higashi-Naruse

The value of the predominant frequency of average observed horizontal transfer function (Fig. 1.d) is around 5.0 Hz with an amplification factor of 12.8. The physical soil properties at this site (Table 1) shows high impedance contrast for the 1st and 2nd interfaces (3.8 and 3.1), but the fundamental frequency of 5 Hz in the theoretical transfer function for the 3rd system (Table 1 and Fig. 1.d) suggest that the 3rd system could be more appropriate than the 2nd system. The shape of the H/V spectra of simulated microtremors (R_F =1) is similar from the 3rd system (correlation coefficient of 0.94 in Table 1 as well as Fig. 1.d). The predominant frequency is around 5 Hz with a spectral ratio of 7.9.

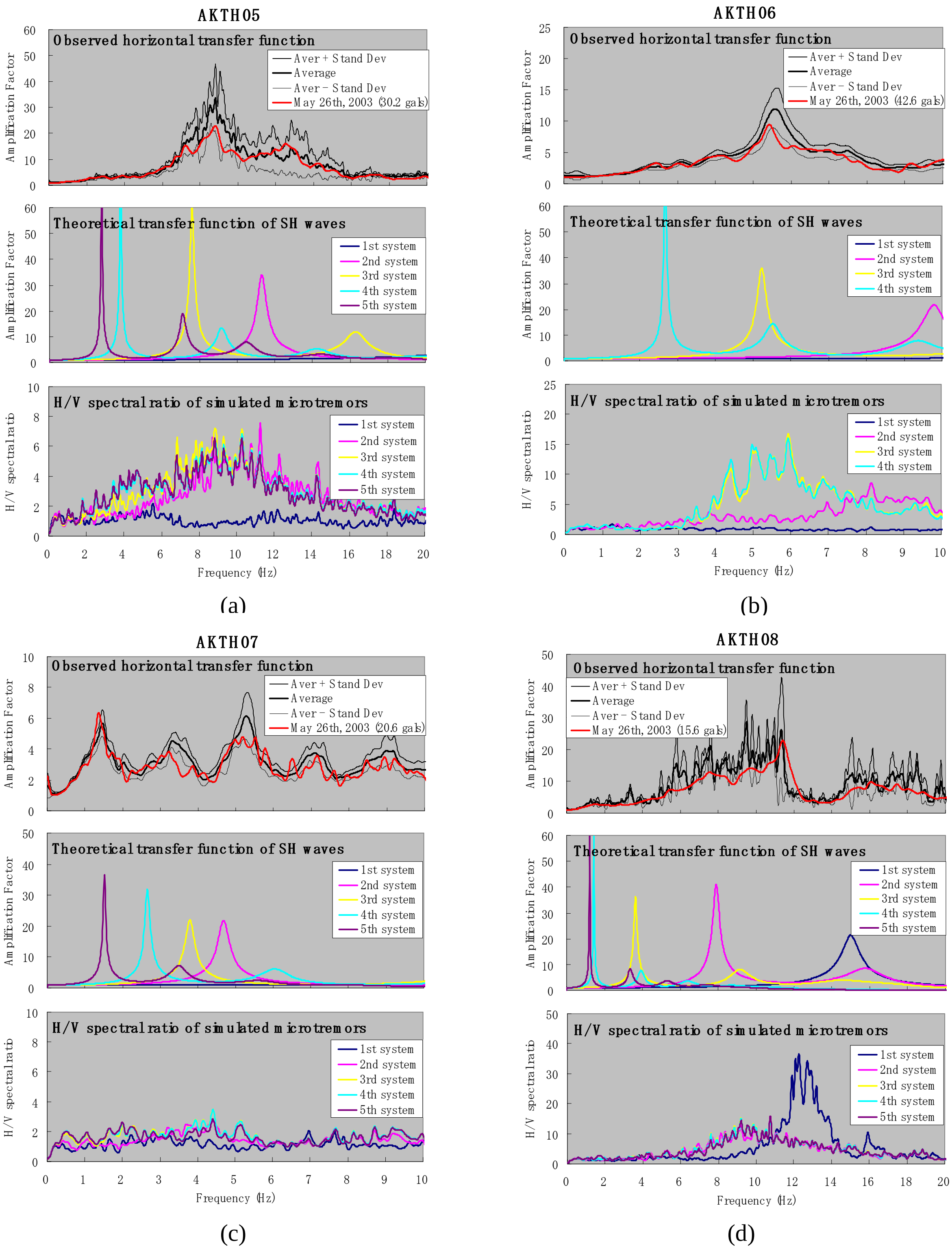

Figure 2. Comparison of spectra at (a) AKTH05, (b) AKTH06, (c) AKTH07 and (d) AKTH08 Kik-net seismological observation sites in Akita Prefecture. [TOP: average observed horizontal transfer function of moderate earthquake ground motions (bold line), variations with standard deviation (thin lines) and observed horizontal transfer function of May 26th 2003 earthquake ground motions (red line), which maximum acceleration is in parenthesis. CENTER: theoretical transfer function of SH waves for each system. BOTTOM: H/V spectral ratio of simulated microtremors for each system].

AKTH05: Chokai

The average observed horizontal transfer function (Fig. 2.a) shows a predominant frequency at 8.8 Hz with amplification factor of 33.1. The Table 1 shows a high impedance contrast of 2.3 for the second interface, suggesting that the 2nd system could be predominant. However, a comparison between the values of the fundamental frequency for the 2nd and 3rd systems of the theoretical transfer function of SH waves and the predominant frequency of H/V spectra of simulated microtremors, suggests that even tough the H/V spectral ratio of the 2nd system is predominant, the 3rd system could be more appropriated for better modeling of the ground. High correlation coefficients were obtained from the 3rd system (>0.92) support this suggestion. The H/V spectra of simulated microtremors show similar shape from the 3rd system with a predominant frequency at 8.8 Hz and H/V spectral ratio of 7.6. Quite different values for amplification factor of observed horizontal transfer function and for H/V spectral ratio would indicate special topographical conditions at this site. Further detailed analysis is needed

AKTH06: Ogachi

A high impedance contrast of 4.2 was obtained for the third interface (Table 1). The average observed horizontal transfer function (Fig. 2.b) shows a predominant frequency at 5.6 Hz with amplification factor of 11.7. The shape of the H/V spectral ratio of simulated microtremors for the 3rd system in comparison with the 2nd system is quite different, indicating that the amplification effect is strongly defined by the high impedance contrast of the third interface. The predominant frequency of 5.9 Hz with H/V spectral ratio of 16.6, are acceptable when comparing with the values obtained in the average observed horizontal transfer function.

AKTH07: Kosaka

Analogously to sites AKTH01 and AKTH03, impedance contrasts lower than 2 for all interfaces (Table 1) suggest that the effect of surface waves could reach depths about 100 m. The fundamental frequency for the 5th system is 1.5 Hz. The average observed horizontal transfer function (Fig. 2.c) shows a low predominant frequency around 1.5 Hz with amplification factor of 6. Also, an increasing peak around 2 Hz is shown as higher systems are considered in the H/V spectral ratio of simulated microtremors. A low H/V spectral ratio of 2.6 was obtained.

AKTH08: Fujisato

The average observed horizontal transfer function (Fig. 2.d) shows a predominant frequency at 11 Hz with amplification factor of 24. A high value of 6.5 for impedance contrast was obtained for the first interface (Table 1) suggesting a high predominant frequency for this site. However, the shape of the H/V spectral ratio of simulated microtremors for the 2nd system or superior systems in comparison with the shape of the 1st system are quite different, indicating that the amplification effect is strongly defined in the 2nd system. The predominant frequency of 9.2 Hz with a spectral ratio of 13, which is half of the amplification factor in the average observed horizontal transfer function, would imply special topographical conditions at this site. Further detailed analysis is needed.

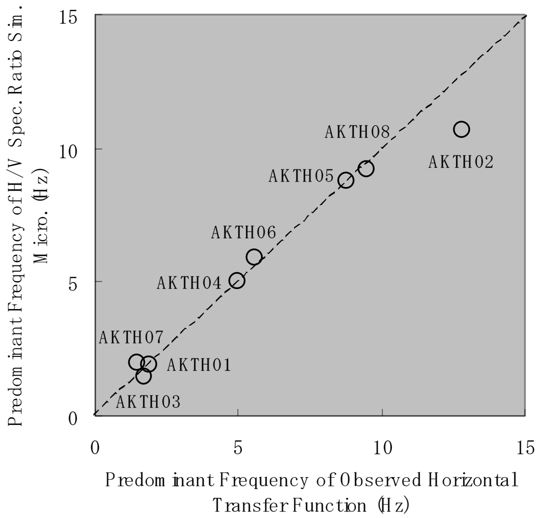

Figure 3: Comparison between the predominant frequency of observed horizontal transfer function and the predominant frequency of H/V spectral ratio

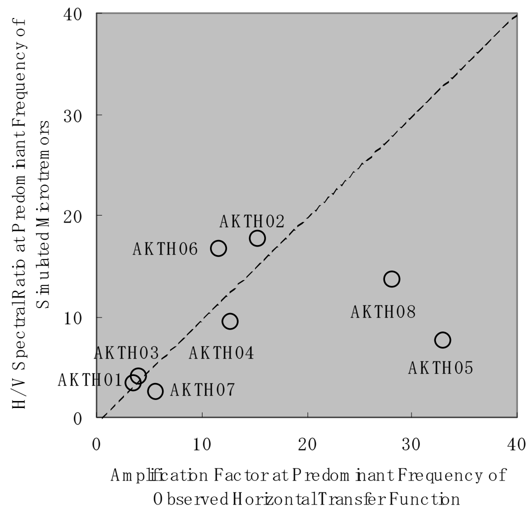

Figure 4: Comparison between the amplification factor of observed horizontal transfer function and the H/V spectral ratio of simulated microtremors

Estimation of amplification characteristics of the ground using simulated microtremors

A summary of the results at 8 Kik-net seismological observation sites in Akita prefecture is displayed in Fig. 3 ans Fig. 4.

Excepting the case for AKTH02, the predominant frequencies of H/V spectral ratio using simulated microtremors showed good agreement with predominant frequencies of observed horizontal transfer function of the ground (Fig. 3).

The Fig. 4 shows a comparison between the amplification factor of observed horizontal transfer function of moderate earthquake ground motion and the value of the H/V spectral ratio at predominant frequency of simulated microtremors. An acceptable correlation factor of 0.90 was obtained for six observation sites.

According to the results for AKTH01, AKTH04 and AKTH08 sites, the effect of the first upper layer with thickness equal or less than 2 m. would be not predominant, even though high impedance contrast exists at the first interface. Taking into consideration previous comment, sites with predominant frequency lower than 2 Hz and impedance contrast ratio lower than 2, such as AKTH01, AKTH03 and AKTH07, showed amplification factors lower than 6.

However, estimation of the amplification factor at AKTH05 and AKTH08, which amplification factors were more than 28, was without success. Some special topographical conditions at these sites are speculated and further additional surveys are needed.

CONCLUSIONS

A comparison of the observed horizontal transfer function of moderate earthquake ground motion and the H/V spectral ratio of simulated microtremors (R_F =1) was performed at 8 Kik-net seismological observation sites of Akita Prefecture.

1. In general, the estimation of the predominant frequency of the ground during moderate earthquake through the predominant frequency of H/V spectral ratio of simulated microtremors was verified successfully.
2. The use of simulated microtremors to estimate the possible amplification effects of surface wave with the depth of the model of the ground was introduced.
3. An acceptable correlation of 0.90 between the magnitude of the H/V spectral ratio of simulated microtremors and the amplification factor of observed horizontal transfer function for 6 sites was obtained. However, estimation of high amplification factors at two sites was without success. Some special topographical conditions at these sites are speculated and further additional surveys are needed.

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