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RELATIONSHIP BETWEEN SOIL AMPLIFICATION, SURFACE-TO-BOREHOLE SPECTRAL RATIO AND HORIZONTAL-TO-VERTICAL SPECTRAL RATIO FOR EARTHQUAKE RECORDS

S. Noguchi[1], O. Murakami[2] and Y. Asai[3]

[1] *Research Staff, Association for the Development of Earthquake Prediction, noguchi@8f.adep.or.jp*
[2] *Vice Senior Research Staff, Tono Research Institute of Earthquake Science, murakami@mail.tries.jp*
[3] *Senior Research Staff, Tono Research Institute of Earthquake Science, asai@mail.tries.jp*

Abstract

We calculated the soil amplifications for ground acceleration, the surface-to-borehole spectral ratios for horizontal motions (H/H spectral ratios) and the horizontal-to-vertical spectral ratios (H/V spectral ratios) at surface stations. These records are derived from the dense seismic network around Tono region containing mountains and small basins located on middle Japan. In this region, Tono Research Institute of Earthquake Science operates the seismic observation network including both dozens of near surface borehole stations with depths of 4 m and several deep borehole stations with depths from 500 m to 1020 m. We investigated the possibility to utilize the H/V spectral ratios for earthquake records which are easy to derive at any sites for the estimations of the surface soil amplifications. First, we calculated the spectral ratios at 25 near surface stations. As a reference, we chose BYB station whose seismometer was installed at the depth of 1020 m. Fourier amplitude spectra for NS, EW and UD components at each station were calculated from the S-wave portion for 29 earthquakes occurred beneath the Tono region. In this research, we targeted the frequency band from 1 Hz to 10 Hz only, because of the magnitude range of earthquake (3~5.1).We calculated the H/H spectral ratios and the H/V spectral ratios. Because H/V spectral ratios were sensitive to the vertical motions, we calculated the normalized peak values of the H/V spectral ratios that are the peak values of H/V spectral ratios divided by the mean levels of H/V spectral ratios. Moreover, we calculated the ratios of the peak ground acceleration (PGA) for the horizontal motion (1-10 Hz) at each station to that at BYB borehole station. PGA ratio represents the amplification in the time domain. As a result, the peak frequencies of H/H spectral ratios correspond to that of H/V spectral ratio at most stations. The peaks of H/H spectral ratios were also related to the normalized peaks of H/V spectral ratios, but not well as to their frequencies. This result shows the effect of vertical motion on H/V spectral ratios. Both peaks of H/H spectral ratios and the normalized peaks of H/V spectral ratios also show the relationships to the horizontal PGA amplifications, though the distributions of them are considerably dispersed. Such dispersions show the sensitivities of H/V spectral ratios to the vertical motions, and the variations of the incident angles to each surface station which differ from the ones to BYB borehole station. Stations with higher soil amplification were located at both mountain and valley. It would means that the soil amplifications of stations we used are depend strongly on the quite local soil conditions.

Keywords: Soil Amplification, Surface-to-borehole spectral ratio, H/V spectral ratio

1. Introduction

To investigate site amplification during an earthquake, the spectral ratio method has been used widely. We can derive spectral ratios representing site amplification characteristics by dividing the amplitude spectrum from ground motion time series by that from reference site -- outcrop or borehole site. However, it is difficult to find proper reference site for most of seismic stations. In such case, it was proposed that the spectral ratios of the horizontal amplitude spectrum to the vertical amplitude spectrum at the same station instead of reference site (H/V spectral ratio), also could represent the soil amplification characteristics [1]. Especially, the dominant peaks of amplification due to soil in fundamental mode (lowest in frequency) can be detected by H/V spectral ratios because the soil amplifications on the vertical motions always appear on the higher frequencies. In this research, we examine the relationships among H/V spectral ratios, spectral ratios to reference and soil amplifications on maximum ground motions, using the seismic records during earthquakes, observed by the dense seismic network and a 1020 m deep borehole site.

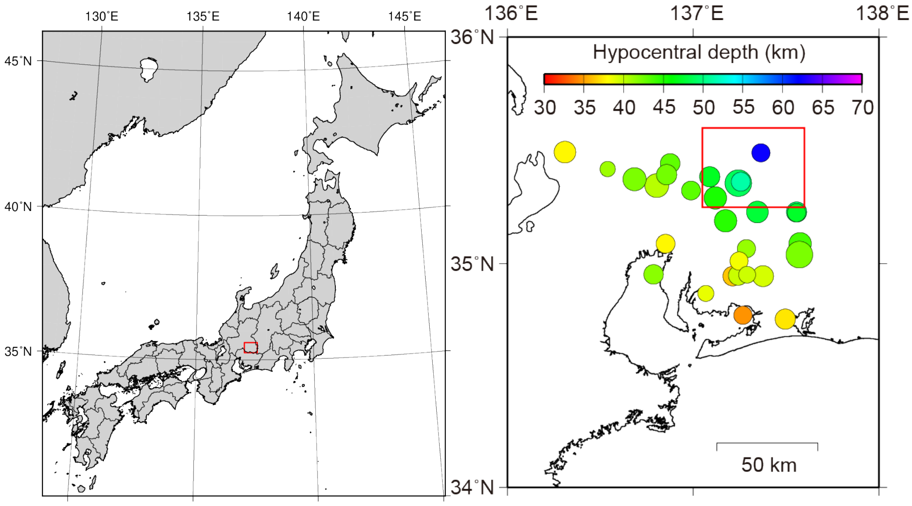

Fig. 1 – Hypocentral distribution of events used in this research.

Red square means the region of left panels in Fig. 6

2. Data and method

As surface stations on soil, we used 25 seismic stations (H003~H055) at Tono region located on middle Japan (red square in Fig. 1) operated by Tono Research Institute of Earthquake Science (TRIES)[2]. They were installed at the depth of GL-4 m to avoid noise. It can be considered that the reflected waves at surface could influence on seismic records at these stations (ex. [3]). We checked the spectral ratios in this research and concluded that the effect of reflected waves were negligible in our analysis. We also use a 1020 m deep borehole station, BYB (Byobu-san) which is also operated by TRIES, as a reference to surface stations.

We derived H/H spectral ratios, H/V spectral ratios and horizontal PGA amplifications at each surface station, and compared them each other. First, we picked up 29 events occurred at the depth of around 35~60 km (Fig. 1 and Table 1). We used the seismic records whose hypocentral distance were less than the twice of hypocentral depth only to avoid the influence of surface waves and incident angle. Then we calculated Fourier amplitude spectra for S-wave portion with 20.48 s time window for three components of seismic records at each station using FFT. Each spectrum was smoothed using Parzen window with the window width of 0.4 Hz. Horizontal amplitude spectra were derived as geometrical means of two amplitude spectra of the horizontal components. Surface-to-borehole spectral ratios of the horizontal components (H/H spectral ratios) were calculated by dividing horizontal spectrum at surface by that at BYB borehole. Horizontal-to-vertical spectral ratios at surface (H/V spectral ratios) were calculated by dividing the horizontal amplitude spectrum by the vertical amplitude spectrum. Finally, all spectral ratios at each station were averaged with respect to each station. Derived H/H and H/V spectral ratios at all surface stations are shown in Fig. 2.

In this research, we used the peak of H/H spectral ratios (Fig. 3(a)) that would control the amplification of the waveform. For H/V spectral ratio, we used the normalized peak amplitudes by the mean of spectral ratios (Fig. 3(b)) because the levels of H/V spectral ratio are sensitive to not only horizontal amplitudes but also to vertical amplitudes. Different from H/H spectral ratios, H/V spectral ratios are not necessary converge on 1. Both the peaks of H/H spectral ratios and the normalized peaks of H/V spectral ratios were picked up from the frequencies between 1 Hz and 10 Hz, because the magnitudes of events were limited between 3 and 5.1. The amplitudes of seismic records would be controlled by the power of around this frequency band during events with such magnitudes.

Table 1 – List of events used in this research

	Latitude	Longitude	Hypo.dep.	
Origin time (JST)	°N	°E	km	Mjma
2010/06/23,22:17:30.12	35.3228	136.9878	43.14	3.6
2010/08/20,15:34:50.84	34.9507	136.7875	41.68	3.7
2010/08/26,05:54:28.76	34.9438	137.3763	39.34	4.0
2010/09/10,09:34:48.45	34.9433	137.2127	36.21	3.7
2010/10/10,00:37:04.80	35.4182	136.5400	41.09	3.0
2010/12/28,22:07:31.32	34.9457	137.2438	39.71	3.7
2011/07/11,19:28:47.74	35.4892	137.3655	62.33	3.5
2011/12/14,13:01:08.25	35.3555	137.2443	48.82	5.1
2012/01/15,07:12:45.75	35.3610	137.2575	51.23	3.6
2012/05/05,18:56:52.82	35.1892	137.1742	44.77	4.3
2012/10/30,04:05:07.56	35.0872	136.8527	37.77	3.6
2013/02/06,13:42:06.85	35.2278	137.3468	47.78	4.1
2013/04/20,00:48:41.83	35.2272	137.5570	49.23	3.9
2013/04/30,10:07:13.62	35.0648	137.2877	41.29	3.4
2013/07/17,20:32:03.98	35.4430	136.8758	43.00	3.8
2013/09/14,00:09:39.07	34.7700	137.2690	34.60	3.5
2014/01/03,08:10:34.96	34.8667	137.0688	38.71	3.1
2014/04/06,01:24:24.08	35.3832	137.0890	47.08	3.9
2014/09/14,15:57:40.01	35.4927	136.3092	37.78	4.1
2014/12/03,23:19:50.85	35.2908	137.1190	45.23	4.2
2015/03/04,00:04:20.86	35.3443	136.8048	40.24	4.6
2016/03/20,11:42:54.59	35.0108	137.2478	38.37	3.5
2016/04/25,10:00:25.04	35.0875	137.5765	43.82	4.2
2016/09/15,14:13:02.85	35.2243	137.5572	47.30	3.4
2017/05/10,23:11:40.33	35.3922	136.8582	42.39	3.9
2018/04/14,13:51:12.49	34.9500	137.2903	39.62	3.2
2018/08/14,20:51:00.92	34.7520	137.4970	37.22	3.9
2018/10/07,10:14:19.11	35.0380	137.5733	42.13	5.0
2019/03/09,01:08:03.58	35.3723	136.6840	42.11	4.4

Amplifications of the horizontal ground motions due to soil were estimated by dividing the peak ground acceleration (PGA) for horizontal motions at surface stations by that at BYB borehole station. Horizontal PGAs were derived as the maximum amplitudes of the horizontal vector motions synthesized using NS and EW components. Time windows for all waveforms were just same to that for the calculations of spectral ratios mentioned above. We applied 1-10 Hz bandpass filter on these waveforms. Soil amplifications for each station were derived as the geometrical means of PGA amplifications for all events.

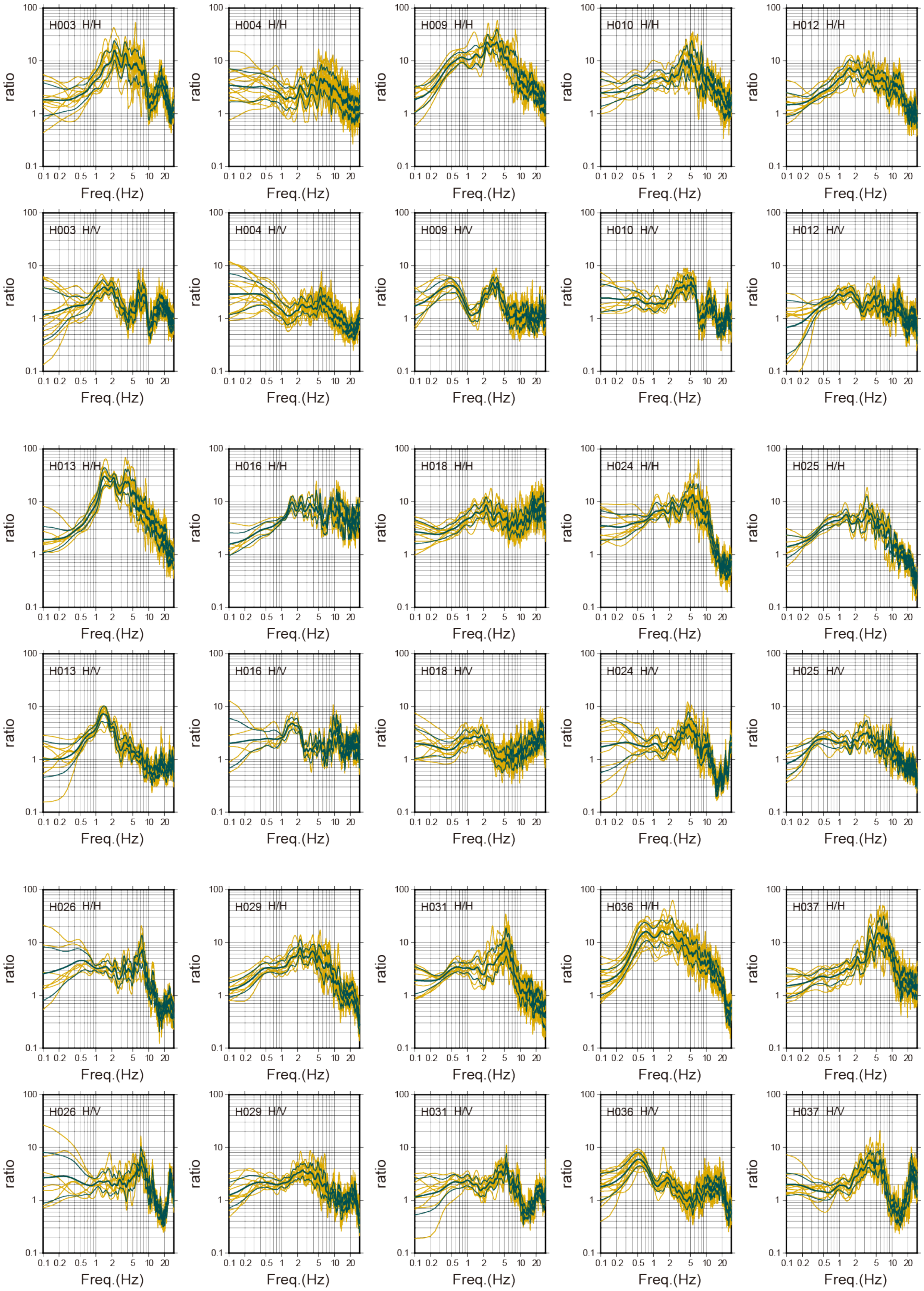

Fig. 2 – H/H spectral ratios and H/V spectral ratios at each station. Yellow lines represent H/H or H/V spectral ratios for each events and green lines mean the average and +/-1 standard deviation for all events.

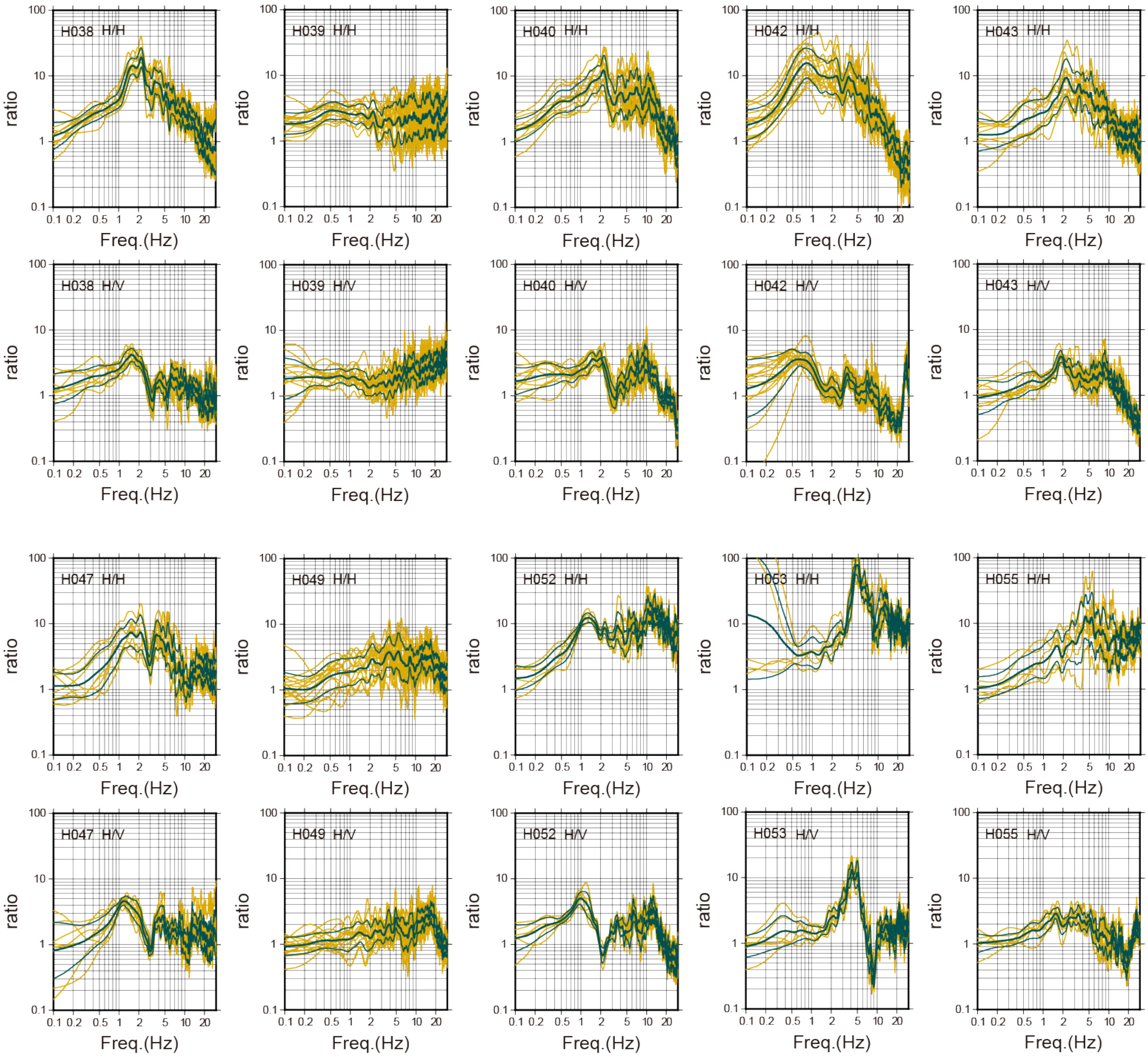

Fig. 2 – (Continued)

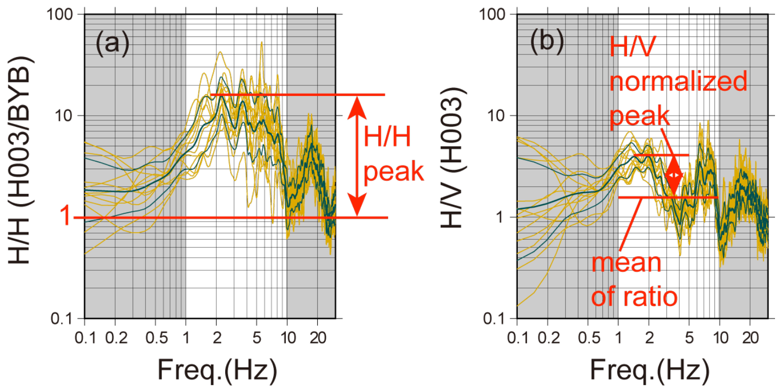

Fig. 3 – Conceptual figures of (a) peak of H/H spectral ratio (1-10 Hz) and (b) the normalized peak amplitude of H/V spectral ratio (1-10 Hz).

3. Results

3.1 Relationship between H/H spectral ratios and H/V spectral ratios

Relationship between the peak amplitudes for H/H spectral ratios and the normalized peak amplitudes for H/V spectral ratios are shown in Fig. 4(a). As a whole, stations with high H/H peak tend to show high H/H normalized peak. Fig. 4(b) also shows the relationship the frequencies of H/H peaks and the ones of H/V peaks. Frequencies of these two peaks are highly correspond to each other, though some stations which have small amplification or multiple peaks show different values. It means that the normalized peak of H/V spectral ratios also can represent the soil amplifications, especially for the resonant frequency. On the other hand, we should note that the normalized amplitudes for H/V spectral ratios at some stations became lower, because of the amplifications of vertical motions.

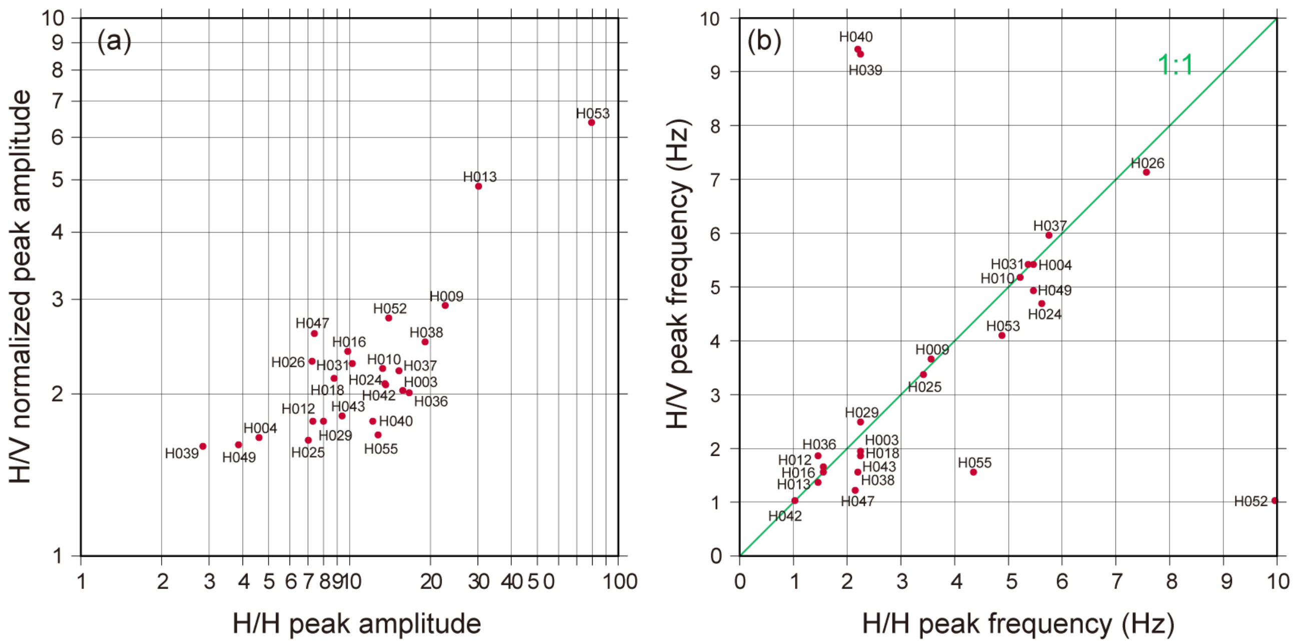

Fig. 4 – Relationship between peaks of H/H spectral ratios and peaks of H/V spectral ratios (1-10 Hz)

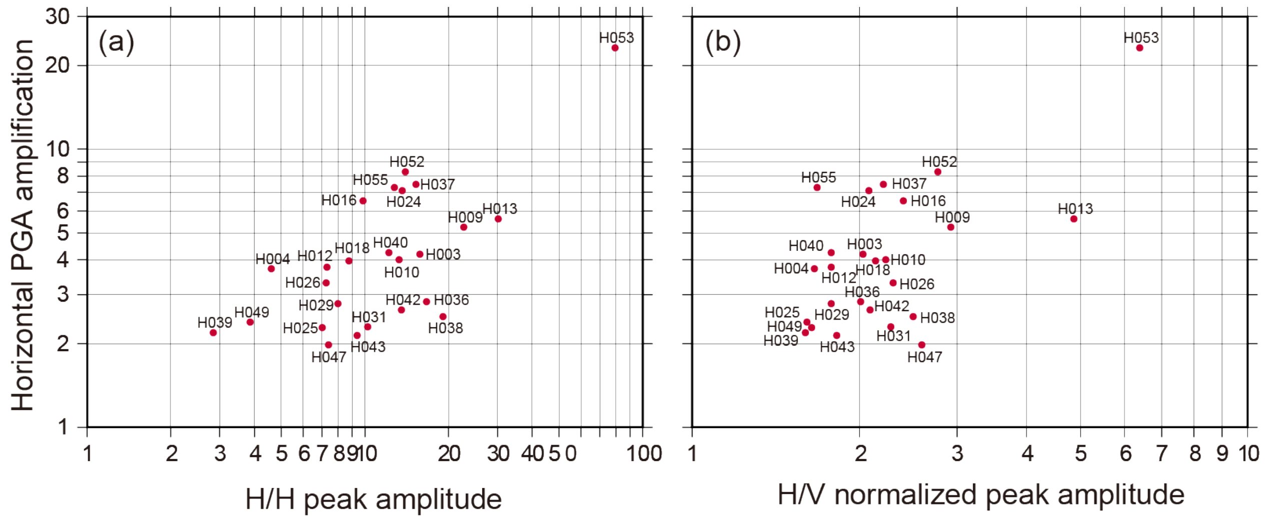

Fig. 5 – Relationships among peaks of H/H spectral ratios, normalized peaks of H/V spectral ratios, and horizontal PGA amplifications

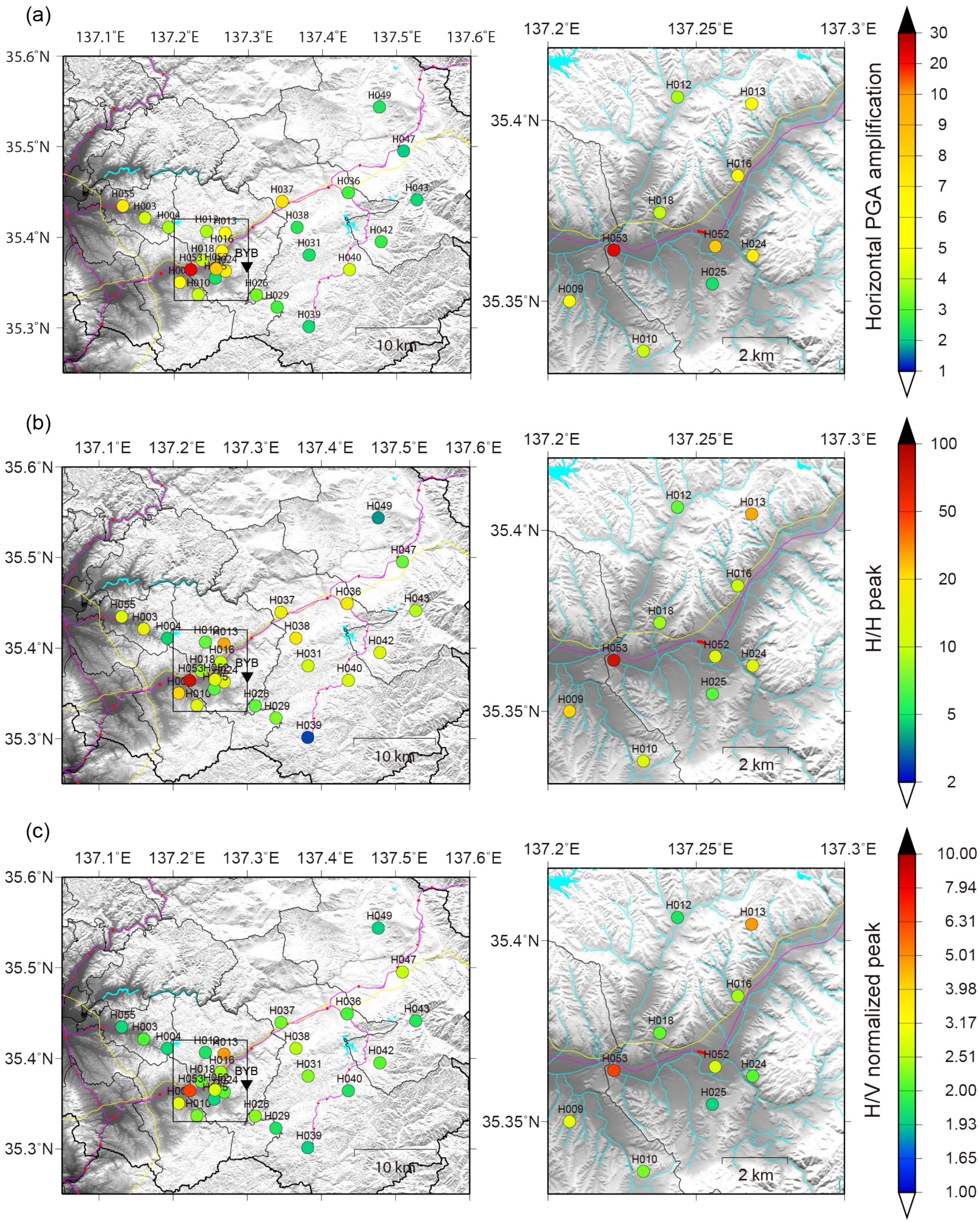

Fig. 6 – Distributions of (a) horizontal PGA amplifications, (b) peaks of H/H spectral ratios and (c) the normalized peak amplitudes of H/V spectral ratios. Squares in left panels mean the region of right panel.

3.2 Relationship between peaks of H/H and H/V spectral ratios and horizontal PGA amplifications

Relationship between peak amplitudes for H/H spectral ratios and the horizontal PGA amplifications is shown in Fig. 5(a). Stations with higher peaks of H/H spectral ratios tend to show the high PGA amplifications, but it is not clear. We can consider that the incident angles at some surface stations could be different from the one at BYB borehole station. We also found that the frequency of dominant period generating maximum amplitudes of time series at some stations was quite different from the one at BYB. This difference would make unclear the relationship between the amplifications of maximum amplitudes (PGA) and soil amplification characteristics (H/H spectral ratios). The normalized peaks of H/V spectral ratios are also related to the PGA amplifications (Fig. 5(b)). This relationship would also show the sensitivities of the vertical motion amplifications at each station.

3.3 Station location and soil amplification

Fig. 6(a) shows the distribution of the horizontal PGA amplifications. Many of stations with higher amplification located at lower lands, valleys or basins. However, there are some exceptions (ex. H037). Stations with small amplification located at lower lands are also exist. This shows that the soil amplification is controlled by the quite local site condition. Fig. 6(b) shows the distribution of peaks of H/H spectral ratios. Some stations at mountain region (around H038) show the higher peak amplitude. It might be attributed to the local amplification due to deeper structure out of BYB. Distribution of the normalized peaks of H/V spectral ratios (Fig. 6(c)) also corresponds to (a) and (b), but some stations show considerably lower values (ex. H055, H037). It would be due to the influence of vertical amplification.

4. Discussion

In this research, we checked the usability of the H/V spectral ratios to estimate soil amplification. The frequencies of peaks of H/V spectral ratios correspond well to the resonance frequencies of surface soil. The normalized peaks of H/V spectral ratios were also related to the soil amplifications, but we should consider the effects of the vertical amplifications. Soil amplifications for vertical motion in S-wave portion could appear on the amplitude spectrum for UD component similar to the horizontal motions. When we use H/V spectral ratios to estimate soil amplification, we should check the raw amplitude spectrum of three components.

In general, H/H spectral ratios represent the soil amplification characteristics for horizontal motions. It can be considered that horizontal PGA amplifications during earthquake would be related strongly to peaks of H/H spectral ratios, if the dominant periods of ground motion corresponded to the H/H peaks. But we obtained poor relationship among them in this research. As one of the causes, we speculate that the region (~20 km x ~30 km) was too wide to use only one reference site, BYB. In addition to this, the target field which consists of mountain regions and many valleys can make soil structure at each station highly complicated and would be independent to each other. The better relationships might be derived in case that all surface stations were located in a basin with a reference borehole station.

5. Conclusions

We investigated the relationship among surface-to-borehole spectral ratios for horizontal components (H/H spectral ratio), horizontal to vertical (H/V) spectral ratios, and soil amplifications for horizontal motion for S-wave portion during earthquakes, using 25 surface stations and a borehole reference station. Frequency of peaks of H/H spectral ratios and that of H/V spectral ratios corresponded well to each other. Peak amplitudes of H/H spectral ratios and the normalized peaks of H/V spectral ratios were also related, but some of peaks of H/V spectral ratios were influenced considerably by amplifications of vertical motion. Soil amplifications for horizontal motion were also related to both peaks of H/H spectral ratios and the normalized peaks of H/V spectral ratios but not so well. There is a possibility that the incident waves to surface sites can differ from the one to the reference borehole station. In future, we would like to clarify the causes of fluctuations of relationships we derived above in detail, and to develop the method utilizing H/V spectral ratios to estimate soil amplification.

6. Acknowledgements

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7. References

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