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APPLICATION OF THE H/V SPECTRAL RATIOS FOR EARTHQUAKE GROUND MOTIONS AND MICROTREMORS AT K-NET SITES IN TOHOKU REGION, JAPAN TO DELINEATE SOIL NONLINEARITY DURING THE 2011 OFF THE PACIFIC COAST OF TOHOKU EARTHQUAKE

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ABSTRACT: To understand the reason why observed accelerations in Miyagi Pref. during the main shock were so high, we deployed several aftershock observation stations near two K-NET sites. We determined detailed velocity structures based on the H/V spectral ratios of aftershock records. Then we compared H/V spectral ratios of strong motions during the main shock with those averaged weak motions to see soil nonlinearity effects. We found strong peak frequency shift during the main shock in comparison to weak motions, which suggests shear rigidity reduction of approximately 25 %.

Key Words: The 2011 Off the Pacific Coast of Tohoku Earthquake, H/V spectral ratio, strong motion, microtremor, grid-search, velocity structure, nonlinearlity

INTRODUCTION

During the 2011 Off the Pacific Coast of Tohoku earthquake which occurred on March 11, 2011, the maximum acceleration of the NS component reached 2,700 cm/s^2 and JMA seismic intensity 7 was recorded at K-NET Tsukidate (MYG004) station of the K-NET strong motion network (for the network description see Kinoshita, 1998). However, damages near the observation site were rather small. The authors, therefore, observed aftershocks around MYG004 in order to identify factors for generating high acceleration and investigate the relationship between high acceleration and damages in the vicinity. Also, prior to the aftershock observation, we measured microtremors to focus on the effect of cliff topography near MYG004. The H/V spectral ratios (HVRs) of these data were compared to identify the ground motion characteristics of the area, and the HVRs of ground motion records were used to identify the soil structure directly below MYG004. Also, we deployed temporary aftershock observation sites at Furukawa in Ohsaki City, which is near the damaged area in Furukawa, Miyagi Prefecture. Based on the HVRs of the ground motion recordings, the ground motion characteristics at Furukawa were investigated and compared with those in Tsukidate.

TEMPORARY AFTERSHOCK OBSERVATION AT TSUKIDATE

On April 29 and 30, 2011, four survey sites were established around MYG004. One site was set at the center and other three sites were set on the circumference of a circle with a diameter of approximately 400 m around MYG004. Figure 1 shows the locations of MYG004 and temporary aftershock observation sites (TKDZ01-TKDZ04). At these sites, data have been continuously recorded using SMAR-6A3P (Mitutoyo Corporation) which data logger was replaced by LS8800 (Hakusan Corporation). These sites were set under eaves of residential properties with AC power. GPS was used for time correction and data sampling had been performed at 100 Hz.

Fig. 1 Locations of the observation sites in Tsukidate

INFLUENCE OF THE CLIFF TOPOGRAPHY

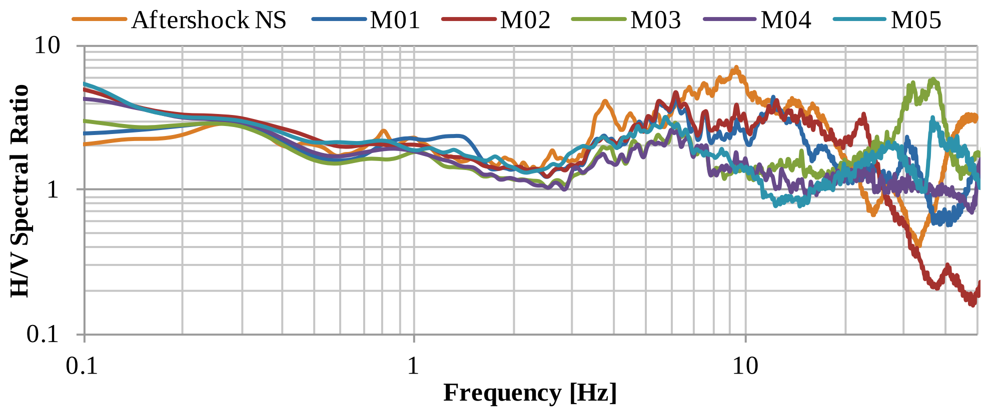
Microtremor observation

Before the establishment of the temporary aftershock survey sites, in order to determine the effects of the cliff topography near MYG004, microtremor array observation was performed at five sites: two sites were set on top of the cliff and three sites were set at the base of the cliff. Figure 2 shows the array arrangement. M01 and M02 were set on top of the cliff with M02 located right in front of MYG004, and M01 was set approximately 10 m south of M02. M03, M04 and M05 were set at the base of the cliff with M03 located immediately beneath the cliff and M4 and M05 located 10 m and 30 m apart from M03, respectively. Microtremors were recorded for 30 minutes.

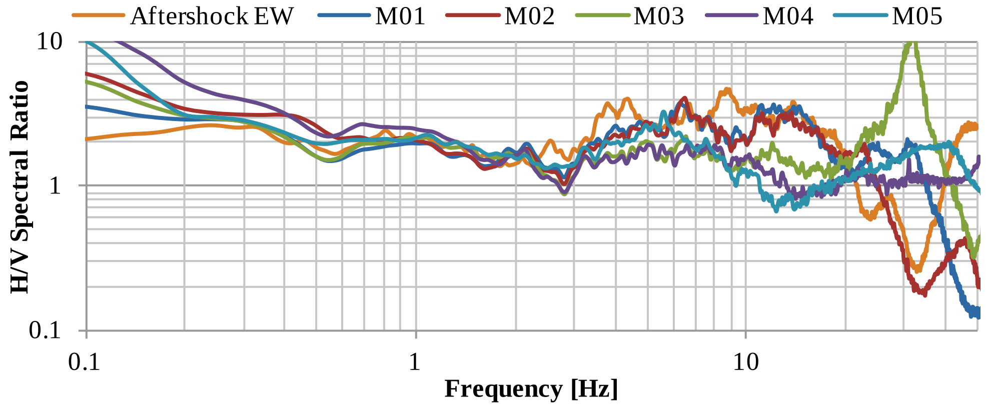
Fig. 2 Schematic figure of microtremor array arrangement across the cliff

Microtremor HVRs

A time window of 40.96 seconds was extracted (50% overlapped), and HVRs were computed for the NS and EW components from average Fourier spectra, separately. Figure 3 shows the HVRs for NS/UD and EW/UD respectively. While the HVRs were similar among the sites up to 7 Hz, at frequencies higher than 7 Hz, the HVRs for the cliff-top sites (M01 & M02) were two to three times as high as the HVRs for the cliff-base sites. This is believed to be the effect of the cliff topography.



(a) NS/UD



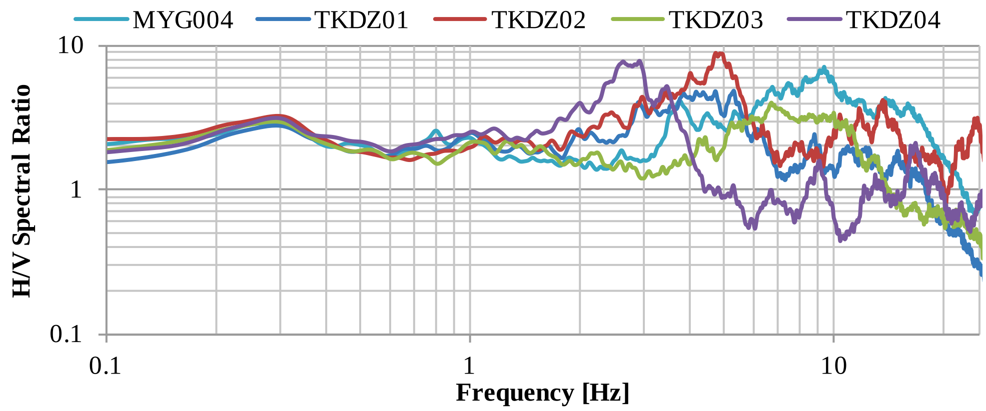
(b) EW/UD

Fig. 3 Microtremor HVRs with aftershock HVR for MYG004

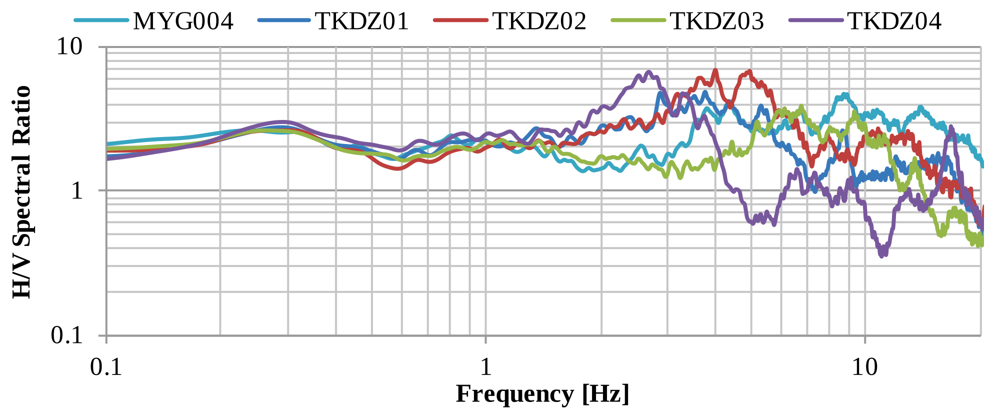
AFTERSHOCK DATA AT TSUKIDATE

Comparison of weak motion HVRs at temporary observation sites

From the aftershock data recorded between April 30 and September 20, 2011 at four temporary observation sites shown in Figure 1, a time window of 81.92 seconds from the onset of the S wave was extracted and the average Fourier spectrum of each component was computed to determine the HVRs, that is, NS/UD and EW/UD, for the 77 earthquakes recorded at MYG004. Figure 4 shows the aftershock HVRs for NS/UD and EW/UD as well as those for MYG004 respectively. The aftershock HVRs has peaks at around 0.3 and 1.0 Hz at all five survey sites including MYG004, which is believed to be the effect of the deep soil structure. On the other hand, at frequencies higher than 1.5 Hz, HVRs are significantly different among the observation sites, except for TKDZ01 and TKDZ02. The NS component at MYG004, in particular for 7-10 Hz, showed higher HVRs than those at other observation sites. This is consistent with the results discussed in the previous section, where the effects of the cliff topography were apparent at frequencies higher than 7 Hz. Note that at TKDZ04 where there were some damages occurred to buildings, a peak can be seen at around 2.5 Hz, indicating the relationship between dominant frequency and damages.



(a) NS/UD

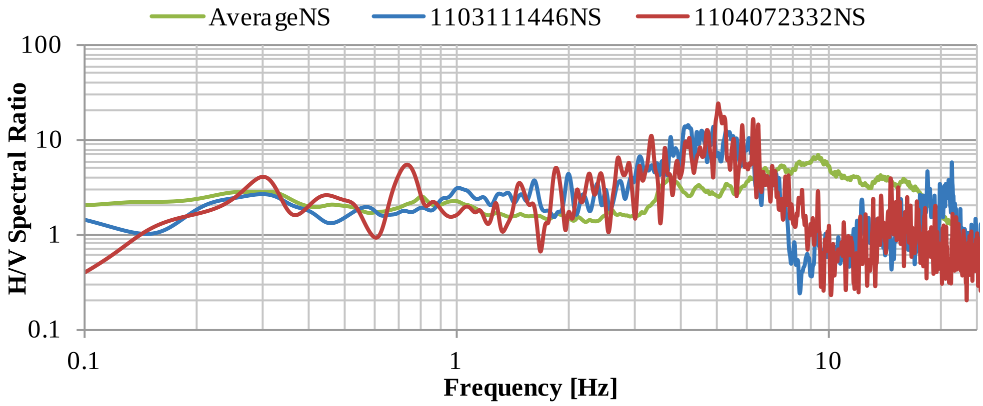


(b) EW/UD

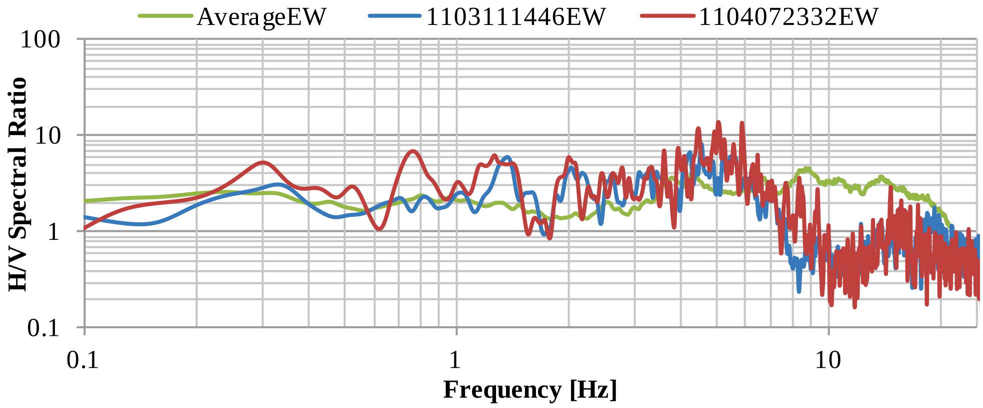
Fig. 4 Aftershock HVRs in Tsukidate

Comparison between the main shock, the April 7 strongest aftershock and average of other aftershocks at MYG004

Next, we compare the strong motion HVRs of the main shock, and the largest aftershock that occurred at 23:32 on April 7 (M7.1) with weak motion HVRs of average of other aftershocks. Figure 5 compares NS/UD and EW/UD of these HVRs. With regard to the maximum acceleration (PGA), the NS and EW components for the main shock were 2,700 cm/s^2 and 1,268 cm/s^2, respectively, and those for the April 7 aftershock were 1,242 cm/s^2 and 886 cm/s^2, respectively, showing large differences between the two events (1.5~2 times), but the HVRs were similar between them. Compared with the weak motion HVRs, the peaks of the strong motion HVRs were shifted to lower frequencies, indicating the effect of nonlinearity. The peak frequency was shifted from 9 Hz to 4~5Hz for strong motion HVRs in comparison to weak motions HVRs, and shear rigidity may have dropped to approximately 25 % of the linear values during the strong shaking.



(a) NS/UD



(b) EW/UD

Fig. 5 HVRs of main shock, largest aftershock and average of other aftershocks at MYG004

IDENTIFICATION OF THE SOIL STRUCTURE AT MYG004

Lastly, identification of the soil structure immediately below MYG004 was attempted based on the HVRs of weak motion data recorded at the site. First, for the 55 waves observed between March 9 and May 17, 2011, average HVRs of the EW components which are believed to be less influenced by the cliff topography was used as the target to identify the soil structure at MYG004, by making the residual sum of squares smallest with theoretical HVRs. For the initial model, the data published by the National Research Institute for Earth Science and Disaster Prevention (NIED, 2011) were used for shallow soil layers and the results of previous study (Kawase and Matsuo, 2004) were used for deep soil layers. Layers 2 and 3 of the eight-layered model of Kawase and Matsuo (2004) had similar PS logging results and densities, so they are treated as one layer to make a seven-layered model (the Initial Model in Table 1). The theoretical HVRs were calculated based on the concept of Kawase *et al*. (2011), and were identified by changing the thickness of layers 1 to 6. As a result, the velocity structure that explains the observed HVRs well was identified as shown in Figure 6. The velocity structure model is shown in Table 1 and Figure 7. Comparing the identified model with the initial model, layers near the surface got thinner and layers 5 and 6 got thicker, creating peaks at 0.3 and 1.0 Hz, and hence quite nicely reproducing the observed HVR as shown in Figure 6.

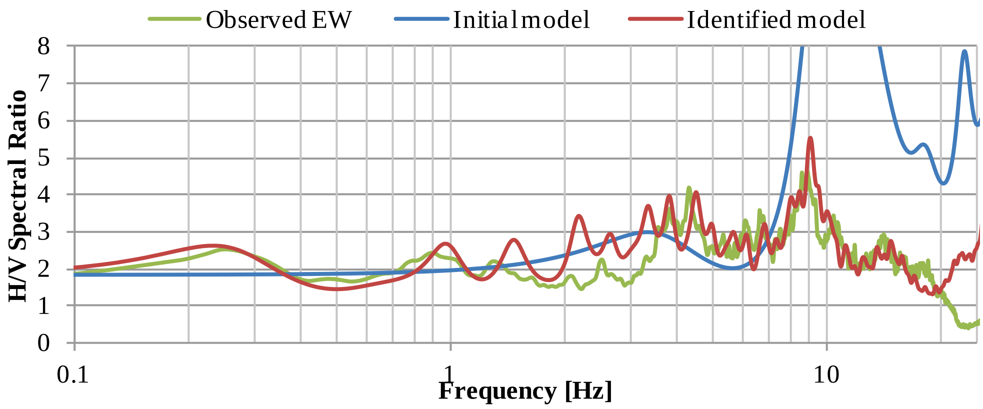
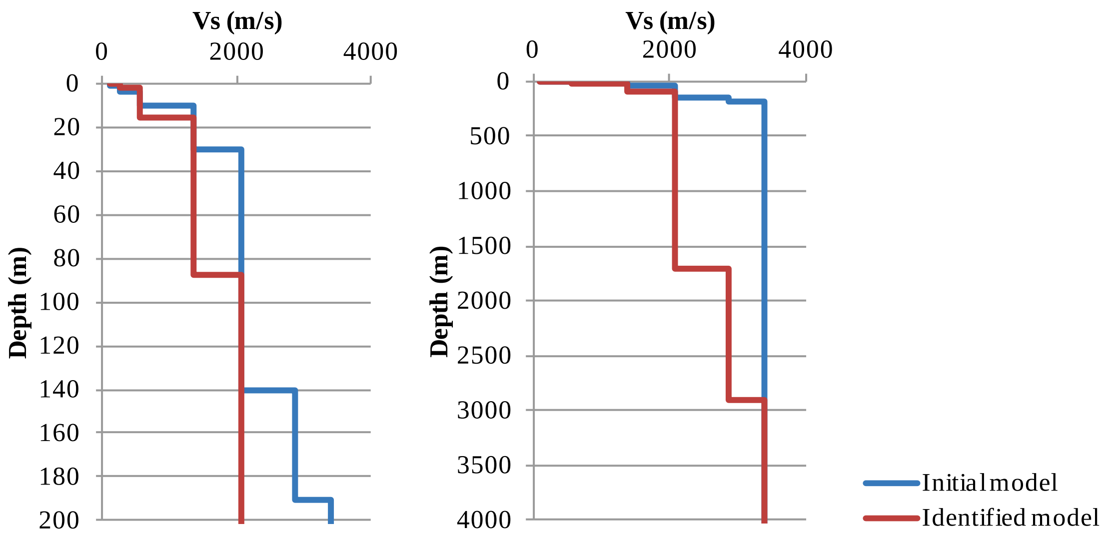


Fig. 6 Comparison of HVRs for observed EW/UD, initial model and identified model

Table 1 Velocity structure of the initial and identified model

No	Initial Model Vs (m/s)	Initial Model Thickness (m)	Initial Model Depth (m)	Identified Model Thickness (m)	Identified Model Depth (m)
1	100	1	1	0.4	0.4
2	240	3	4	1.12	1.52
3	550	6.25	10.25	14.25	15.77
4	1364.29	20	30.25	71.4	87.17
5	2075.17	110	140.25	1624.7	1711.67
6	2874.27	50	190.25	1200	2911.67
7	3400	-	-	-	-



(a) Shallow part (b) Deep part

Fig. 7 Shallow and deep part of the velocity structure

TEMPORARY AFTERSHOCK SURVEY AT FURUKAWA

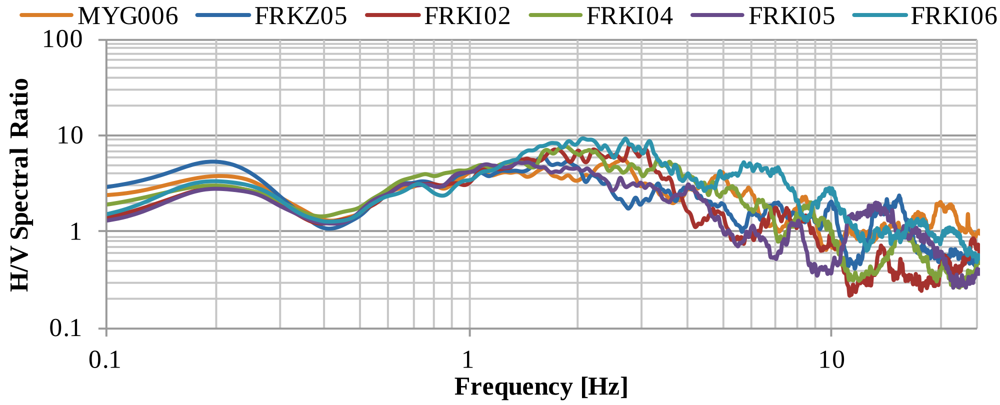
On June 6 and 7, 2011, five observations sites were deployed around K-NET Furukawa (MYG006) station; two sites were set at the center and three sites were set on the circumference of the circle with a diameter of approximately 800 m close to MYG006. Figure 8 shows the locations of the temporary aftershock observation sites (FRKZ05, FRKI02, FRKI04, FRKI05 and FRKI06) and MYG006. At these temporary observation sites, data had been continuously recorded using SMAR-6A3P which data logger was replaced by LS8800 at FKRZ05 and ITK seismometer with K-NET95 accelerometer (a-Lab) at the other four stations. GPS was used for time correction and data sampling had been performed at 100 Hz.

Fig. 8 Locations of the observation sites in Furukawa

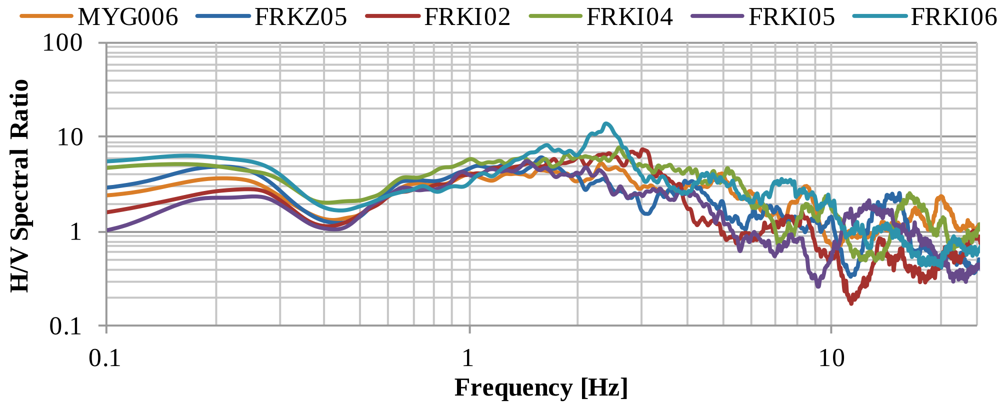
AFTERSHOCK RECORDS AT FURUKAWA

Comparison of weak motion HVRs

Among the 63 aftershocks triggered at MYG006 between June 6 and September 21, 2011, the observed data at the temporary aftershock observation sites shown in Fig. 8 were used. A time window of 81.92 seconds from the onset of the S wave was extracted and average Fourier spectra were computed for the NS and EW components to determine the HVRs of NS/UD and EW/UD. Figure 9 shows the aftershock HVRs at our temporary observation sites for NS/UD and EW/UD, respectively, as well as those for MYG006. As for the aftershock HVRs, a peak was observed at around 0.2 Hz at all six observation sites including MYG006, and all of the sites recorded similar HVRs in the frequencies below 1.5 Hz. Only FRKI06 showed higher HVRs in the ranges 2-3 Hz and 5-8 Hz. This may be because, 1) the observation site is located at the warehouse of an occupational training center with a workshop containing processing machines in the north, 2) there is a gutter at the site with water constantly flowing, 3) the highway located near the site (to the west) ascends toward the south to cross over the railroad tracks, creating topographic effects.



(a) NS/UD

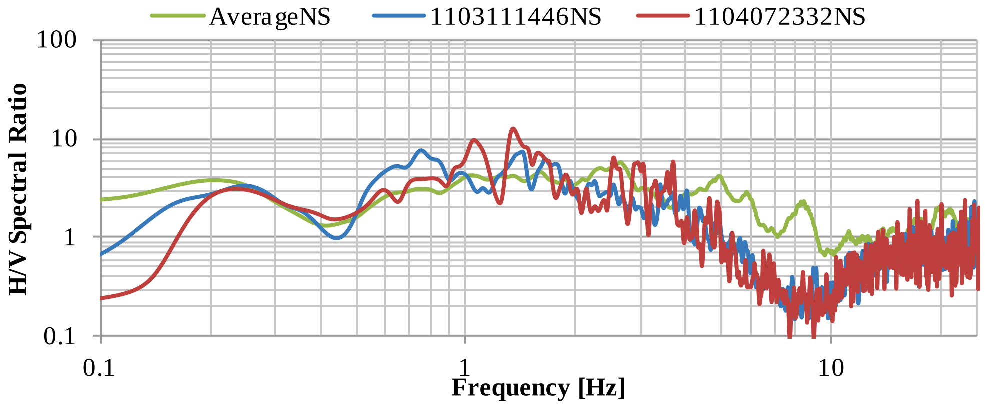


(b) EW/UD

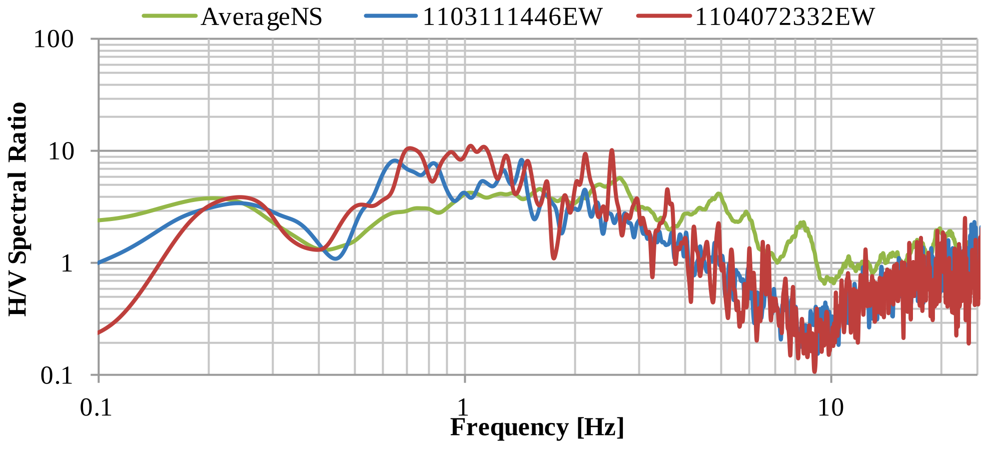
Fig. 9 Aftershock HVRs in Furukawa

Comparison between the main shock, the April 7 strongest aftershock and other aftershocks at MYG006

Finally, the strong motion HVRs for the main shock and the aftershock that occurred at 23:32 on April 7 (M7.1) and weak motion HVRs of average of other aftershocks were compared. Figure 10 shows the comparison of NS/UD and EW/UD, respectively. With regard to the maximum acceleration, the NS and EW components for the main shock were 444 cm/s^2 and 571 cm/s^2, respectively, and those for the April 7 aftershock were 415 cm/s^2 and 478 cm/s^2, respectively. While these components were nearly 10% higher in the main shock, the HVRs were almost the same between the two events and the effect of nonlinearity of the strong motion HVRs was also observed. During the strong motion, due to the effect of nonlinearity, the frequencies that are said to cause damages to buildings, 0.5-2 Hz, were greatly amplified and this is believed to be one of the causes for the building damages in Furukawa. If we focus our attention to the troughs around 8 to 10 Hz, we can see weak frequency shift from the average HVRs of small aftershocks to the two strong motion HVRs.



(a) NS/UD



(b) EW/UD

Fig. 10 HVRs of main shock, largest aftershock and average of other aftershocks at MYG006

SUMMARY AND CONCLUSIONS

With the aim of identifying the factors for generating high acceleration recorded at two K-NET sites in Miyagi Prefecture (MYG004 and MYG006) and investigating the relationship between high acceleration and building damages, aftershocks were observed at sites near K-NET Tsukidate (MYG004) and K-NET Furukawa (MYG006). Based on the observed H/V spectral ratios, ground motion characteristics due to the soil around the sites were determined. Small peaks were observed at 0.3 and 1.0 Hz for all sites near K-NET Tsukidate, which are believed to be the effect of deep soil layers. The HVRs varied among the survey sites at frequencies higher than 1.5 Hz and were, in particular, significantly different at MYG004 over the range of 7-10 Hz. This is consistent with the inline microtremor array measurement results which confirmed clear amplification at frequencies higher than 7 Hz only for the cliff-top points.

The sites near K-NET Furukawa all showed a peak at 0.2 Hz and recorded similar HVRs in the frequencies up to 1.5 Hz. The HVRs for the March 11 main shock and April 7 aftershock were compared with the average HVRs for small or moderate-sized earthquakes; both at K-NET Tsukidate and K-NET Furukawa, showed peak with lower frequency (longer period), and this is believed to be the effect of soil nonlinearity. Furthermore, the one-dimensional soil structure at K-NET Tsukidate was identified based on the concept of Kawase *et al*. (2011). By widening the layer with Vs=3,400 m/s to 2,900 m to reproduce peaks at 0.3 and 1.0 Hz, the structure that reproduces the observed records well was identified.

In the future, we will estimate incident seismic waves by removing the effects of the cliff topography and nonlinearity. Using them, ground motion characteristics of the main shock near K-NET Tsukidate will be estimated and the relationship between them and actual damages will be fully investigated.

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