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Investigation of Ground Motion Waveforms at a Dam Site of the 2011 Off the Pacific Coast of Tohoku Earthquake

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ABSTRACT:
The waveforms and frequency characteristics at K-NET stations associated with the 2011 off the Pacific coast of Tohoku Earthquake (main shock) and its aftershocks are discussed. The rupture process of the main shock was inferred to consist of three large slips. It is found that the phases of the first rupture and the second rupture have dominant frequency from 4 to 7 Hz, and the phase of the third rupture has lower dominant frequency lower than 1 Hz. It can be inferred that the three large slips had different dominant frequencies. The first rupture occurred off Miyagi had high dominant frequencies. Another massive rupture then occurred also had high dominant frequencies. The third rupture occurred off the coast of northern Ibaraki released low dominant frequency waves. The same analysis was applied to the waveforms of the main shock and its aftershocks at a dam site located in Fukushima prefecture. Aftershocks used in this analysis were selected in the conditions that their CMT solutions were similar to that of the main shock. The aftershocks occurred near the third rupture region had different dominant frequencies from the aftershocks occurred in northern area. This result shows the different rupture regions have different dominant frequencies.

Keywords: site effects, Green's function method, the 2011 off the Pacific coast of Tohoku Earthquake, aftershock, dam site

1. INTRODUCTION

At present, seismographs have been greatly improved and densely located throughout Japan. Furthermore, seismic data are now much more available to the public and institutions, especially on the Internet, with the help of authorities like K-NET (conducted by National Institute for Earth Science and Disaster Prevention: NIED). They have a huge database including data on strong motion, as well as pre- and aftershocks of main events.

After the second proposal of Japan Society of Civil Engineering (JSCE), following the Southern Hyogo prefecture earthquake in 1995, simulation of earthquake ground motions using the Green's function approach for a potential rupturing fault, has been included in one of the seismic resistant design codes (JSCE, 1996). Since the empirical Green's function method mainly depends on and uses small ground motion histories, small events can be used automatically taking into account the source, site and path effects. The advantage of using the empirical Green's function led many researchers and designers to investigate applicability and limitations of the approach. The analysis of waveforms associated with aftershocks helps the selection of Green's functions.

In this study, the waveforms and frequency characteristics observed at K-NET stations associated with the 2011 off the Pacific coast of Tohoku Earthquake, Japan (main shock, M_W 9.0, March 11, 2011) are discussed. The same analysis was applied to the waveforms of the main shock and its aftershocks at a dam site located in Fukushima prefecture. The different rupturing points are significant for the results of the seismic simulation using the empirical Green's function method.

2. RUPTURE PROCESS AND WAVEFORMS OF THE 2011 OFF THE PACIFIC COAST OF TOHOKU EARTHAUKE

Furumura *et al*., (2011) showed the rupture process of the main shock using acceleration record sections obtained by K-NET and KiK-net. According to the study, the first rupture occurred off Miyagi, and strong seismic waves were released all over Tohoku (the phase 1, marked by the red star in Fig. 1). After several tens of seconds, another massive rupture occurred and a strong seismic waves were released (the phase 2, marked by the blue star in Fig. 1). The third rupture occurred at the offshore near land of the northern Ibaraki, and strong seismic waves were radiated toward Ibaraki prefecture (the phase 3, marked by the green star in Fig. 1). The rupture property and the radiation characteristics of the third slip were different from those of the others.

Fig. 1 shows acceleration records of the main shock recorded at eight K-NET stations. This shows that the phase 1 and the phase 2 dominate at IWT009 (DAITOH) and MYG004 (TSUKIDATE) stations, which recorded maximum acceleration at the main shock. At FKS004 (IITATE) and FKS017 (SUKAGAWA) stations, the phase 1 and the phase 2 – 3 are overlapped. The phase 1 and 2 are attenuated and the phase 3 dominates completely at IBR007 (NAKAMINATO), IBR015 (IWAI), IBR018 (KASHIMA), and CHB024 (INAGE) stations.

Fig. 1 also shows Fourier acceleration spectra on the seismic basement. To eliminate the effects of the local sedimentary layers, the surface spectra were divided by the site amplification factors (Nozu and Nagao, 2005). Fourier spectra at IWT009 and MYG004 stations have the peak frequency near 6 Hz and they have similar form. FKS004 has the peak frequencies at 6 Hz and near 3 – 4 Hz. FKS017 has the peak frequencies at 0.4 Hz, 1 – 2 Hz and 5 Hz. IWT009 and MYG004 stations, which are located at a large distance from the third rupture point, have different frequency properties from FKS004 and FKS017 stations which are located within 100 km from the third rupture point. IBR007 has the peak frequencies at near 1 – 2 Hz, 3 Hz and 5 Hz. IBR015 has the peak frequencies at near 1 – 2 Hz, 3 – 4 Hz and 0.1 – 0.2 Hz. IBR018 which is located near Itako city whose liquefaction damage was serious has the peak frequencies at near 1 – 2 Hz, 4 Hz, 0.2 Hz and 0.5 Hz. High frequency component of these three stations have similar frequency properties, which are south from the third rupture point. These stations commonly have more low frequency component than northern stations. The phase 3 slips are inferred to contain more low frequency component than the phase 1 or 2. CHB024, which is located in Urayasu city and suffered intense liquefaction damage, has different property from the others; the spectrum form is on the downside.

Figures. 2 to 7 show the Fourier spectra of each phase. Acceleration records at FKS004 and FKS017 stations were not subjected to this analysis, since separating into the individual phases were difficult. The phase 1, 2 and 3 are represented by red solid lines, blue dashed lines and green solid lines, respectively. In the case that the phase 1 and 2 are overlapped and are difficult to divide, "phase 1 + phase 2" is represented by purple solid lines. Figs. 2 and 3 show that the peak frequency of the phase 1 appears near 5 – 7 Hz, and that of the phase 2 appears near 4 – 7 Hz. At the southern four stations (IBR007, IBR015, IBR018 and CHB024), the phase 1 and 2 are overlapped and they are difficult to divide. The phase 1 and 2 shows flat form since they attenuate (Figs. 4 to 7). Figs. 4 to 6 show that their phase 3 waves have similar form in high frequency and their peaks appear in 1 – 2 Hz and near 5 Hz. CHB024 shows that the phase 3 dominates completely in low frequency (Fig. 7). Therefore, predominant frequencies of the phase 3 are considered to be low frequency lower than 1 Hz, in addition to 1 – 2 Hz, and 5Hz.

It turns out that the phase 1 and 2 have dominant frequencies at 5 – 7 Hz and 4 – 7 Hz, respectively. The phase 3 has dominant frequencies at lower than 1 Hz, 1 – 2 Hz, and 5 Hz. The phase 1 and 2, which occurred off Miyagi, have comparatively high frequency, conversely the phase 3, which occurred at northern Ibaraki, has comparatively low frequency. It fits the result of damage investigation (Sugano, 2011). FKS017, which is located between the phase 1, 2 rupture points and the phase 3 rupture point, has frequency characteristics influenced by these three large slips.

3. OBSERVED WAVEFORMS AT THE DAM SITE

The target dam site is located in Fukushima prefecture, and the location is marked by a red circle in Fig. 1. This dam is a rock-fill dam. Seismographs are installed at the tops and the base of the dam. Seismic waveforms of horizontal upstream-downstream (orthogonal to the enclosing bund) component recorded at the base of the dam site were used in this study.

The aftershock records used in the analysis are selected by their CMT solutions. Fig. 8 shows the CMT analysis results of the main shock and its aftershocks. The mechanism of the main shock was a reverse dip-slip fault which has a pressure axis along the direction of east-southeast and west-northwest. The main shock occurred on the boundary of the Pacific plate and the continental plate. The selected aftershocks have similar mechanisms to that of the main shock. The main shock record is considered that the phase 3 dominates, since the dam site locates near FKS017 station.

Fig. 9 shows the distribution of the epicentres of the main shock and its aftershocks, and their Fourier spectra of the accelerations observed at the target dam site. The spectra of the aftershocks are plotted along the solid lines, and those of the main shock are plotted along the dashed lines. To compare the aftershock spectra with the main shock spectrum, the peak frequencies are aliened.

Fig. 9 shows that two aftershocks (*M* 7.4, 23:32 March 11 and *M* 5.8, 08:24 March 13), which occurred off Miyagi in the northern part of the source fault of the main shock, have similar forms to that of the main shock, their peaks appear around 1 Hz. Although the hypocenters of these aftershocks are located near the source points of the phase 1 or 2, the frequency properties of these records have different properties from the characteristics of the phase 1 and 2 mentioned in the

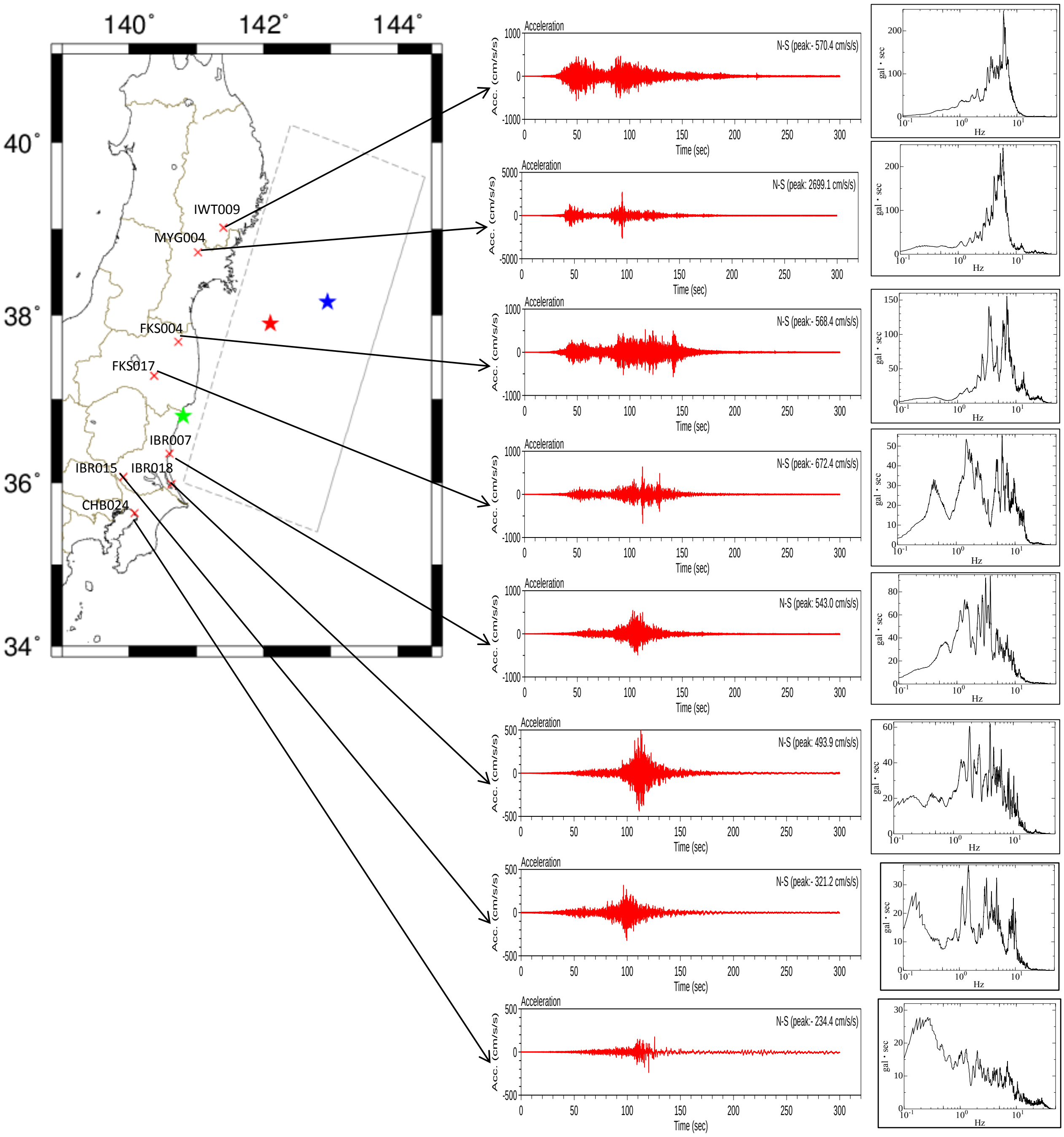

Figure 1. Acceleration waveforms and their Fourier spectra of the main shock recorded at eight K-NET stations. In the left map, locations of three large slip shown by Furumura et al., (2011) are indicated as stars. The phase 1, 2 and 3 are marked as a red star, blue star and green star, respectively. The target dam site is marked as a red circle.

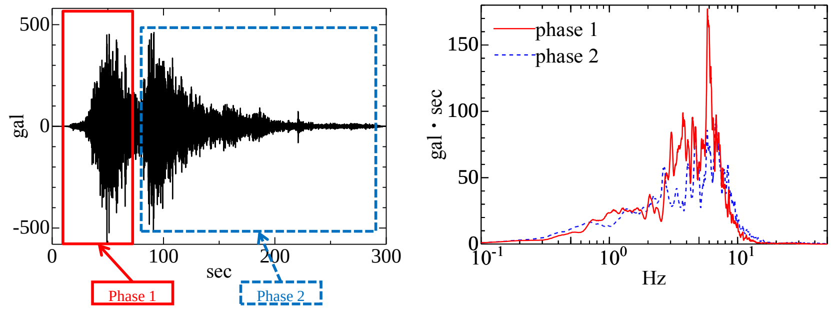

Figure 2. The acceleration waveform and Fourier spectra (NS component) at K-NET IWT009 (DAITOH) station. The spectra (right) were plotted with the divided phases (left).

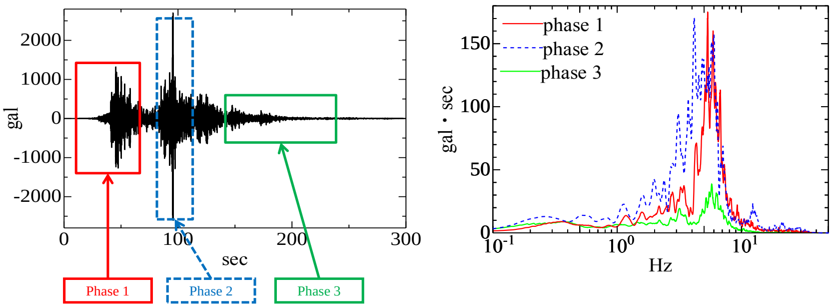

Figure 3. The acceleration waveform and Fourier spectra (NS component) at K-NET MYG004 (TSUKIDATE) station. The spectra (right) were plotted with the divided phases (left).

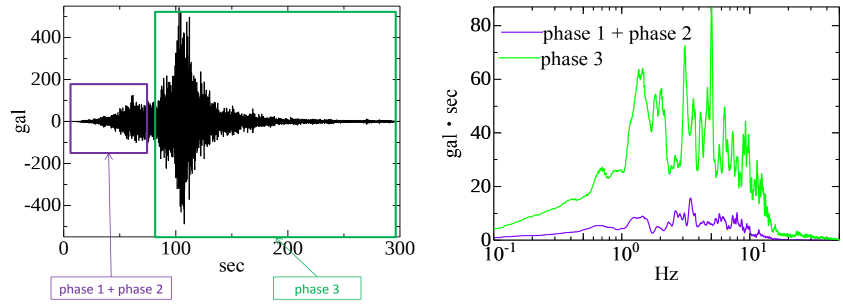

Figure 4. The acceleration waveform and Fourier spectra (NS component) at K-NET IBR007 (NAKAMINATO) station. The spectra (right) were plotted with the divided phases (left).

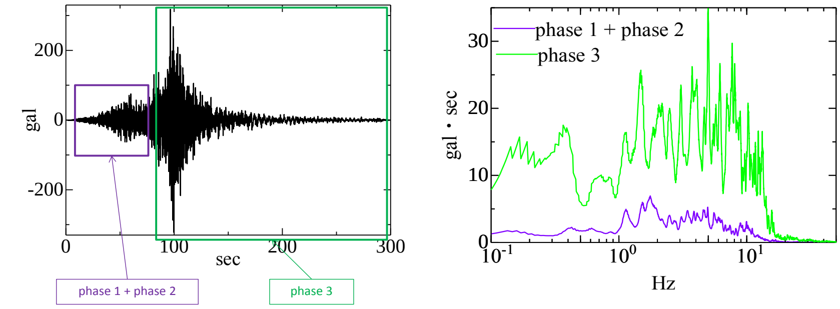

Figure 5. The acceleration waveform and Fourier spectra (NS component) at K-NET IBR015 (IWAI) station. The spectra (right) were plotted with the divided phases (left).

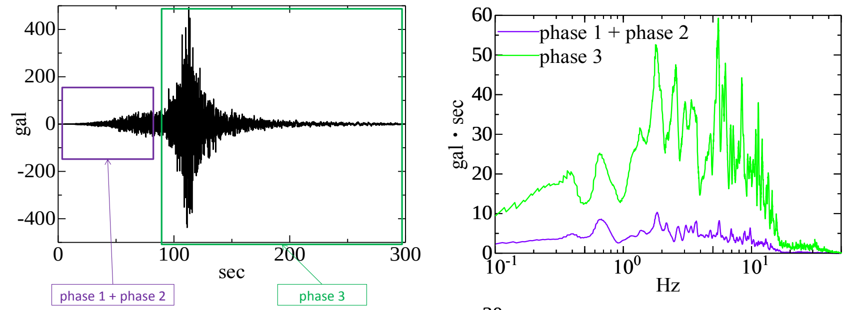

Figure 6. The acceleration waveform and Fourier spectra (NS component) at K-NET IBR018 (KASHIMA) station. The spectra (right) were plotted with the divided phases (left).

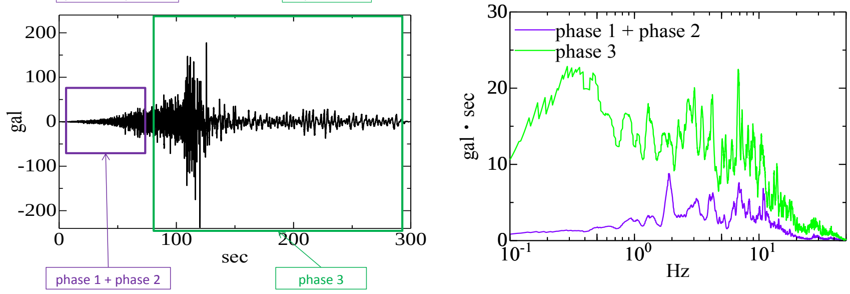

Figure 7. The acceleration waveform and Fourier spectra (NS component) at K-NET CHB024 (INAGE) station. The spectra (right) were plotted with the divided phases (left).

previous chapter.

Two aftershocks (*M* 5.6, 01:11 April 22 and *M* 5.6, 18:27 April 28), which occurred off Fukushima, have higher dominant frequencies over 1 Hz than the off Miyagi aftershocks. These aftershocks have dominant frequencies around 3 Hz and 5 Hz, as well as a clear dominant frequency at 1 Hz.

On the other hand, two aftershocks (*M* 7.8, 15:15 March 11 and *M* 6.5, 16:14 Mach 11), which occurred at off Ibaraki in the southern part of the source fault of the main shock, contain more low-frequency components around 0.5 Hz than the aftershocks occurred at other areas. This result coincides with the characteristics of the phase 3 discussed in the chapter 2.

Fourier spectra of the main shock and its all aftershocks commonly have a peak at near 1 Hz. This may indicate that this frequency is a characteristic frequency at the target site. The dominant frequencies changed from high-frequency to low-frequency as the hypocenters of aftershocks transfer from north to south, considering frequency characteristics other than 1 Hz.

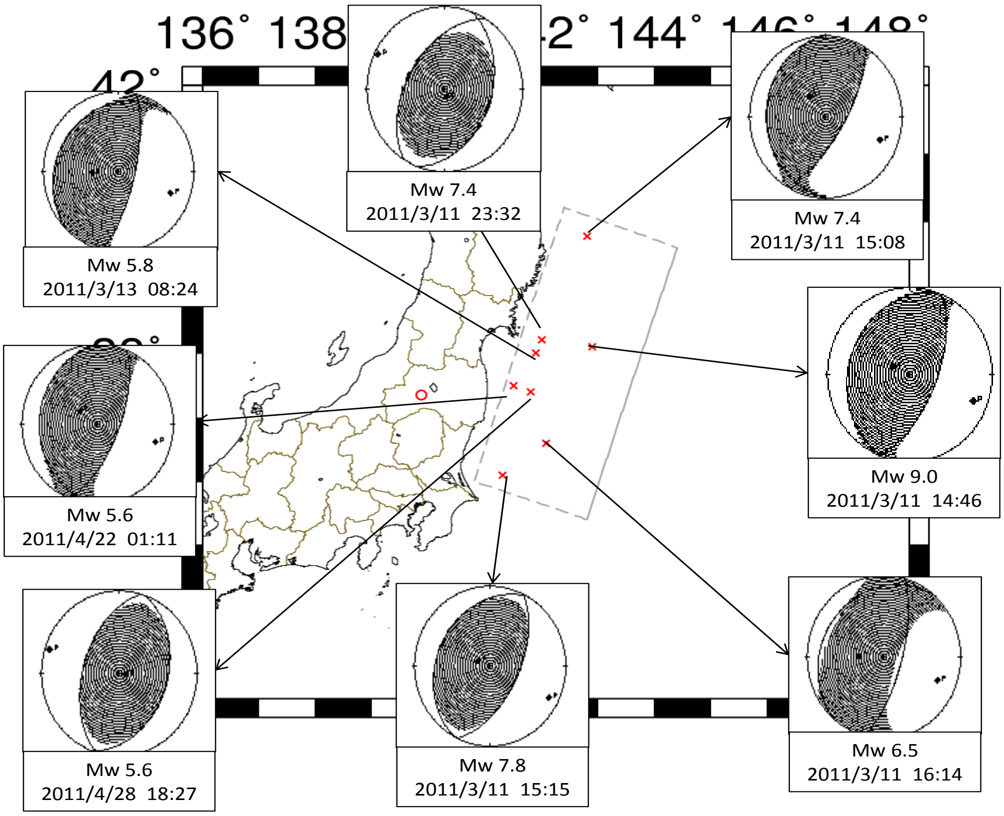

Figure 8. CMT solutions of the main shock and its aftershocks, whose waveforms were recorded at the target dam site. Red cross marks show the epicenters of the main shock and its aftershocks. The target dam site is marked as a red circle.

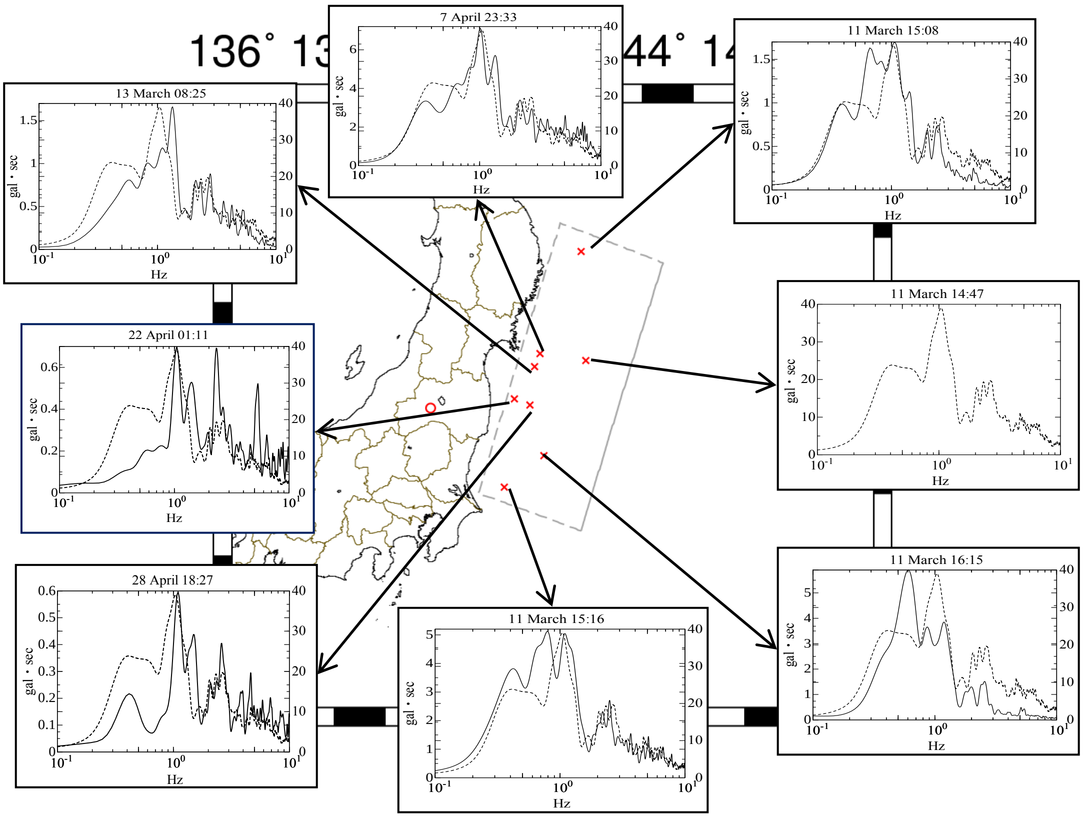

Figure 9. Fourier spectra of the main shock and its aftershocks at the target dam site. The spectra of the main shock are represented by dashed lines and those of aftershocks are represented by solid lines. In each graphs, left vertical axis shows the value of the aftershock's Fourier amplitude, right axis shows the value of the main shock's amplitude, conversely.

4. SUMMARY

The acceleration waveforms recorded at K-NET stations and the target dam site associated with the 2011 Off the Pacific coast of Tohoku Earthquake were analyzed and compared with the rupture process. The rupture process of the main shock inferred to consist of three large slips. The analysis of K-NET records revealed that the first rupture and the second rupture, which occurred off Miyagi, had higher dominant frequency from 4 to 7 Hz, and the third rupture, which occurred off the coast of northern Ibaraki, had lower dominant frequency lower than 1 Hz. This tendency was common to the frequency characteristics at the target dam site recorded at aftershocks of the main shock. The aftershocks occurred near the third rupture region had different dominant frequencies from the aftershocks occurred in the northern area. The dominant frequencies changed from high-frequency to low-frequency as the hypocenters of aftershocks transfer from north to south. This result shows the different rupture regions in the fault zone have different dominant frequencies.

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