Preliminary Analysis for Characteristics of Strong Ground Motion from Gigantic Earthquakes

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SUMMARY:
The 2011 off the Pacific coast of Tohoku earthquake (Mw9.0), which produced many strong motion records, provides an opportunity to examine the characteristics of strong ground motion from a gigantic earthquake. In this paper, the preliminary analysis of the ground motion attenuation, spectral shape and duration was performed using the selected strong motion records of the earthquake. The results were compared with those from the other gigantic earthquakes such as the 2003 Tokachi-oki (Mw8.3), the 2010 Chile (Mw8.8), the 2001 Peru (Mw8.4) and the 2007 Sumatra (Mw8.4) earthquakes. The attenuation and spectral characteristics of the records from the Mw9.0 earthquake are similar to those from the other gigantic earthquakes. The duration of the records from the Mw9.0 earthquake, however, is much longer than that from the other gigantic earthquakes.

Keywords: ground motion characteristics, gigantic earthquake, the 2011 Off the Pacific Coast of Tohoku earthquake

1. INTRODUCTION

The gigantic earthquake, the 2011 Off the Pacific Coast of Tohoku earthquake (hereafter the Tohoku earthquake), that hit northeastern Japan, registered Mw of 9.0, the largest ever recorded in Japan. To understand the characteristics of strong ground motion from such a gigantic earthquake is of great significance in preparing measures to reduce disaster from a similar event in the future. Because such gigantic earthquakes rarely occur, their strong motion records are only limited. Many of the records available in the United States are from earthquakes with a magnitude of 7.5 or lower and those in Japan are from earthquakes with a magnitude of around 8 or lower. Few examinations have been done for the characteristics of ground motion from an earthquake of a scale exceeding them.

Many strong motion records were obtained from the Tohoku earthquake. K-NET and KiK-net records by the National Research Institute for Earth Science and Disaster Prevention (NIED) were made available immediately after the earthquake (NIED, 2010). Records by the other institutions such as the Japan Meteorological Agency are also going to be released. These records will provide valuable information to reveal ground motion characteristics of gigantic earthquakes. At the same time, it will be necessary to confirm whether the characteristics seen in these records are common to all such gigantic earthquakes. This paper carries out a preliminary analysis of their attenuation and spectral characteristics as well as duration using the selected strong motion records released as of August 2011, and examines these characteristics in comparison with records from other gigantic earthquakes in Japan, Chile, Peru and Sumatra (Mw8.3 to 8.8).

2. STRONG MOTION RECORDS FROM THE 2011 OFF THE PACIFIC COAST OF JAPAN EARTHQUAKE AND THEIR CHARACTERISTICS

As shown in Fig. 1, the Tohoku earthquake have a very large source area, causing strong shaking in wide areas of northeastern Japan. Strong motion records were available at about 1,200 K-NET and KiK-net observation stations as a result. Figure 2 shows relations between the shortest distance from the fault plane and the peak ground acceleration (PGA) in order to examine attenuation characteristics of these records. The data were taken from the K-NET and KiK-net (on the surface ground). The shortest distance from the fault plane was calculated on the basis of the fault model as shown in Fig. 1 (Miyake et al., 2011). Although observed data were widely dispersed, the PGAs generally were 200 to 1,000 cm/s^2 for the distance of 50 kilometers, 100 to 500 cm/s^2 for 100 km, and 20 to 200 cm/s^2 for 200 km. Figure 2 also shows attenuation curves obtained from an existing attenuation relationship (Si and Midorikawa, 1999) for earthquakes with a magnitude of 8.0, 8.5 and 9.0, respectively. The inclination of attenuation of observed data is greater than the attenuation curves, but on the average, it appears to be smaller than the curve for M9.0 and come between curves for M8.0 and M8.5.

In order to examine the spectral characteristics, two each records were chosen for soft soil sites, stiff soil sites and rock sites in southern Iwate Prefecture and northern Miyagi Prefecture for preliminary analysis. The sites are in Ohsaki and Sendai in Miyagi (soft soil), Towa in Iwate and Toyosato in Miyagi (stiff soil) and Ohfunato and Kamaishi in Iwate (rock), all of which are located at much the same distance from the fault plane. Figure 3 shows the locations of these six sites. For classifications of soft soil, stiff soil and rock, standards by NEHRP (Building Seismic Safety Council, 1997) were used as reference: the average shear-wave velocity to a depth of 30 meters at 360m/s or less for soft soil; 360 to 760m/s for stiff soil; and 760m/s or greater for rock. At sites where the S-wave velocity was not available, microtremor measurements were also used as reference.

Figure 4 shows the velocity response spectra for the six sites. In this study, the two-dimensional horizontal velocity response spectra (h=0.05) are used for analysis. The spectra for rock sites (Ohfunato and Kamaishi) are rather flat between the periods of 0.1 and 10 seconds, with comparatively small amplitudes of 20 to 40 cm/s. At stiff soil sites (K-NET Towa and K-NET Toyosato), the spectra differ in shape from each other. They do not have especially sharp peaks and their amplitudes are between 50 and 100 cm/s. At soft soil sites (JMA Ohsaki and K-NET Sendai), on the other hand, the spectra have notable peaks, with the amplitudes at those peak periods reaching 300 to 400 cm/s. These results indicate that soil characteristics affect amplifications of seismic motion. The spectra of records from the Tohoku earthquake, which are rather flat at rock sites and which have peaks at soil sites, with spectral amplitudes becoming rather flat for long-period portions,

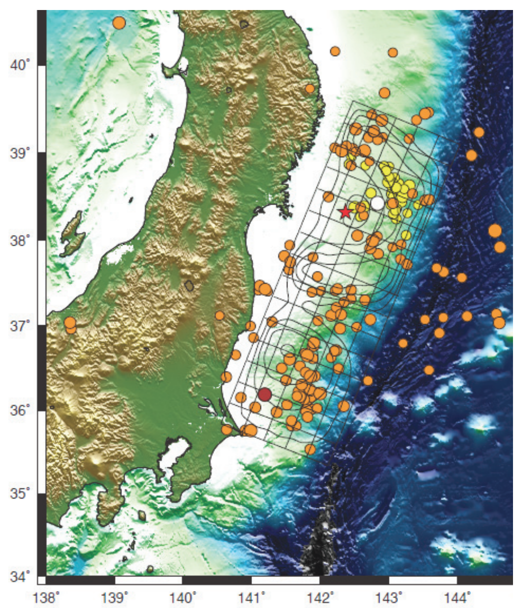

Fig. 1 Distribution of aftershocks of the 2011 Tohoku earthquake and its fault plane (after Miyake et al., 2011)

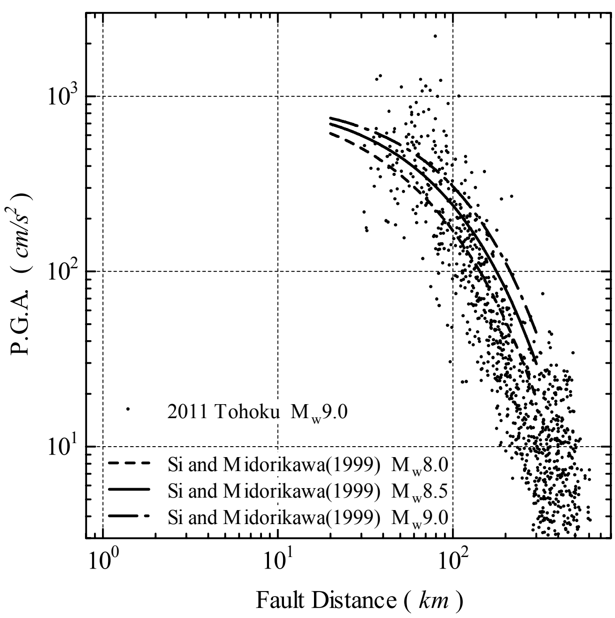

Fig. 2 Attenuation of peak ground acceleration observed in the 2011 Tohoku earthquake

are similar to those from magnitude 8-class earthquakes in the past. There were no peculiar characteristics observed in these records.

Figure 5 is for comparison of acceleration time histories at the six sites. Each record shows that large-amplitude ground motion continued for two minutes or more. The duration appears to be longer at soft soil sites than at rocks. The duration of strong ground motion, calculated as the time interval between 5 percent and 95 percent of the total power of acceleration (Trifunac and Brady, 1975), comes to approximately 120 seconds, 100 seconds and 70 seconds for soft soil, stiff soil and rock sites, respectively, as shown in Fig. 6. The duration is much longer than those in the past records.

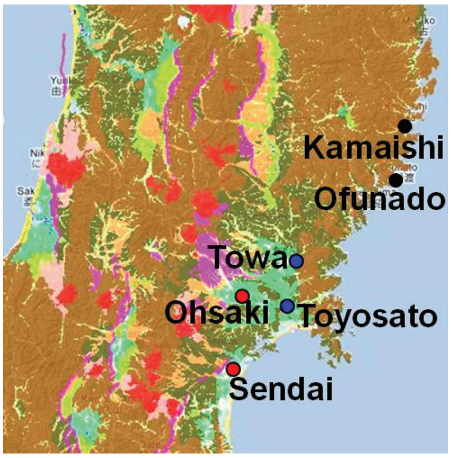

Fig. 3 Observation stations at soft soil sites, stiff soil sites and rock sites used in this study

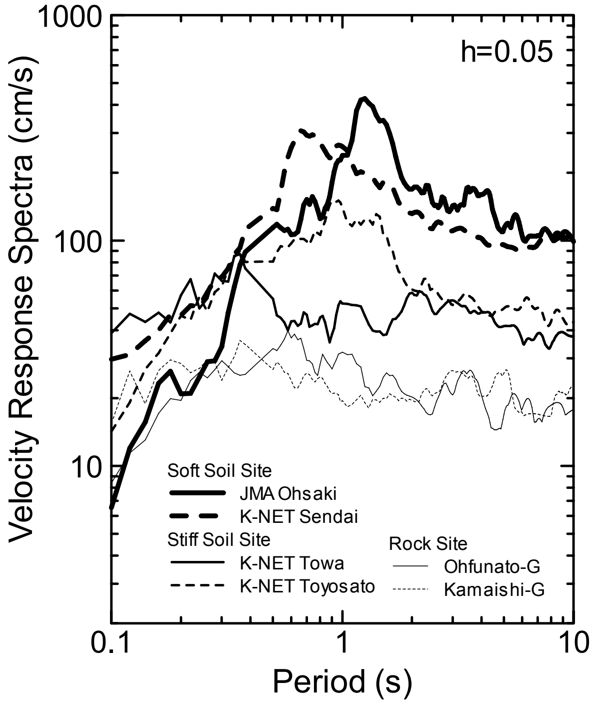

Fig. 4 Comparison of velocity response spectra observed at six sites

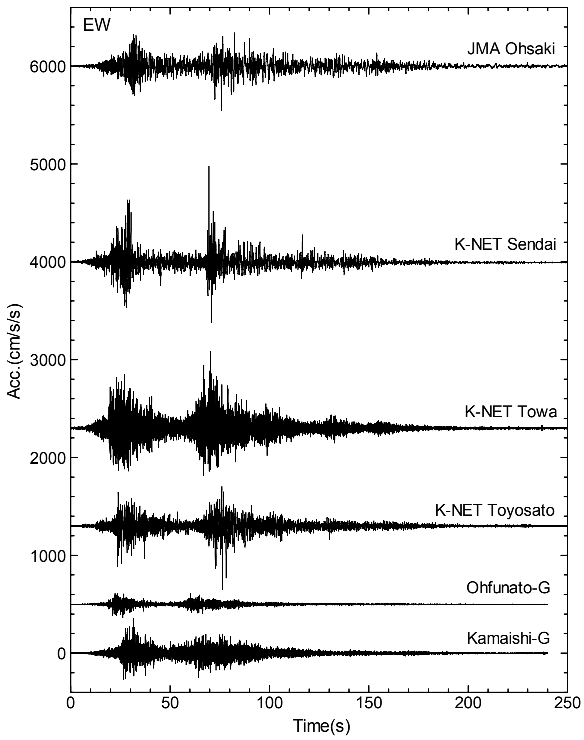

Fig. 5 Comparison of acceleration time histories at six sites

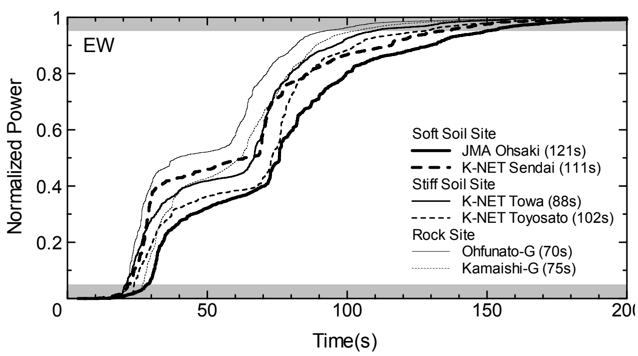

Fig. 6 Comparison of ground motion durations at six sites

3. COMPARISON WITH STRONG MOTION RECORDS FROM OTHER GIGANTIC EARTHQUAKES

Strong motion records obtained from the Tohoku earthquake is the first ever available from a magnitude-9 event, but there have been records from several gigantic earthquakes with a magnitude of greater than 8.0 in the world. In Japan, many records were obtained in the 2003 Tokachi-oki earthquake (Mw8.3). Outside Japan, the 2010 Chile earthquake (Mw8.8) produced a considerable number of strong motion records (Borochek et al., 2010). Records were also available, though limited in number, from the 2001 Peru earthquake (Mw8.4) and the 2007 Sumatra earthquake (Mw8.4) (Rodriguez-Marek et al., 2010; Aydan, 2007). This section examines ground motion characteristics common to the gigantic earthquakes by comparing these records with those from the Tohoku earthquake.

In Fig. 7, open triangles show correlations between peak ground accelerations and distances from the fault in records from the 2003 Tokachi-oki earthquake. Records from the Tohoku earthquake are shown with dots. As has been pointed out by Si et al. (2011), records of the Mw8.3 Tokachi-oki earthquake and of the Mw9.0 Tohoku earthquake almost overlap, indicating that attenuation characteristics of the two earthquakes are almost the same. They also are almost in agreement with an attenuation curve obtained from an existing attenuation relationship (Si and Midorikawa, 1999) for Mw8.3.

Open squares and open triangles in Fig. 8 show attenuation of the 2010 Chile earthquake (Mw8.8) and the 2001 Peru earthquake (Mw8.4), respectively. The 2007 Sumatra earthquake was omitted because there is only one strong motion record available. The Chile earthquake's records almost match those of the Tohoku records and the attenuation curve for Mw8.3. Records from the Peru earthquake show rather large accelerations, but considering the fact that the sites were located in the direction of rupture propagation, making amplitudes larger due to directivity effects, the records can also be interpreted as having attenuation characteristics similar to those of other gigantic earthquakes.

As have been seen so far, attenuation characteristics of the Tohoku earthquake generally match those of records from Mw8.3 to 8.8 earthquakes. They are also largely in line with the attenuation curve

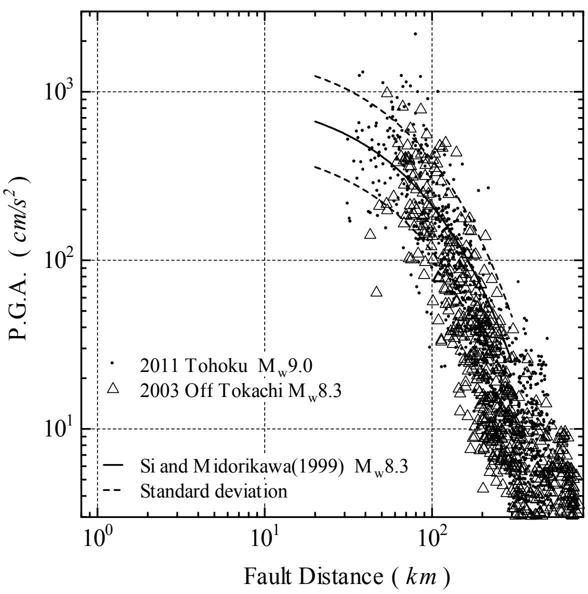

Fig. 7 Comparison of attenuations between the 2011 Tohoku earthquake (Mw9.0) and the 2003 Tokachi-oki earthquake (Mw8.3)

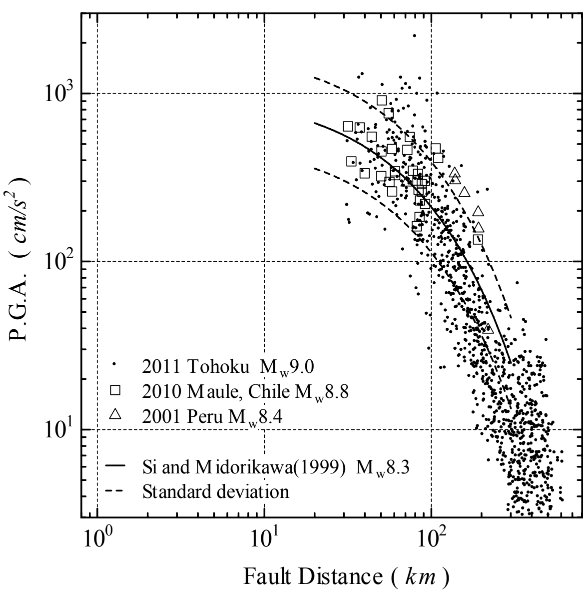

Fig. 8 Comparison of attenuations between the 2011 Tohoku earthquake (Mw9.0), the 2010 Chile earthquake (Mw8.8) and the 2001 Peru earthquake (Mw8.4)

for Mw8.3 obtained from an existing attenuation relationship. These indicate that attenuation curves begin to saturate when a moment magnitude surpasses 8, and that, when the magnitude comes to 8.3 or more, an increase in magnitude brings about very little change in attenuation. It has been expected from seismic source spectra of the ω^2 model that short-period ground motion intensity saturates when a magnitude becomes extremely large (Fukushima, 1996).

To examine spectral characteristics, the data from the 2003 Tokachi-oki eathquake (Mw8.3), from which many records were available, are used. As in the examination of data from the Tohoku earthquake shown in Fig. 4, two sites each were chosen for soft soil, stiff soil and rock, which were located rather close to, and at much the same distance from the fault plane. As shown in Fig. 9, the velocity response spectra are rather flat at the rock sites (K-NET Meguro and K-NET Honbetsu), with amplitudes mainly hovering between 20 and 60 cm/s. At the stiff soil sites (KiK-net Shiranuka and K-NET Ikeda), the spectra are also rather flat, mainly staying around 100 cm/s. At the soft soil sites (KiK-net Toyokoro and WISE Otsu), however, the spectra have conspicuous peaks that reached approximately 300 cm/s, but level off in long-period portions. These spectra thus show tendencies similar to those recorded in the Tohoku earthquake, as has been shown in Fig. 4.

A comparison has also been made with records from other major earthquakes at rock sites, where effects of local site characteristics are small, to find out differences in characteristics of seismic source spectra. Figure 10 is a comparison of records at rock sites from the 2003 Tokachi-oki earthquake, the 2010 Chile earthquake and the Tohoku earthquake. In the Chile earthquake, the velocity response spectrum at a rock site (Cerro El Roble) was generally rather flat, as in the records at rock sites from the other two earthquakes. The figure also includes velocity response spectra at rock sites from the 1985 Mexico earthquake (Ms8.1) and its aftershocks, shown with fine lines (Anderson and Quaas, 1988). These data show that when magnitudes are small, amplitudes become smaller as periods get longer. But the tendency becomes less notable as magnitudes become larger. The spectrum of the M8.1 main shock is rather flat, like the spectra from the other three gigantic earthquakes. These indicate that when an earthquake has a magnitude of 8 or larger, velocity response spectra at rock sites are rather flat at periods of about 10 seconds or shorter, meaning that characteristics of seismic source

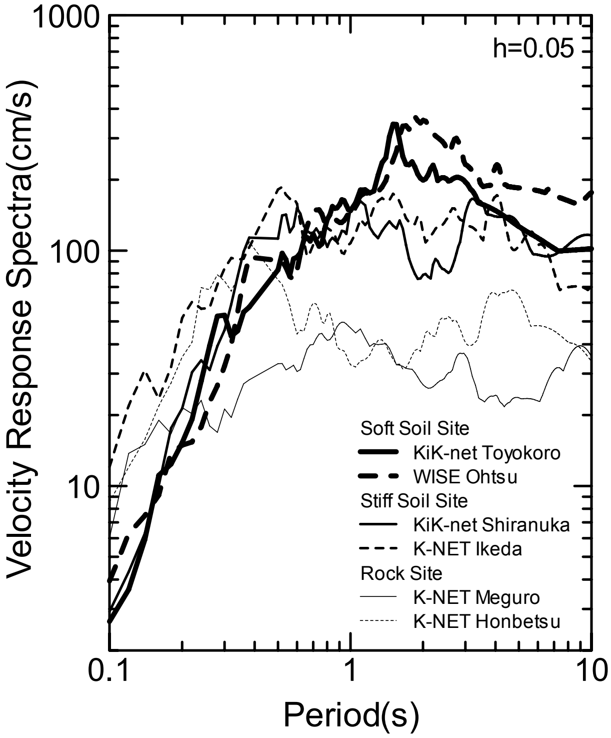

Fig. 9 Velocity response spectra observed in the 2003 Tokachi-oki earthquake

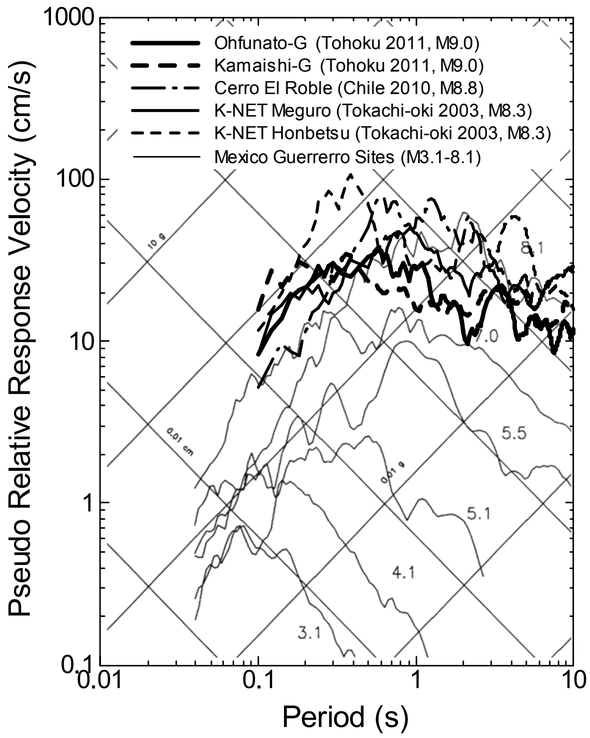

Fig. 10 Comparison of velocity response spectra at rock sites

spectra do not change significantly.

No rock site records are available from the 2001 Peru earthquake (Mw8.4) and the 2007 Sumatra earthquake (Mw8.4), but records at stiff soil sites (Monquegua and Sikuai Island, respectively) are instead available. To check whether these two earthquakes have common spectral features with the Chile, Tokachi-oki and Tohoku earthquakes, a comparison of spectra has also been made for records at stiff soil sites. Figure 11 shows comparison of stiff soil records of the five earthquakes. For the 2010 Chile earthquake, the record at Concepcion San Pedro was used. In this figure as well, the spectral shape from the Tohoku earthquake shows no prominent dominance of long-period components, compared with those of the other earthquakes. Spectral shapes are generally similar to one another.

Figure 12 is comparison of acceleration time histories in records at stiff soil sites in these five earthquakes to examine durations, which tend to become longer as the magnitude becomes greater. The durations reflected differences in their magnitudes: close to 40 seconds for the 2003 Tokachi-oki (Mw8.3), the 2001 Peru (Mw8.4) and the 2007 Sumatra (Mw8.4) earthquakes; about 70 seconds for the 2010 Chile earthquake; and approximately 100 seconds in the Tohoku earthquake, as shown in Fig. 13.

Figure 14 plots relationship between ground motion durations and magnitudes for the records of earthquakes discussed above. It can be seen that duration is around 40 seconds for M8.3, and comes close to 100 seconds for M9. This confirms that duration becomes longer as magnitude becomes greater. Also shown in the figure is an empirical relationship between duration and magnitude obtained from earthquakes in California, with magnitudes of up to 7.6 (Dobry et al., 1978). The duration of a magnitude-5 quake is 2 seconds, compared with some 25 seconds for an earthquake with a magnitude of 7.5. The results from the analysis thus fall largely in line with an extension of the relationship by Dobry et al. (1978), and the logarithm of duration and magnitude appear to be generally in a linear relationship across a broad range of magnitudes.

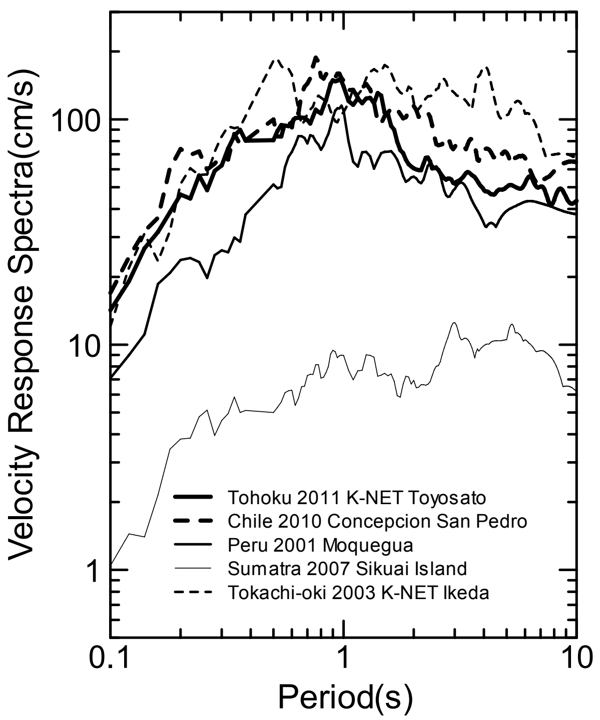

Fig. 11 Comparison of velocity response spectra at stiff soil sites

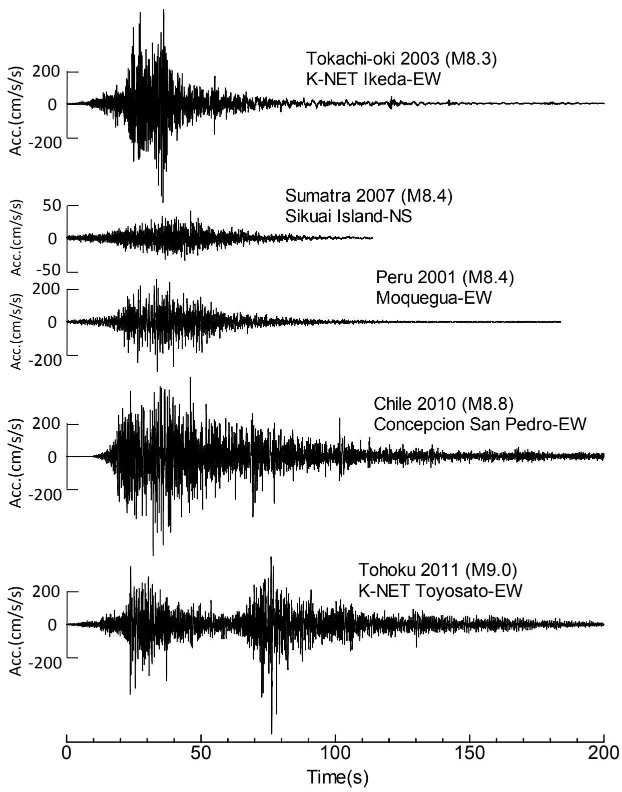

Fig. 12 Comparison of acceleration time histories at stiff soil sites

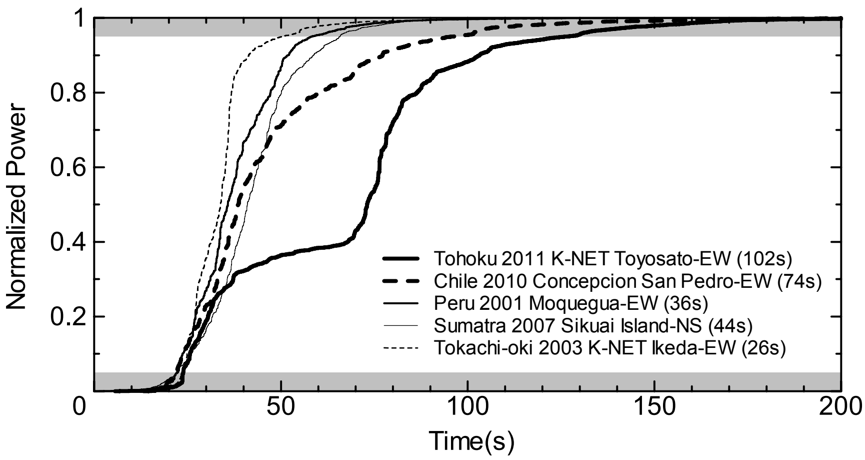

Fig. 13 Comparison of ground motion durations in five gigantic earthquakes

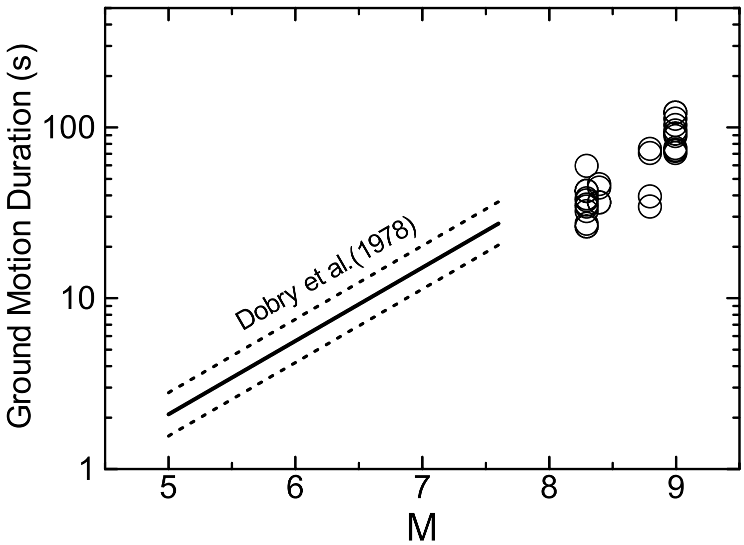

Fig. 14 Relationship between ground motion durations and magnitudes of earthquakes

4. CONCLUSIONS

Strong ground motion characteristics of gigantic earthquakes are examined by conducting a preliminary analysis of strong motion records from the 2011 Off the Pacific Coast of Tohoku Earthquake (Mw9.0) for its attenuation characteristics, spectral characteristics and duration and by comparing them with strong motion records from other gigantic earthquakes in Chile and elsewhere (Mw8.3 to 8.8). The examinations have found that attenuation characteristics and spectral characteristics of ground motions over a period range of up to 10 seconds were much the same for the Tohoku earthquake (Mw9.0) and the other events (Mw8.3 to 8.8). The results has also showed that when magnitude exceeds 8, no major differences are seen among the earthquakes in terms of peak ground acceleration amplitudes and spectral characteristics, suggesting that seismic source spectral characteristics remain much the same over a period range of up to 10 seconds. It has been also pointed out that duration, by contrast, tends to become longer as magnitude becomes greater even after it exceeds 8. Strong motion records from the Tohoku earthquake show that duration reached approximately 100 seconds. The logarithm of duration and magnitude are largely in linear relationship over a broad range of magnitudes. For more detailed examinations, further analysis with the additional strong motion records should be necessary.

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