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Strong ground motions from the 2011 off-the Pacific-Coast-of-Tohoku, Japan (Mw=9.0) earthquake obtained from a dense nationwide seismic network

Abstract The dense recordings of the K-NET and KiK-net nationwide strong motion network of 1,189 accelerometers show clearly the radiation and propagation properties of the strong ground motions associated with the 2011 off-the-Pacific Coast-of-Tohoku, Japan (Mw=9.0) earthquake. The snapshots of seismic wave propagation reveal strong ground motions from this earthquake that originate from three large slips; the first two slips occurred over the plate interface of off-Miyagi at the southwest and the east of the hypocenter, and the third one just beneath the northern end of Ibaraki over the plate interface or in the crust. Such multiple shocks of this event caused large accelerations (maximum 1–2G) and prolonged ground shaking lasting several minutes with dominant high-frequency (T<1s) signals over the entire area of northern Japan. On the other hand, ground motions of relatively longer–period band (T=1–2s), which caused significant damage to wooden-frame houses, were about 1/2–1/3 of those observed near the source area of the destructive 1995 Kobe, Japan (M=7.3) earthquake. Also, the long-period (T=6–8s) ground motion in the Kanto (Tokyo) sedimentary basin was at an almost comparable level of those observed during the recent Mw=7 inland earthquakes, but not as large as that from the former M=8 earthquakes. Therefore, the impact of the strong ground motion from the present M=9 earthquake was not as large as expected from the previously M=7–8 earthquakes and caused strong motion damage only to short-scale construction and according to instruments inside the buildings, both have a shorter (T<1s) natural period.

Keywords The 2011 Tohoku Earthquake · K-NET · KiK-net · Long-period ground motions

Introduction

A destructive, Mw 9.0 earthquake occurred off the coast of Japan in the Pacific Ocean on March 11, 2011 causing extreme disasters in northeastern Japan due to high tsunami waves and strong ground motions. The toll of dead and missing persons is estimated at more than 20,000. Before the occurrence of this earthquake, Mw= 7.5 off Miyagi earthquake had been repeatedly occurred with a recurrent period of about 40 years at the plate boundary between the Pacific and the North American plates. Since no large earthquakes occurred for more than 30 years after the 1978 off-Miyagi event, it was anticipated that the next earthquake should occur within 30 years with a probability of 99% (The Headquarters for Earthquake Research Promotion 2001). However, the earthquake which occurred was a much larger, megathrust event where fault rupture spreads entirely over the plate boundary of off-Miyagi, off-Fukushima, and off-Ibaraki earthquakes with a nucleation area of 500×200 km in total. Due to this earthquake, the area of large ground accelerations exceeding 1–2 G and a displacement of over 1 m spread entirely over northern Japan along the Pacific Ocean side, along the source rupture area.

In spite of such destructive disasters, all the relevant features of this earthquake were well-recorded by the nationwide K-NET and KiK-net strong ground motion network of over 1,800 stations across Japan. They are spaced at an interval of 20–25 km and are operated by the National Institute for Earth Science and Disaster Research, Japan. By making full use of these observational data, though some stations were destroyed due to large tsunami waves, we could explore the source rupture process and wave propagation properties of this severe earthquake in order to make a detailed study of the cause of strong ground motion. In this study, we examine the characteristics of the high-frequency ground motions that create the large ground accelerations near the source area, and which cause significant effects on the sea surface and damage on land. These long-period ground motions developed within sedimentary basins and caused resonance in high-rise buildings. We also examine the significance of the high-frequency and long-period ground motions associated with the present earthquake by comparing those from past destructive M6-8 events, such as the 1995 Kobe earthquake (M=7.3), the 2004 SE Off-Kii Peninsula earthquake (M=7.4), the 2004 Mid-Niigata earthquake (M=6.8), and the 1944 Tonankai (M=8) earthquake, which occurred relatively recently in Japan.

Visualization of wave propagation by dense strong motion network

Figure 1 illustrates the visualized seismic wavefield derived by interpolation of accelerograms for the 1,189 K-NET and KiK-net strong motion stations following the visualization procedure of the seismic waves (Furumura et al. 2003). The K-NET and the KiK-net consists of three-component accelerometers with a maximum scale of 4 G and with a resolution of 24 bit and sampling interval of 100 Hz, so that they could encompass all of the relevant strong motion phenomenon on land associated with the earthquake. The visualized seismic wavefield offers direct means to study development and propagation of the strong ground motions during the earthquake in detail.

In the first frame of the snapshot at 60 s after source initiation, we see that large ground motions are built up from the radiation produced by a bilaterally rupturing fault from a hypocenter at off-Miyagi (marked by star in Fig. 1) from north and to south, illustrating the extent of a rectangular rupture area with increased raised ground motions. In the second (110 s) frame of the snapshot, a second large shock, almost as large as the first, spreads again over northern Japan, producing intense and long-term shaking of ground motions over northern Japan. As the strong ground motions propagate to Ibaraki, about 200 km

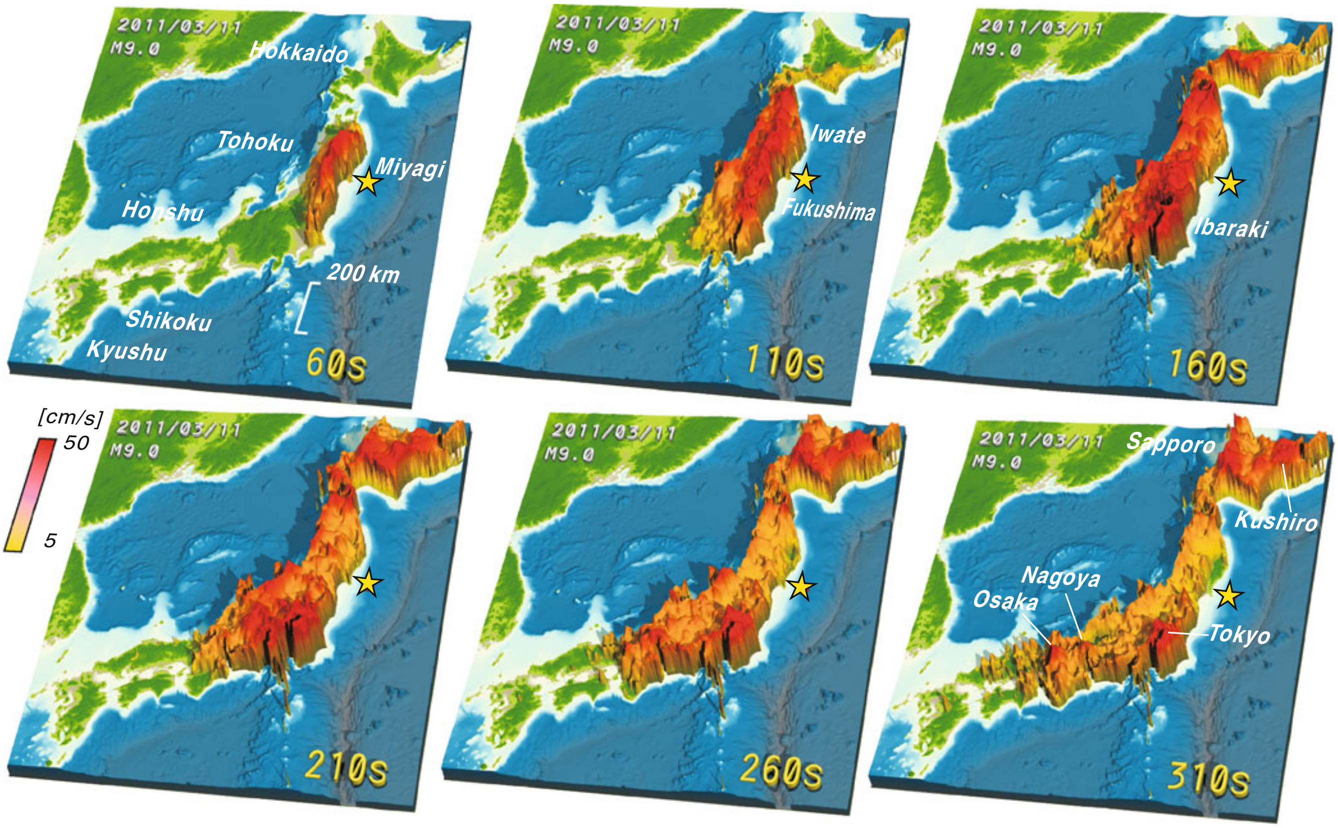


Fig. 1 Snapshots of seismic wave propagation following the 2011 off-the-Pacific-coast-of-Tohoku, Japan (Mw=9.0) earthquake. The amplitude of ground–velocity motions are shown for times of 60, 110, 160, 210, 260, and 310 s after the earthquake rupture. *Star* the hypocenter of this earthquake. Major city and prefecture are marked

southwest of the hypocenter, a third shock illuminates the surface area around Ibaraki. Then, the overlap of these strong ground motions extends the large, prolonged shaking area from Ibaraki to Tokyo (160 and 210 s). In the last two frames of the snapshot (260 and 310 s), we see amplified and prolonged ground shaking in populated cities, such as Sapporo, Tokyo, Nagoya, and Osaka due to the resonance of long-period ground motions within sedimentary basins. In these areas, the ground motions occur in low wave-speed sediments with a large velocity contrast between surrounding rigid (high wave-speed) bedrock. The large ground motions within the basin continued for several minutes.

Radiation of high-frequency signals from the large slips

A plot of vertical-component ground acceleration records of a linearly aligned K-NET and KiK-net stations from north to south along the Pacific coast shows a couple of hyperbolic curves (green and red lines in Fig. 2) of lumped ground accelerations spreading from Miyagi (MYG012) with a time separation of 50 s between the two curves. Since the large radiated energy propagates bilaterally from the hypocenter to the north and south at an apparent velocity of about 4.6–5.3 km/s, it is recognized as the S wave propagating from the source. The first shock appears to be correlated with the first large slip near the hypocenter while the second one with a travel time curve of relatively less curvature indicates the second large slip occurred at the east of the hypocenter. We calculated the theoretical travel time curves of the first and the second large slips assuming a standard P- and S-wave velocity model of Japan (Ukawa et al. 1984) and determined the location and depth of these slips. We assume that these two large slips occurred on the plate boundary, and confirmed that the first large slip occurred 30 km southwest of the hypocenter over the subducting Pacific plate at 33 km depth (marked by green star in Fig. 2), and the second large slip occurred 75 km east of the hypocenter on the plate boundary at 19 km depth (marked by red star in Fig. 2).

The distribution of the peak ground acceleration (PGA) as shown in Fig. 2 shows starched PGA contours from north to south along the coast of the Pacific Ocean side due to the large fault rupture along this direction. Significant attenuation of the PGA in the Japan seaside is due to the stronger attenuation of seismic waves in the mantle structure across the volcanic front (Furumura and Kennett 2005). The PGA map confirms that the burst of the high-frequency multiple shocks from the two large slips raised ground accelerations over 500–1,000 cm/s/s around the Miyagi area. The prolonged shaking and large ground motion as illustrated in Fig. 1 is also caused by multiple shocks at interval of about 50 s with large ground accelerations from both sources.

It is also apparent from the snapshots of seismic wave propagation (Fig. 1) and the record section (Fig. 2) that a third shock occurred at Ibaraki at about 130 s after the earthquake rupture (marked by purple star in Fig. 2). The spread of large ground accelerations from Ibaraki (IBR003) to the north and south of the epicenter at a relatively slow apparent velocity and with a stronger curvature of the travel–time curve (blue line in

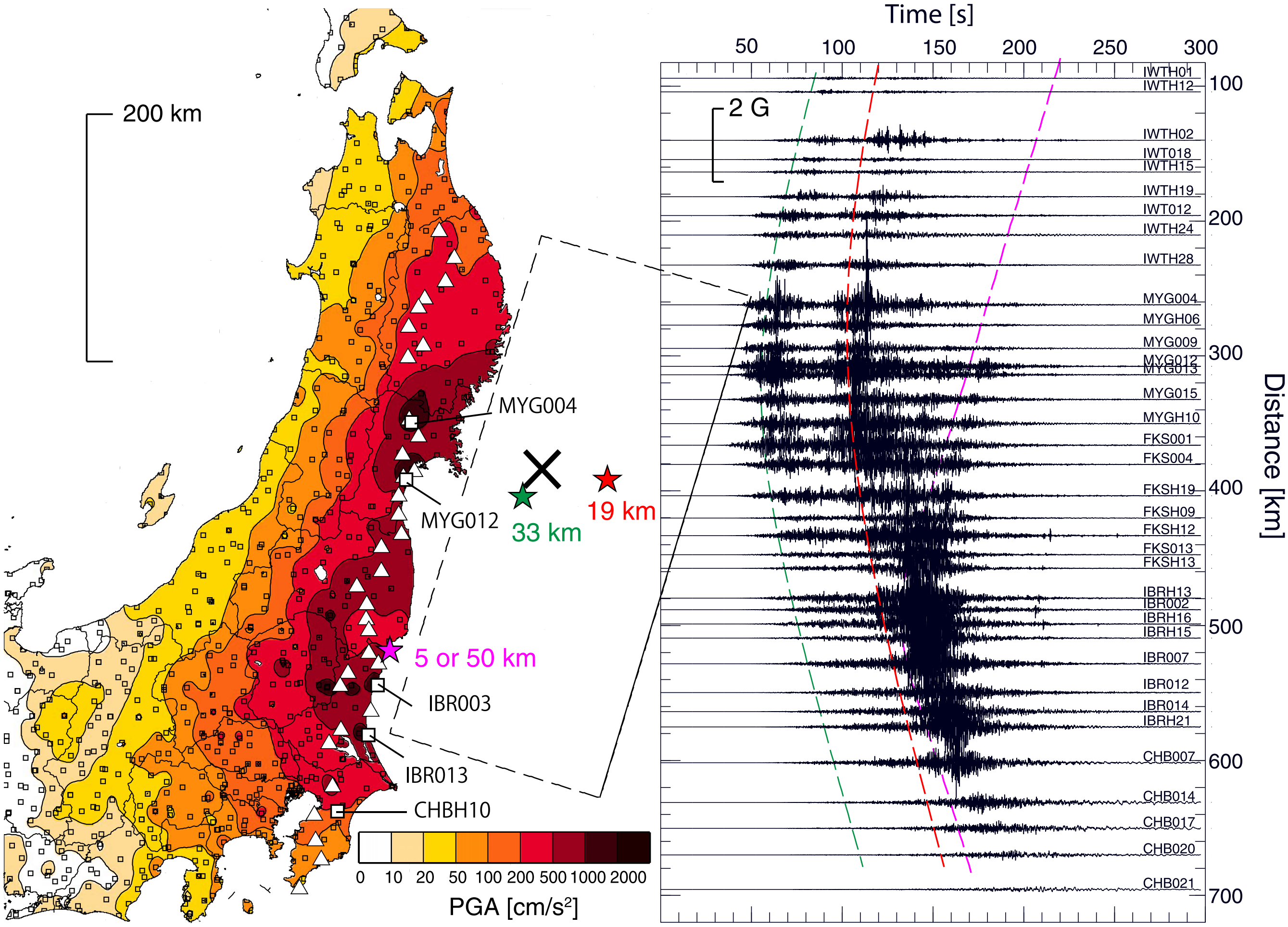


Fig. 2 Distribution of peak ground acceleration (PGA; cm/s/s) and record section of the vertical component ground acceleration recorded at linearly aligned 42 stations from north to south (*triangles* in the PGA map). The hypocenter (*cross*) and three large slips (*green*, *red*, and *purple* stars) with their theoretical travel–time curves are indicated

Fig. 2) indicates that the third large slip most probably occurred close to Ibaraki. The hypocenter of the third large slip was found on land at the margin of Fukushima and Ibaraki prefectures. It can be inferred that the third large slip occurred either on the fault plane of the main shock or in the crust as an induced earthquake triggered by the large ground motion of the second event. Aftershock distribution of shallow earthquakes in the area beneath the Fukushima and Ibaraki prefectures supports the later. Thus, the large PGA observed in Ibaraki might be due to the superposition of strong ground motions from large slips off Miyagi or a shallow earthquake at the Fukushima and Ibaragi boundary.

PGA attenuation function

Figure 3 illustrates attenuation of the PGA as a function of fault distance obtained by the K-NET and the KiK-net of 1183 stations for the present earthquake. A standard PGA attenuation function predicted for interplate earthquakes in Japan (Shi and Midorikawa 1999a, b) for Mw=9.0, 8.0, and 7.0 earthquakes are also illustrated. The empirical attenuation function was determined by using large number of data from recent Japanese earthquakes with magnitude range from Mw=5.3 to 8.3 and epicentral distance from 6 to 120 km. The PGA attenuation function of an Mw=9.0 event was simply estimated by extrapolation of this function.

It is confirmed that most of the PGA values during the present earthquake lies within the PGA value expected from the empirical attenuation function between Mw=7.0 and 8.0 and not exceeding the value of the Mw=9.0 event, except some PGA values near the fault rupture area are less than $D<$ 100 km. It is apparent that the largest PGA from the present earthquake was not as large as that we have ever observed during previous large earthquakes with magnitude less than Mw=8.0.

Near-field strong ground motions

Large ground accelerations in excess of 1–2 G were recorded at Miyagi and Ibaraki near the source rupture area which is much larger than that expected from the empirical attenuation function of the Mw=9.0 earthquakes in Japan.

We calculated the velocity response spectrum of horizontal ground motions recorded at the K-NET stations in Miyagi (MYG004 and MYG012) and in Ibaraki (IBR003 and IBR013), assuming a damping coefficient of $h=0.05$ (Fig. 4) in order to understand the impact of these strong ground motions in causing strong motion earthquake disasters. The result shows a sharp

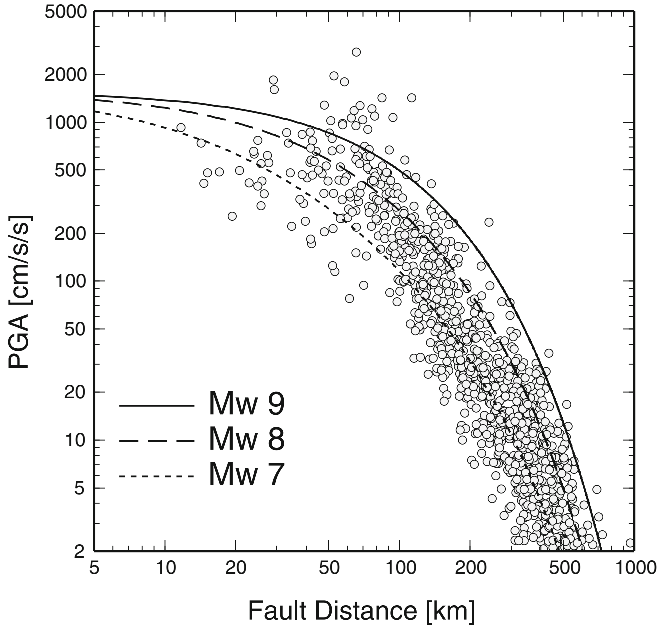


Fig. 3 Attenuation of peak ground acceleration as a function of fault distance. *Solid* and *dashed lines* represent the expected PGA attenuation function for Mw=9.0, 8.0, and 7.0 earthquakes of an interpolate type source mechanism in Japan (Shi and Midorikawa 1999a, b)

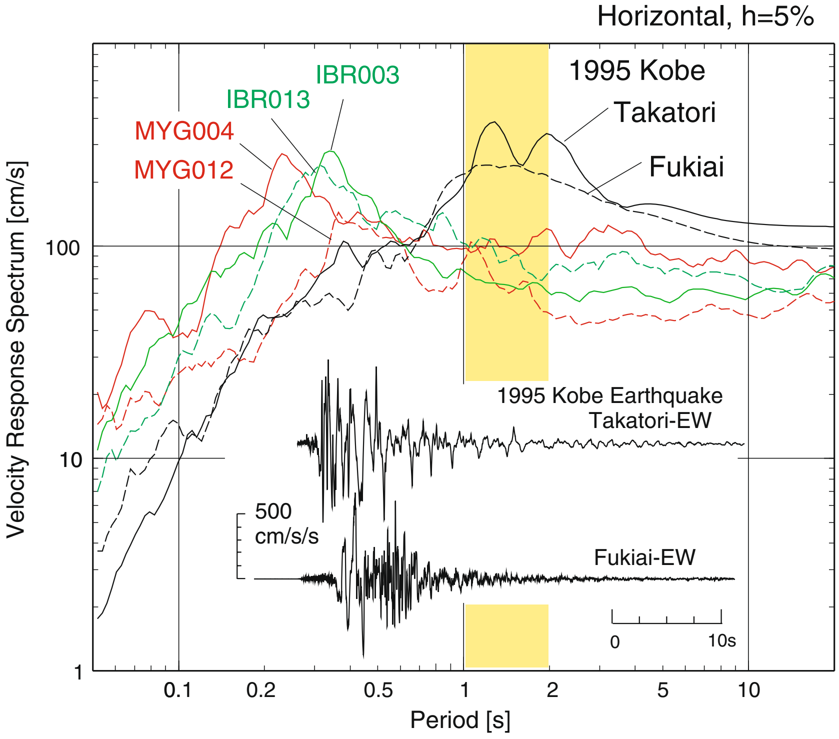
resonance in the relatively short-period range of about T=0.2–0.4 s, with a maximum amplitude of over 150–200 cm/s, at stations MYG004, MYG012, IBR003, and IBR013 (Fig. 3). Such large high-frequency signals might be developed by large slips as discussed above and may represent irregular source rupture propagation over the fault. Also, an efficient propagation of high-frequency signals along the high-Q subducting Pacific plate (Furumura and Kennett 2005) and amplification of high-frequency signals in a thinner, very low wave-speed layer embedded over rigid bedrock along the Pacific Ocean side of Tohoku region might cause the increased ground motions. Such an effect of high-frequency signals with a long time duration of large ground accelerations might cause increased effects to structures that have a shorter resonant period.

In spite of large response in the high-frequency ground motions, a relatively weak response amplitude is found in long-period range (T>0.6 s), which is about half of the observed strong ground motions at Fukiai and Takatori during the 1995 Kobe, Japan (M=7.3) earthquake. It indicates that the impact of the strong ground motions during the present earthquake on Japanese wooden-frame houses (most effective resonant period is about T=1–2 s) was not as large as that of the destructive 1995 Kobe earthquake.

Long-period ground motion developed in the Kanto basin

The velocity response spectrum for the strong ground motions that occurred in Chiba (CHBH10) from the present earthquake is compared with those from the recent earthquakes of the 2004 mid-Niigata (M=6.8) and the 2004 SE-off-Kii-Peninsula (M=7.4) earthquakes (Fig. 5a). Seismograms of N–S component velocity ground motions in Chiba are also illustrated in Fig. 5b. It is well recognized that a thick and low shear-wave speed in a sedimentary layer (Vs<2 km/s) of more than 3,500 m thick beneath the Kanto (Tokyo) sedimentary basin causes significant resonance in the long-period range of about T=6–10 s and is associated with large earthquakes occurring in nearby Tokyo (e.g., Koketsu and Kikuchi 2000). The long-period ground motion in central Tokyo during the 2004 mid-Niigata earthquake caused a significant resonance in tall buildings of about 70 floors (about 350 m in height; Furumura and Hayakawa

Fig. 4 Velocity–response spectrum of horizontal ground motions recorded at stations (squares in Fig. 2) near the source area at Miyagi (MYG004, MYG012) and Ibaraki (IBR003, IBR013) during the earthquake and comparing those recorded at Takatori and Fukiai during the 1955 Kobe earthquake. The *yellow*-highlighted period band (1–2 s) corresponds to the most effective period for wooden-frame houses. The observed acceleration records at Takatori and Fukiai from the 1995 Kobe earthquake are also shown



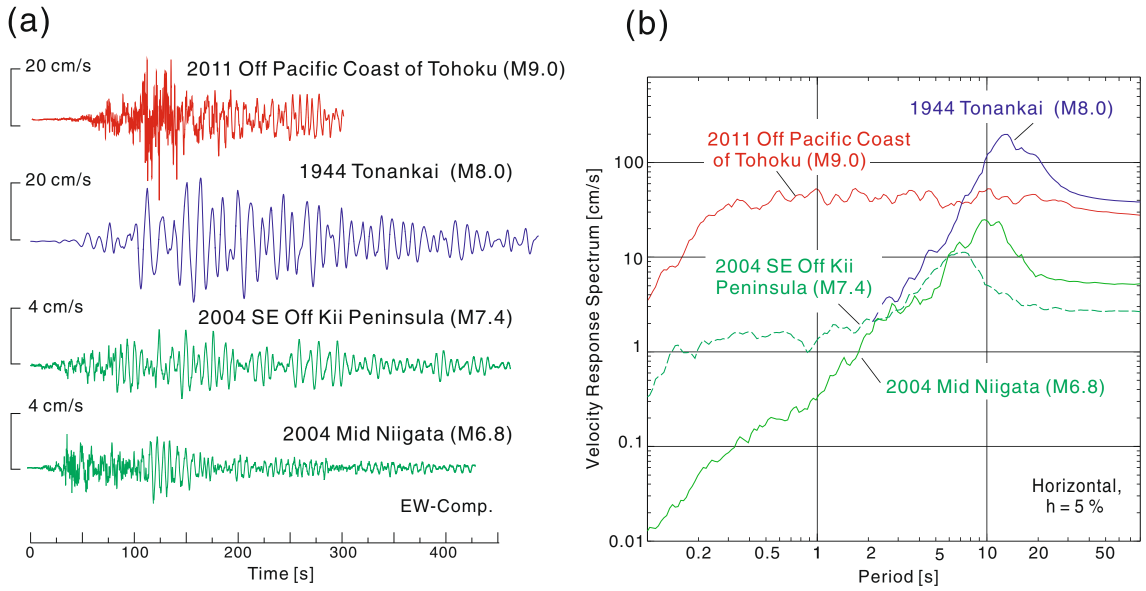


Fig. 5 Velocity–response spectrum of horizontal ground motions recorded in Chiba (CHBH10; *square* in Fig. 2) during the present earthquake, comparing those from the 2004 mid-Niigata, the 2004 SE-off-Kii-Peninsula, and the 1944 Tonankai earthquakes

2007). Also, some sloshing damage occurred in the large oil storage tanks at the coast of Chiba during the 2004 SE-off-Kii-Peninsula (M=7.4) earthquakes (Hayakawa et al. 2005; Hatayama and Zama 2005; Miyake and Koketsu 2005; Furumura et al. 2008). Therefore, it is an urgent matter to understand the development and amplification properties of the long-period ground motions in Kanto basin associated with large earthquakes.

We calculated the velocity response spectrum of horizontal ground motions in order to compare the strength of the long-period ground motion in the center of Tokyo basin (Chiba) during the present Mw=9.0 earthquakes. The velocity response spectrum of horizontal motion assuming a damping coefficient of $h=0.05$ show that the ground motion from the present earthquake caused a larger response in a relatively wide period ranging from 0.5 to 30 s, with maximum amplitude of over 30 cm/s. The level of the velocity response spectrum for the present earthquake is roughly 1.2–1.5 times the maximum value for that of the 2004 mid-Niigata (M=6.8) earthquake which caused a large response in the narrow-period range of about 9–12 s. The long-period ground motion from the present earthquake caused a significant impact on many low-layer to high-rise buildings, though it caused significant resonance only in high-rise buildings and in large oil storage tanks in the period range of 6–8 s during the 2004 mid-Niigata and the 2004 SE off-Kii Peninsula earthquakes.

The level of the long-period ground motions developed in central Tokyo during the present Mw 9.0 earthquake was significant, however, the level of long-period ground motion was only 1.2–1.5 times larger than those that occurred during the inland M=6.8 earthquakes in Niigata. Also it should be noted that the peak level of the long-period ground motions (30 cm/s) in the frequency band between 0.5 and 20 s is half of that observed in Togane city, Chiba during the 1944 Tonankai (M=8.0) earthquake which occurred in western Japan at similar distances from Chiba to that of the present earthquake (Furumura and Nakamura 2006). Such a difference in the level of the long-period ground motions between the present Mw=9.0 earthquake and the 1944 Tonankai (M=8.0) earthquake may be due to either the source radiation properties of these earthquakes at different subduction zones or the propagation path effects from the source to Tokyo basin or both. Different amplification properties of the long-period ground motions due to 3D structure of the Kanto basin and relation of the incidence direction of seismic waves might also be examined as a possible cause of the present observation.

Discussion and conclusion

The dense recordings of the K-NET and the KiK-net strong ground motions networks for the recent Mw=9.0 megathrust earthquake demonstrate clearly the occurrence of anomalous strong ground motions that we have never seen previously. The visualized seismic wavefield from the dense recording data illustrates the complicated source rupture process over the large fault plane of 500×200 km, along with an induced earthquake on land. As such, there is a complicated source–rupture process causing large ground acceleration (>1–2 G) in a wide area of northern Japan.

Actually, the spread and the level of ground acceleration is very significant from the large earthquake, but the level of the PGA and strength of relatively long-period ground motion near the source area and the developments of the longer period ground motion in the Kanto basin was not so significant and is almost of comparable level of previous M=7–8 earthquakes. It reveals that the level of the long-period motions depends not only on earthquake magnitude, but also on the source rupture process and/or wave propagation directions in the 3-D heterogeneous structure of the Kanto basin.

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