EARTHQUAKE SOURCE AND GROUND MOTION CHARACTERISTICS IN EASTERN JAPAN DURING THE 2011 OFF THE PACIFIC COAST OF TOHOKU EARTHQUAKE

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The 2011 off the Pacific coast of Tohoku earthquake brought severe damage caused not only by the tsunami but also by the ground motions. The present manuscript summarizes the source mechanism/process and the characteristics of ground motions around eastern Japan during the earthquake. For the last two years after the earthquake, many researchers have devoted their efforts to analyzing and discussing the source and ground motions. New findings from some recent works are also cited. We, furthermore, introduce characteristics of ground motions at some typical damaged sites, where no records of ground motions were obtained during the main shock, using time histories of after shocks.

Key Words : *the 2011 off the Pacific coast of Tohoku earthquake, source mechanism, recorded data, earthquake ground motions, seismic intensity, PGA (peak ground acceleration)*

1. INTRODUCTION

On March 11, 2011, a huge earthquake hit the eastern part of mainland Japan. The earthquake caused a huge tsunami that killed more than ten thousand people¹⁾. Structures were also severely damaged over the area of eastern Japan by the tsunami, ground motions, liquefaction, and so on.

Strong ground motions during the earthquake were observed over almost the entire Japan. At least 18 stations observed peak horizontal accelerations of over $980 \text{ cm/s}^2 = 1 \text{ G}$, and three stations observed seismic intensities of 7 in the Japan Meteorological Agency (JMA) scale^{2),3)}: MYG004 (K-NET Tsuki-

date), TCGH16 (KiK-net Haga), and CCHG (Small-Titan Shichigo junior high school). However, the relationships between the damage and the large ground motions were not clear. Except for the damage by the tsunami, the structural damage was not much, though we found severe damage at some limited areas, such as Furukawa, Miyagi Prefecture, etc.

For the last two years after the huge and destructive 2011 earthquake, many researchers have devoted their efforts to analyzing its source mechanism, which includes the source process or rupture process, and characteristics of ground motions. This manuscript is a review of the last two-year results related to the source and ground motions. Furthermore, estimated

ground motions were introduced at some typical damaged sites, where no records were available, using records of aftershocks.

It is, of course, very difficult to cover all the researches because of certain authors' limitations. Some details have been omitted to introduce as many works as possible. The authors expect that the readers will use the references. Although many references are written in Japanese, we believe that basic information can be gathered without much language-related problems.

2. EARTHQUAKE SOURCE

The earthquake, officially named “The 2011 off the Pacific coast of Tohoku Earthquake” by Japan Meteorological Agency (JMA), occurred at 14:46 (JST, GMT+9) on March 11, 2011. The hypocenter was located in the offshore region of the eastern part of mainland Japan, and the depth was 24 km. The moment magnitude (M_w) was 9.0⁴⁾; it was the largest earthquake observed in Japan since 1900, and the 4th largest earthquake in the world since 1900⁵⁾. The distribution of aftershocks occurring within 24 hours after the main shock almost covers the fault zone of the main shock as shown in **Fig.1**. It implies that dimensions of the fault zone were about 500 km in length along the coast line by about 200 km in width⁶⁾. The centroid moment tensor (CMT) solutions estimated by JMA⁴⁾ and F-net organized by the National Research Institute for Earth Science and Disaster Prevention (NIED), are shown in **Fig.1**. They indicate that the mechanism was a reverse fault with a compressional axis in an almost east-to-west direction, which was estimated as N103°E by JMA and N110°E by NIED, respectively. The location of the seismic fault and the mechanism imply an inter-plate earthquake on the plate boundary between the North American plate and the Pacific plate.

The Headquarters for Earthquake Research Promotion (HERP) had warned of the occurrence of an earthquake in offshore Miyagi Prefecture with a probability of 99% and a scale of local magnitude defined by JMA (M_{JMA}) 7.5 within 30 years. The event was expected to be similar to the Miyagi-oki earthquake (M_w 7.6) of 1978. However, the events corresponding to the Tohoku earthquake were not evaluated⁸⁾. The earthquake ruptured over several segments, which had been evaluated as independent earthquakes. After the earthquake, HERP revised the long-term probability; the same scale at that of the Tohoku earthquake was considered in the Tohoku region, and M8–9 class earthquakes were considered in

Fig.1 Aftershock distribution within 24 hours after the main shock, and CMT solutions estimated by JMA and F-net (NIED). The rectangle area indicates the seismic fault⁷⁾.

the Nankai trough region.

The earthquake caused severe tsunami damage along the coast line of the eastern part of mainland Japan⁹⁾. The large tsunami was generated by a large deformation of the seafloor. A geodetic observation very near the epicenter indicated 24-m and 3-m displacements in horizontal and vertical direction, respectively. They were obtained from the geodetic data before and after the earthquake¹⁰⁾. A differential bathymetry image across the trench also indicated 50-m and 10-m displacements, respectively¹¹⁾. The displacements were only available at the specific sites, although they imply that the seafloor deformation was at least in the order of 50 m in horizontal direction.

Slip distribution during the earthquake has been reported by many research groups in the field of earth science by using various types of data sets. The slip distributions were estimated from teleseismic waves^{12),13)}, geodetic data^{14),15)}, low-frequency components of regional ground motion data^{7),16)}, and tsunami data^{17),18)}. Some results were obtained from their combination^{19),20)}. Notice that the applied data sets correspond to static deformations and/or low-frequency ground motions. More details of the slip distributions were described in another review article⁵⁾. The maximum slip about 35–50 m was estimated, which was almost in the same order as the direct observation of the seafloor deformation^{10),11)}. A region of the large slip was located on the shallower side of the seismic fault with the exception of a few models¹⁹⁾, and the non-zero slips were estimated at the trench. The deformations at the trench were

Fig.2 Slip distribution estimated from long period ground motions⁷⁾ and SMGA locations²²⁾. The star mark indicates the epicenter location.

also observed from the reflection image¹¹⁾. They imply that the source rupture reached the seafloor during the earthquake.

Strong ground motions observed in the eastern part of the mainland incorporated the other important feature of the earthquake source: high-frequency radiations. Several articles emphasized the propagation of wave groups^{6),21),22)}. The first and second wave groups, with an interval of about 50 seconds, were mainly observed at the northern stations than in the epicenter. The wave groups were not clear at the southern stations, but a third wave group was mainly observed at the southern stations. This implies that the rupture process of the earthquake involved at least three significant events radiating high-frequency energy. The first two wave groups mainly affected the ground motions observed in Iwate and Miyagi Prefectures, while the third one affected the ground motions observed in Ibaraki and Tochigi Prefectures.

The corresponding source models were also investigated by several research groups. High-frequency energy radiation areas were estimated by the back-projection method^{23),24),25)} and the envelope inversion²⁶⁾. More typical models characterized by strong motion generation areas (SMGAs)^{22),27)} and by super asperities²⁸⁾ were established. Please refer to the references for the concrete definitions of SMGA^{22),27)} and super asperity²⁸⁾. The models emphasize the high-frequency aspects of the source rupture process higher than 0.1 Hz. All the results imply that the high-frequency energies radiated from the deeper side of the seismic fault.

Fig.3 Distribution of peak ground accelerations (PGA) in horizontal components.

Fig.2 shows the slip distribution estimated by Suzuki *et al.*⁷⁾, and the locations of SMGAs estimated by Asano and Iwata²²⁾. The slip distribution corresponds to the low-frequency ground motions (0.01–0.125Hz), and SMGAs correspond to the high-frequency ground motions (0.1–10Hz). Obviously the locations of the large slips and the SMGAs do not overlap. The large slips are located at the eastern side, and SMGAs are located at the western side of the epicenter, which is indicated by a star mark in **Fig.2**. It implies that the locations of seismic wave radiation areas depend on the frequency band. The frequency dependency of the source models has been discussed in several articles^{29)–32)}.

Although there are various source models, we emphasize that the high-frequency radiations are relatively important in discussing the strong ground motion characteristics from an engineering point of view. The origins were closer than either the hypocenter or the large slip region, especially for Fukushima and Ibaraki Prefectures.

In addition to the results, physics-based approaches are required to understand the mechanism of the source rupture process. Several researches had attempted physics-based simulations during the Tohoku earthquake^{33)–37)}. For example, the ground motions observed in Miyagi and Iwate Prefectures consisted of two major wave groups with an interval of about 50 seconds. The origins were estimated to be on the deeper side of the hypocenter, and located close to each other^{22),27)}, e.g., SMGA1 and SMGA2 in **Fig.2**. A time lag of about 50 seconds was required between the events. Goto *et al.*³⁶⁾ suggested that reflection

Table1 Top 8 records of PGA in horizontal components

PGA [cm/s^2]	Station
2765	K-NET MYG004
1970	K-NET MYG012
1913	PARI Onahama-G
1844	K-NET IBR003
1807	K-NET MYG013
1614	K-NET IBR013
1425	K-NET TCG009
1425	K-NET FKS016

waves from the free surface affected the generation of the latter event based on the physics-based simulations.

3. GROUND MOTIONS

(1) Overview

Ground motions during the earthquake were observed by several seismic networks organized by NIED, JMA, Port and Airport Research Institute (PARI), Building Research Institute (BRI), National Institute for Land and Infrastructure Management (NILIM), and other organizations. These organizations have published their own reports on the data observed during the earthquake, including waveforms and even response spectra. The readers can refer to these reports and many of them can be accessed through the Internet^{(38)~(42)}.

Fig.3 shows the distributions of peak ground accelerations (PGA) in the horizontal components calculated from the available records of the ground motion. The PGAs in this figure were obtained from the combined time histories for two horizontal components.

The PGA values in **Fig.3** do not simply attenuate from the east coast; they vary strongly along the coast line, similar to the seismic intensity distribution. Large PGAs were mainly observed in the regions of 1) Miyagi Prefecture, and 2) Tochigi and Ibaraki Prefectures, which are close to the locations of the SM-GAs.

Table 1 lists the top 8 records of PGA in horizontal components. The largest PGA, 2765 cm/s^2 , was observed at K-NET MYG004. It is almost three times larger than the gravitational acceleration. Even the second largest PGA observed at K-NET MYG012 is about twice larger than the gravitational acceleration. K-NET MYG004 and MYG012 are located in Miyagi Prefecture, while PARI Onahama-G and K-NET IBR003 are located in Fukushima and Ibaraki Prefectures, respectively (see **Fig.3**). Large pSv values with periods in the range of 1.0–2.0s are concentrated in the northern part of Miyagi Prefecture⁽⁶⁾.

Fig.4 Distribution of seismic intensity in JMA scale. **Fig.5** Acceleration records obtained by the 1994, 2008, and 2011 events at Hachinohe city hall (HCN.BRI) and Morioka JMA observatory (MRK.JMA).

(2) Northern Tohoku area

Ground motion characteristics around northern Tohoku region are described in this section. Northern Tohoku region consists of Iwate, Akita, and Aomori Prefectures, where they are located south-east, south-west, and north of the area, respectively, as shown in **Fig.4(b)**. As described previously, ground motions in this region were not so large compared to those in the southern area. Thus, severe damage induced by ground motion was not found except for the southern part of Iwate Prefecture⁽⁴³⁾.

Fig.4(a) shows the distribution of seismic intensities in this region. The figure illustrates the values of seismic intensities provided by JMA and values calculated from the records of K-NET and KiK-net. The highest value of intensity in this figure is 6^- . Stations, where 6^- intensity were recorded, are located around the southern boundary of Iwate Prefecture and the southern part along Kitakami-gawa river. The north-

Fig.6 Distribution of seismic intensities of the 2011 off the Pacific coast of Tohoku earthquake around the southern area of Iwate. The numbers in the legend denote seismic intensity in JMA scale.

ern limit of the area with 6^- intensity is about 40 degrees latitude. On the other hand, there are few sites with 6^- intensity along the eastern coast line, even though the fault plane is located beneath the coast line. Detailed characteristics of ground motions are discussed in the following section for the southern area of Iwate Prefecture.

In Aomori and Akita Prefectures, the highest intensity is 5^+ . Most stations with intensity of 5^+ are located in the south-eastern area of the Aomori Prefecture except for a K-NET station AOM007 (Minamidori), where very stiff layer is covered by very soft peat layer. It has been noted that larger ground motions caused by recent earthquakes have been recorded at the stations where intensity of 5^+ was observed during the 2011 event, than at their surrounding stations⁴⁴.

The northern Tohoku area has been hit by many earthquakes in the last few decades. **Fig.5** compares the 2011 acceleration records with those of the 1994 and 2008 events at two typical sites: Hachinohe city hall (HCN.BRI) of Aomori and JMA observatory at Morioka (MRK.JMA) of Iwate. The site locations and epicenters of the earthquakes are shown in **Fig.4(b)**. The two events were the 1994 Sanriku-Haruka-Oki earthquake, which occurred in the eastern off shore on December 28, 1994, and the 2008 earthquake, which occurred in the northern coastal area of Iwate on July 24, 2008.

These two events brought some damage to Hachinohe city. From **Fig.5(a)**, it is observed that the 2011 event has smaller amplitude and longer duration than the other two events. The seismic intensity of the 2011 event is also smaller than others. This explains why there was less damage around Hachinohe city during the 2011 event.

Fig.7 Distribution of questionnaire seismic intensities in Ichinoseki City, Iwate Prefecture. The seismic intensity is averaged for every 1-km mesh.

Fig.8 Distribution of questionnaire seismic intensities for the mainshock (left panel) and the aftershock (right panel) in the central area of Maesawa District of Oshu City, Iwate Prefecture. The seismic intensity was averaged for every 250-m mesh.

On the other hand, the 2011 event recorded the largest value of JMA intensity at MRK.JMA in its history as shown in **Fig.5(b)**. The peak ground acceleration, however, is only about 200 cm/s^2 . This may not bring any severe damage to well-designed structures in Japan.

(3) Southern area of Iwate Prefecture

In this section, strong motion characteristics are described around the southern area of Iwate Prefecture, Northern Honshu, Japan by the 2011 off the Pacific coast of Tohoku earthquake. We discuss the seismic records observed at the stations of the K-NET and KiK-net strong motion networks operated by NIED. Only records with epicentral distances of less than 250 km were analyzed.

Fig.6 shows the distribution of seismic intensities reported by JMA. In this area, seismic intensities range from 4 to 6⁻. It is observed that the stations with 6⁻ are mainly located in the marginal area of southern Iwate. PGA values are 998 and 852 cm/s² at the IWT010 station (K-NET Ichinoseki) for NS and EW components, respectively. At the same station, the maximum values of peak ground velocity (PGV) are also obtained: 49 and 36 cm/s for NS and EW components, respectively. PGV is relatively small compared to the large value of PGA which is almost 1 G. This suggests that the strong motion includes richer components with high frequencies than low frequencies. Except for the IWT010 station, PGA and PGV are not so large.

Serious damage has been brought to the coastal area by the tremendous tsunami, though damage caused by the ground motions of the main shock was not so severe, because the ground motions were not so large. To confirm this and discuss the detailed distribution of ground motions, seismic intensity mapping was carried out by high-density questionnaire survey at specific cities in southern Iwate^{(45),(46)}.

Fig.7 shows the distribution of questionnaire seismic intensities for the main shock in Ichinoseki City, Iwate Prefecture. The seismic intensities are averaged for every 1-km mesh. The figure shows that the distribution of seismic intensities was inhomogeneous in the area. **Fig.8** shows the distribution of questionnaire seismic intensities for the main shock and the aftershock in the central area of Maesawa District of Oshu City, Iwate Prefecture. The seismic intensities are averaged for every 250-m mesh. Damage in residential structures was mainly due to the aftershocks rather than by the main shock. The figure shows that the seismic intensities of the aftershock are larger than those of the main shock at some meshes.

(4) Miyagi and Yamagata Prefectures

In Yamagata Prefecture, the ground motions were not so large, thus very few notable ground motions and damage were found. In fact, the maximum intensity reported by JMA was 5⁺ and the PGAs observed by NIED were less than 300 cm/s². The maximum value of PGAs recorded by NIED in Yamagata Prefecture was 263 cm/s² at Kaminoyama (KiK-net YMTH04) and the second maximum was 251 cm/s² at Obanazawa (K-NET YMT006). The seismic intensities in JMA scale, which were calculated from time histories observed by NIED were 5⁺ or less than 5⁺.

There were few seismic observation stations around the border area between Yamagata and Miyagi Prefectures, which is a rugged and mountainous district

Fig.9 Pseudo-velocity response spectra ($h = 0.05$) of K-NET MYG004 and JMA Furukawa, compared to JMA Kobe and JR Takatori records during the 1995 Kobe earthquake.

including Zao Mountain Range. Thus, it is very difficult to know the detailed distribution of the ground motions from the observed data. At least, we can say that the differences were not small between the western and eastern sides of the border area. These differences may suggest the complexities of deep ground structure under the northern part of mainland Japan (Honshu).

Seismic intensities of 6⁺ and 7 in the JMA scale were recorded at more than 10 sites in Miyagi Prefecture. There were dense observation networks for strong motion in Sendai City and detailed discussions on the characteristics of ground motions are available^{(47),(48)}. The geological settings in Sendai can be divided into two areas: a plateau in the north-western area and lowland in the south-eastern area, with the Nagamachi-Rifu fault as the boundary. Large ground motions were observed around the eastern part of the fault and the northern area of downtown. The peaks of pseudo-velocity spectra are found around 0.5 to 1.0 second for many of the records. Ohno *et al.*⁽⁴⁷⁾ estimated ground motions during the mainshock around Sendai area, and pointed out that the area with large ground motion depended on its period: 0.2-second motions predominate in the north-western area of the fault, 1-second motions in eastern area of the fault, and 3-second motions in the southern area of downtown.

Typical properties of ground motions can be summarized from the records at Tsukidate and Furukawa. Hereafter, we introduce the characteristics of ground motions at these areas. The Tsukidate area is located in Kurihara City, Miyagi Prefecture, which is about

Fig.10 Pseudo-velocity response spectra observed at some sites in Fukushima. The red line represents the record at FKSH20, blue line at severely damaged area during the 1995 Kobe earthquake, and black lines at FKS001, FKS005, FKS007, and FKS010. Damping coefficient is 0.05.

60 km north of Sendai City. There is one seismic station, K-NET MYG004 (Tsukidate), which observed the largest PGA of 2765 cm/s^2 and a seismic intensity of 6.6 in the JMA scale. However, little damage was reported in this area.

Fig.9 shows the pseudo-velocity response spectra of the MYG004 and JMA Furukawa records. Each line shows the component of a specific direction with the largest peak at each station. The damping coefficient is set to be 0.05. The response spectra are compared with the JMA Kobe and JR Takatori records taken during the 1995 Kobe earthquake. The Takatori record was observed in the *damage belt*, the area with a seismic intensity of 7 in the old JMA scale. The pSv values at K-NET MYG004 exceeded the JR Takatori records at periods shorter than 0.5s, whereas those in the range of 1.0–2.0s were almost 1/4 of those of the JR Takatori records. This means that the frequency content of the records with the large PGAs was not similar to that of the JR Takatori records and that the large PGA did not contribute to the damage around the Tsukidate area.

On the other hand, during the 2011 Off the Pacific Coast of Tohoku Earthquake, severe structural damage occurred in the Furukawa District of Osaki City, which is located at approximately 35 km north of Sendai City, and 20 km south of Tsukidate. The Furukawa station of JR Tohoku Shinkansen (Bullet Train) and JR Riku-u-tosen are located in the center of the district. There are four seismic stations in the area, K-NET MYG006 (Furukawa), JMA Furukawa, Furukawa Gas, and NILIM (National Insti-

Fig.11 Map showing the location of K-NET and KiK-net stations with PGA.

tute for Land and Infrastructure Management) Furukawa. Unfortunately, however, the Furukawa Gas station did not record the time histories of the main shock⁴⁹⁾. The K-NET MYG006, JMA Furukawa, and NILIM Furukawa stations recorded PGAs of 583 cm/s^2 , 568 cm/s^2 , and 483 cm/s^2 , respectively, and the corresponding seismic intensities in the JMA scale were 6.1, 6.2, and 6.1.

The Furukawa district is located on the Osaki plain, which is covered by Holocene sediments⁵⁰⁾, and the terrain is almost flat with elevations from 17 to 21 m. The soil properties at some sites in downtown are available⁵¹⁾.

Damage distribution based on the reconnaissance immediately after the main shock had been reported⁶⁾. Damage due to the liquefaction was observed in the western area of the JR Furukawa station, and damage due to the ground motion was observed in the area neighboring the liquefaction area.

The damage level was different between the areas within several hundred meters from the K-NET MYG006 and JMA Furukawa stations, which are approximately 1 km away from each other. The severe damage was concentrated within the area approximately $1 \times 1 \text{ km}^2$ including the JMA station. From Figure 9, pSv observed in downtown Furukawa show similar shapes, especially in the period range of 1-2s, to those of the Kobe earthquake, which caused destructive damage to structures: this is not the case for the spectra of the MYG006 record. It is noted that the JMA Furukawa station is closer to the severely damaged area than the MYG006 one. This suggests that the power of the ground motions around 1s plays an important role in the structural damage and that the spatial variation of the ground motions may be critical for the damage.

To confirm this, Goto *et al.*⁵¹⁾ installed many

Fig.12 Response acceleration spectra of records with peak ground acceleration more than 1 G.

sensors into downtown Furukawa, and estimated ground structure using some geological survey techniques^{52),53)}. Many records of aftershocks and estimated ground structure suggest clear correlations between damage and spatial variations in ground motions.

(5) Fukushima Prefecture

Some stations recorded more than 1 G of PGA in Fukushima Prefecture, and two seismic stations in Fukushima Prefecture are listed in Table 1, which shows the top 8 records of PGA in horizontal components. These two sites are located in the southern area of Fukushima Prefecture. Onahama (PARI Onahama-G) is located in the maritime area, which is close to the source region and Shirakawa (K-NET FKS016) in the inland area. Large PGAs were also recorded around these two sites, both maritime and inland areas. In the maritime area, remarkably large values of PGAs were observed at Hirono (K-NET FKS010) and Ohkuma (K-NET FKS007). PGAs were also larger than 1000 cm/s^2 around Koriyama, which is located in the inland area. These large values of PGAs seem to correspond to the location of strong motion generation areas (SMGAs), discussed in Fig.2.

The pseudo-velocity response spectra at many stations in Fukushima predominate in period range shorter than 0.5 seconds; however, a few stations show particular spectral peak longer than 1 second as shown in Fig.10. In this figure, pseudo-velocity response spectra are drawn at some sites in Fukushima. The lines in Fig.10 are obtained by the same procedure as described for Fig.9. Only KiK-net FKSH20 (Namie) has a shape closer to the spectrum observed in the severely damaged area during the 1995 Kobe earthquake, and many damaged wooden structures

Fig.13 Response acceleration spectra of records near damage sites or records with predominant period around 1 second.

were found around the Namie station.

Furthermore, Nakamura *et al.*⁵⁴⁾ estimated the detailed distribution of seismic intensities around Koriyama and Sukagawa using questionnaire survey. They divided the target area into small areas with different postal (zip) codes and accepted the small areas with at least three responses to the questionnaire. The seismic intensities were provided by the values averaged over each accepted area. The accepted areas covered the downtown and estimated distribution of the seismic intensities can be used with statistical meaning to discuss the relationships between damage and ground motions.

Although seismic intensities officially reported by JMA in Koriyama, were mainly 6^- or 6^+ , the area with 6^+ was not so large. On the other hand, intensities of 6^- or 6^+ were also reported in Sukagawa, though the results of the questionnaire show that the intensities varied from 5^- to 7 and that the area with 6^+ was relatively larger than the 6^+ area around Koriyama.

(6) Ibaraki and Tochigi Prefectures

Ibaraki and Tochigi are neighboring prefectures in the southern part of Fukushima Prefecture, Tohoku region. As discussed in Section 2, the strong ground motions observed in Ibaraki and its southward area were induced by contribution of the third wave group out of the three main wave groups.

Among the 20 of K-NET and KiK-net stations of NIED, most PGAs exceeding 1 G ⁵⁵⁾ were observed in Ibaraki and Tochigi Prefectures, such as $1,845 \text{ cm/s}^2$ at K-NET Hitachi (IBR003), $1,762 \text{ cm/s}^2$ at K-NET Hokota (IBR013), $1,305 \text{ cm/s}^2$ at KiK-net Haga (TCGH16) and 1291 cm/s^2 at K-NET Motegi (TCG014) as shown in Fig.11. In the response accel-

eration spectra ($h = 0.05$) of these records shown in **Fig.12**, predominant periods shorter than 0.5 second are remarkable. These high acceleration records have similarly large amplitudes within a short period.

Strong ground-motion records in the near-source region provide detailed information about the shorter-period rupture process during the earthquakes. Irikura and Kurahashi⁵⁶⁾ found that five SMGAs, with large slip velocity or high stress drop, distributed across the entire rupture area of the earthquake. One of SMGA close to Ibaraki prefecture appeared to have high acceleration. Nozu *et al.*⁵⁷⁾ also showed super asperity near the above SMGA.

As for the relation of ground motion and damage to civil works, the strong ground-motion at the damage site of Joban expressway embankment, bearing of Nakagawa aqueduct, rubber bearings of Asahi viaduct and Shin-Nakagawa bridge, falling down of Rokko bridge were estimated by Hata *et al.*^{58)~61)}. The acceleration response spectrum of estimated ground motions also has predominant period shorter than 1 second, similar to nearby seismometer stations of K-NET Mito (IBR006), K-NET Nakaminato (IBR007) and K-NET Kashima (IBR018) as shown in **Fig.13**. In Ibaraki Prefecture, except for wooden houses, not much damage to buildings and residential houses due to ground shaking was recorded. Incidentally, the predominant period shorter than 1 second might cause damage to nonstructural components such as falling down of ceilings and exterior walls and breakage of window⁶²⁾.

The ground motion observed at K-NET Ogawa (TCG006) had predominant period around 1 second different from the other stations in Ibaraki and Tochigi Prefectures. The ground motion of the strongest aftershock also had similar predominant period. Tombs near the station turned over and roofs of houses fell down⁶³⁾.

The stations described herein are located on relatively stiff ground and liquefaction was not observed at their vicinity throughout the field investigation. Along the mouth of the Tone River and near the Pacific coast, severe liquefaction was induced by ground shaking.

4. STRONG MOTION ESTIMATION AT DAMAGE SITES

To analyze the damage mechanism by ground motions, it is very important to estimate the strong ground motions at the damage sites⁶⁴⁾. Thus, we estimated the strong motions at the sites of interest as

Fig.14 Location of target sites to estimate strong motions.

shown in **Fig.14** during the 2011 main shock based on the records of temporal observation for aftershocks. The estimation results are summarized for each classification of civil structure, such as slope and so on.

(1) Bridges

The 2011 main shock brought serious damage to some railway bridges including the elevated bridges of the Tohoku Shinkansen (Daiichi Nakasone Viaduct) in Iwate Prefecture⁶⁵⁾, Iwakiri Railway Bridge, Sendai City, Miyagi Prefecture⁶⁶⁾, etc. Although most expressway bridges designed using post-1990 code were not damaged by ground motion, rubber bearings were severely damaged at bridges designed using post-1995 code⁶⁷⁾: e.g., Rifu Viaduct, Tobu Viaduct, Asahi Viaduct, Shin Nakagawa Bridge. Furthermore, Rokko Bridge of National Route 354, Ibaraki Prefecture lost two piers and three spans⁶⁸⁾.

Hata *et al.* estimated ground motions at the site where significant damage was found^{69),70),58),59)}. To obtain appropriate estimations, they applied various techniques such as extended site-effect substitution method⁷¹⁾, a super asperity model²⁸⁾ considering empirical site amplification and phase effects, observation of aftershocks, comparison between estimated waveforms and observed ones, and so on.

(2) Aqueduct

The Naka River Aqueduct in Ibaraki Prefecture also suffered significant damage including pipe dropout in expansion joints⁷²⁾. Hata *et al.*⁶¹⁾ carried out observation of aftershocks using dense array at the damage site and carefully estimated strong motions. On the basis of observed data, differences in site effects between the landside area and the riverside area were presented. The seismic waveforms were also estimated at permanent stations for observation of strong motions using the site-effect substitution method⁷¹⁾ and they agreed well with the observed ones. After the confirming the validity of the analysis technique, the method was applied to estimate strong ground motions at the damage site.

(3) Residential area and landslides

Landslides or slope failure in residential areas were found at some places such as Oritate⁷³⁾ and Midorigaoka⁷⁴⁾ in Sendai City, Midorigaoka⁷⁵⁾ in Shi-roishi City, Asahidai⁷⁶⁾ in Fukushima City, and so on. Hata *et al.* estimated the strong motions at these sites^{77)–80)} on the basis of the site-effect substitution method⁷¹⁾.

Many and/or large-scale landslides were also found around Hanokidaira⁸¹⁾ in Shirakawa City, Kamikamoto⁸²⁾ in Iwaki City, and Kanaga⁸³⁾ in Nasukarasuyama City, etc. Hata *et al.* also estimated the seismic motions at the sites^{84),85),86)}.

(4) Road embankment and fill dam

Slope failure occurred in an embankment of the Joban expressway during the 2011 main shock and its largest aftershock⁸⁷⁾. Much serious damage also occurred in embankments of National Route 6 in Yamamoto, Miyagi Prefecture⁸⁸⁾. The strong motions were estimated at the sites^{60),89)}.

Fuijinuma Dam in Fukushima Prefecture was damaged and completely lost soil embankment⁹⁰⁾. Hata *et al.*⁹¹⁾ applied the site-effect substitution method⁷¹⁾ to estimate the ground motions at the site. The same method was also applied to estimate ground motions at strong motion stations surrounding the dam site. The estimated ground motions at the dam site were significantly different from those observed at a nearby strong motion station in terms of phase characteristics.

(5) Tsunami-affected area

Enormous damage occurred to the disaster countermeasures office, the river bridges and the fishery port facilities in Shizugawa, Minamisanriku due

to the 2011 main shock⁹²⁾. To evaluate the performance of structures before the tsunami, it is necessary to estimate strong motions in Shizugawa Area with sufficient accuracy, taking into account site effects. Seismic waveform in Shizugawa Area was estimated based on a super asperity model⁵⁷⁾ considering empirical site amplification and phase effects⁹³⁾. The estimated seismic waveform will be useful in the detailed study of seismic performance of structures before the tsunami.

5. REMARKS

In this study, we introduce the recent results on the source mechanism/process and ground motions for the 2011 off the Pacific coast of Tohoku earthquake. Furthermore, we also introduce estimated ground motions at some sites where the ground motions of the main shock are not available. We hope this manuscript helps readers in reviewing the last two-year researches on the source and ground motions.

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