EEFIT Field Observations and Lessons from the 11th March 2011 M_w9.0 Tohoku Earthquake: Ground Motion and Shaking Damage

K. Goda
University of Bristol, United Kingdom

S.C. Chian
University of Cambridge, United Kingdom

S. Fraser
Massey University, New Zealand

J. Macabuag
Building Design Partnership, United Kingdom

M. Offord
Sellafield Ltd, United Kingdom

A. Pomonis & K. Saito
Cambridge Architectural Research Limited, United Kingdom

A. Raby
Plymouth University, United Kingdom

P. Sammonds
University College of London, United Kingdom

SUMMARY:
Lessons must be learned from the catastrophic 11th March 2011 Tohoku earthquake to better cope with future earthquake disasters. In particular, from the ground motion point of view, abundant and high-quality shaking data were obtained and have been made available to public through the national strong motion networks. In light of accessible data, field reconnaissance observations from the EEFIT-Tohoku mission are interpreted, and critical features of observed ground shaking in terms of amplitude, duration, and frequency content are identified. The findings from this study offer valuable insight on key features that seismologists and earthquake engineers should focus upon for seismic risk mitigation.
Keywords: 11th March 2011 Tohoku earthquake; Reconnaissance; Ground motion; Ground shaking damage

1. INTRODUCTION

The strong ground shaking and subsequent tsunami due to the 11th March 2011 M_w9.0 earthquake deprived of more than 19,000 lives and caused devastation in the Tohoku region of Japan (AIJ Tohoku, 2011; NILIM and BRI, 2011). In particular, the scale of destruction due to tsunami in coastal cities/towns was colossal. At several locations (e.g. Onagawa, Minami Sanriku, and Yamamoto), 15m+ tsunami waves washed away existing communities completely and overtopped coastal defence measures. In the Tokyo Bay area, long duration, relatively intense ground motions were experienced and widespread liquefaction caused significant disturbance to buildings and underground pipes on reclaimed land (Bhattacharya *et al.*, 2011; Tokimatsu *et al.*, 2011). Many structures and infrastructure were also destroyed and severely damaged, revealing weakness and vulnerability of urban cities and modern society in Japan, which were thought to be one of the most earthquake-prepared nations in the world.

From a ground motion recording perspective, this event offers invaluable information that was critically missing in the existing ground motion database. The national strong ground motion networks in Japan, K-NET and KiK-net (http://www.kyoshin.bosai.go.jp/index_en.html), recorded about 1200 ground motion during this event. The unprecedented amount of high-quality data is now available. Important features of this dataset include: large magnitude event (M_w9.0), uniform spatial coverage of recording stations (various distance ranges), and availability of local site information (shear wave velocity profile).

Earthquake damage field surveys/observations provide first-hand and raw data to develop empirical correlation between ground motion intensity and damage severity in past and current events. This is essential to assess the damage potential of future earthquakes. To gain useful lessons/experiences from this tragic event, an Earthquake Engineering Field Investigation Team (EEFIT) was organised by the Institution of Structural Engineers and dispatched to the Tohoku region (28th May to 4th June 2011). During the EEFIT-Tohoku mission, various cities/towns were visited by EEFIT members to investigate both ground shaking damage and tsunami damage. This paper summarizes key findings on ground motion and shaking damage; more comprehensive field investigation results, covering ground shaking, tsunami damage, and emergency response/recovery, are available in EEFIT (2011). Specifically, this study investigates ground motion characteristics of the 2011 Tohoku earthquake using observed data from the K-NET and KiK-net, and discusses ground shaking damage surveys at Sendai, Shirakawa, and Sukagawa, where the Japan Meteorological Agency (JMA) intensity of 6+ was observed and instrumentally recorded ground motion data were available.

2. GROUND MOTIONS OF THE 11TH MARCH 2011 TOHOKU EARTHQUAKE

2.1. Fault Rupture and Ground Motions

The 2011 Tohoku earthquake occurred about 150 km off-shore Sendai, the largest city in the Tohoku region. This was a subduction mega-thrust earthquake, caused by a sudden release of accumulated strain energy at the plate boundary interface between the North American plate and the Pacific plate. Major subduction earthquakes are not unusual (e.g. 1978 Miyagi earthquake); in the off-shore Miyagi region, many have occurred in the past with M_w7.0-8.0 with average recurrence interval being 30-40 years. What was unexpected about the 2011 Tohoku earthquake was the coupled co-seismic ruptures of multiple major fault segments, resulting in a M_w9.0-class event.

The estimated rupture plane of the 2011 Tohoku earthquake was 400-500 km long and 100-200 km wide. Rupture planes indicated by Shao *et al.* (2011) and by the Geo-Spatial Information Authority (GSI) of Japan (2011) are illustrated in Figure 1a, covering a wide spatial area from northern Iwate prefecture to southern Ibaraki prefecture. They were derived by focusing on macroscopic features of observed ground deformation and inversion of teleseismic data (i.e. long-period motions). The contour map of the estimated slip distribution indicates a significant amount of permanent ground deformation/slip occurred along the trench line off-shore the Tohoku region, which is responsible for the generation of massive tsunamis. The mainshock also triggered numerous aftershocks; persisting tremors and occasional major aftershocks made evacuees and residents uneasy and disrupted rescue and restoration activities in a post-disaster situation. Figure 1b shows aftershock activities following the mainshock. About 100 aftershocks with magnitudes greater than 6.0 occurred; several major aftershocks aggravated seismic damage to buildings and infrastructure (e.g. M_w7.1 inslab event on 7th April 2011 and M_w6.6 crustal event on 11th April 2011).

The complexity of the rupture process can be seen by inspecting recorded acceleration time-series data at six K-NET stations along the coast (Figure 1c). Although these acceleration time-history data were observed at similar rupture distances (R_{rup}) from the fault plane and similar local site conditions (represented by the average shear wave velocity in the top 30 m V_{S30}), they show very different temporal features as well as frequency content of the acceleration data. For the latter, 5%-damped response spectra of the six ground motions are compared in Figure 1d. For instance, two phases of seismic wave arrivals are present in acceleration data at IWT007, MYG001, and MYG013, while a single phase of seismic wave arrivals with very large amplitudes is featured at IBR003. Large observed ground accelerations are generated from localised strong motion generation areas or asperities along the coast (Kurahashi and Irikura, 2011); such areas within the fault plane are indicated in Figure 1a with grey ellipses. These localised zones are associated with large stress drops (thus radiating strong short-period motions). The proximity to the southernmost asperity led to a single strong phase of seismic wave arrivals at IBR003, whereas more than two localised ruptures contributed to the two-phase arrival of seismic waves at IWT007, MYG001, and MYG013 (note: there are time gaps between the ruptures of the asperities). Figure 1d shows that the dominant frequency content varies significantly, depending on the locations. Generally, they are rich in the short-period range, whereas response spectra at MYG013, FKS001, and FKS011 have rich spectral content in the intermediate-period range (between 0.5 s and 1.5 s). It is also noteworthy that the shape of the response spectra varies significantly among the six stations (e.g. FKS011 versus IBR003), suggesting the importance of capturing local features of the rupture propagation process for improved prediction of ground motion parameters due to a large earthquake.

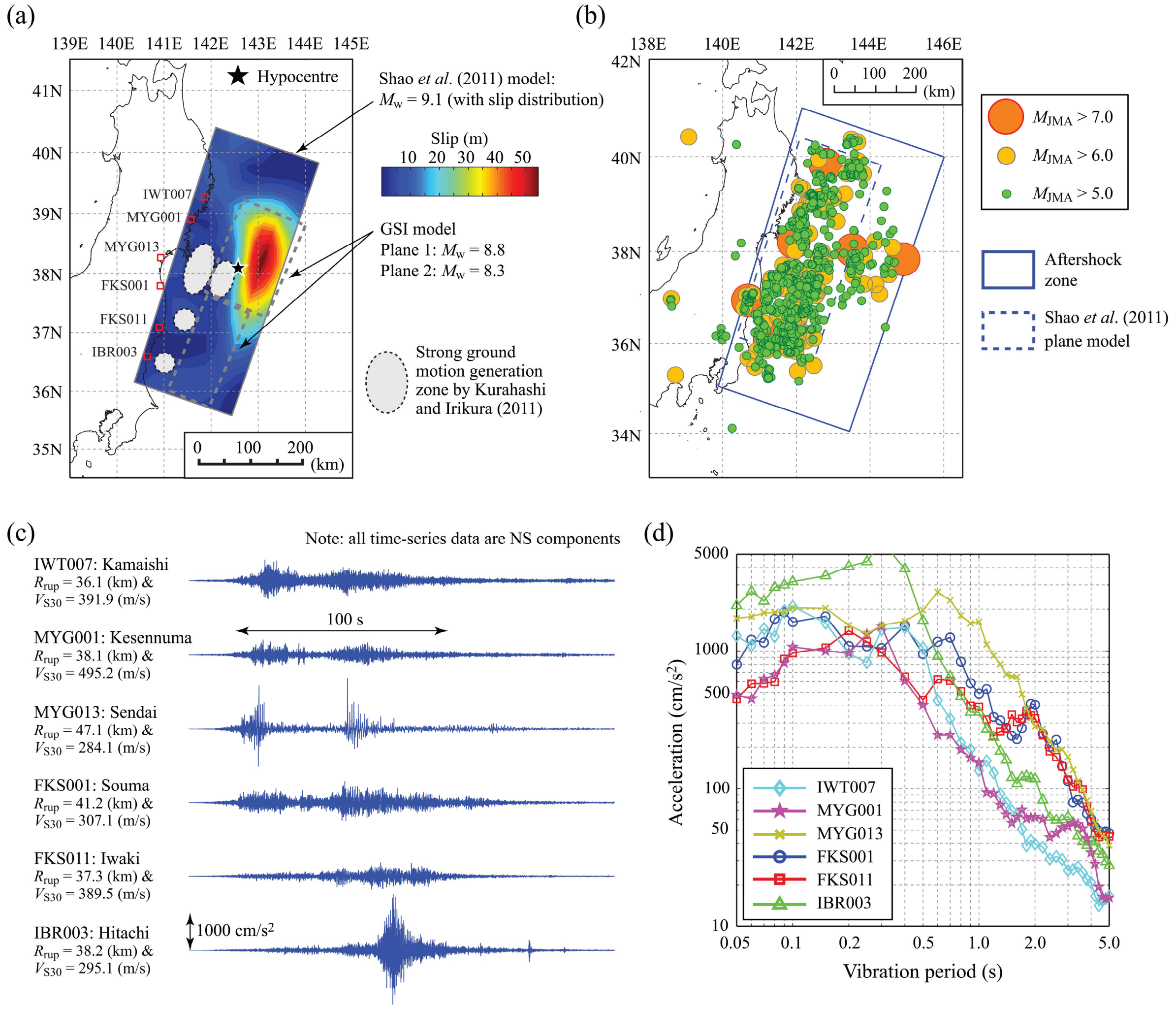

Figure 1. Characteristics of fault rupture and ground motions of the 2011 Tohoku earthquake: (a) fault plane, (b) aftershock activity, (c) acceleration time-history data at six K-NET stations, and (d) 5%-damped response spectra at six K-NET stations.

From a geotechnical viewpoint, the 2011 Tohoku earthquake caused extensive and widespread liquefaction in the Tokyo Bay area (Bhattacharya *et al.*, 2011; Tokimatsu *et al.*, 2011). The liquefied areas were mostly located at reclaimed land with low soil strength. To show typical recorded ground motions in the Tokyo Bay area, recorded acceleration time-series data at four K-NET stations are presented in Figure 2a. The selected stations are at soft soils (V_{S30} less than 200 m/s). The recorded ground motions at the four stations are similar and have the peak ground acceleration (PGA) of about 100-200 cm/s^2, and the duration of strong ground motion part is long (100 s or more). Such site and ground motion characteristics promote the occurrence of significant liquefaction. Moreover, to show the frequency content of the observed ground motion records, 5%-damped response spectra of the four records are shown in Figure 2b. The dominant period of the recorded ground motions at these sites ranges from 0.75 s and 1.25 s, and short-period content of these records is relatively low.

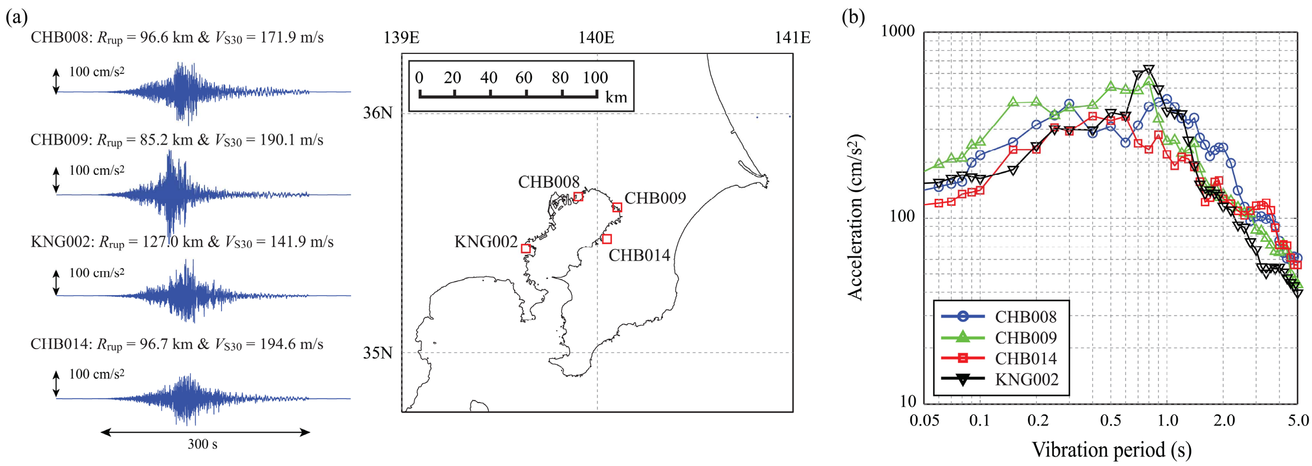

Figure 2. Characteristics of ground motions of the 2011 Tohoku earthquake in the Kanto region: (a) acceleration time-history data at four K-NET stations, and (b) 5%-damped response spectra at four K-NET stations

2.2. Spatial Variation of Ground Motions

The spatial extent of observed ground motions provides valuable information on the locations of significant damage to buildings and infrastructure. By overlaying demographic information as well as building stock information on ground motion information layer, first-hand loss estimation can be carried out. Recorded accelerograms for the 2011 Tohoku mainshock are analysed to evaluate various ground motion measures, such as PGA, response spectra, Arias intensity (Arias, 1970), and cumulative absolute velocity (CAV; EPRI, 1988). Different measures capture different ground motion characteristics. For example, PGA and spectral acceleration (SA) are focused on peak responses. In contrast, Arias intensity and CAV incorporate both large-amplitude and long-duration effects, which are more suitable for assessing liquefaction hazard (Kramer and Mitchell, 2006). The contour maps of PGA, Arias intensity, and CAV for the 2011 Tohoku mainshock are shown in Figure 3. Furthermore, to compare the ground motion measures for other significant earthquakes in the Tohoku region, the same analysis is repeated for the M_w7.1 inslab aftershock on 7th April 2011 and the M_w7.2 Miyagi-Oki interplate earthquake on 16th August 2005. The contour maps for these two earthquakes are also included in Figure 3. More comprehensive results for several other major events can be found in EEFIT (2011). Direct comparison of the contour maps for different measures is facilitated as ground motion measures for different earthquakes are evaluated for the same site. The consideration of both interplate and inslab earthquakes is of particular importance in light of the detailed earthquake source inversion analysis carried out by Kurahashi and Irikura (2011), which indicated that several asperities with high stress drop happened at deeper segments of the fault plane (Figure 1a).

Inspection of the results shown in Figure 3 indicates:

1. For PGA, spatial extent of the ground shaking (red/yellow-coloured areas) for the Tohoku mainshock is much larger than other events, affecting a larger population and building stock. This is important from regional/national earthquake risk management viewpoints, because seismic damage and disruption of lifelines and essential services can happen simultaneously in widespread areas.

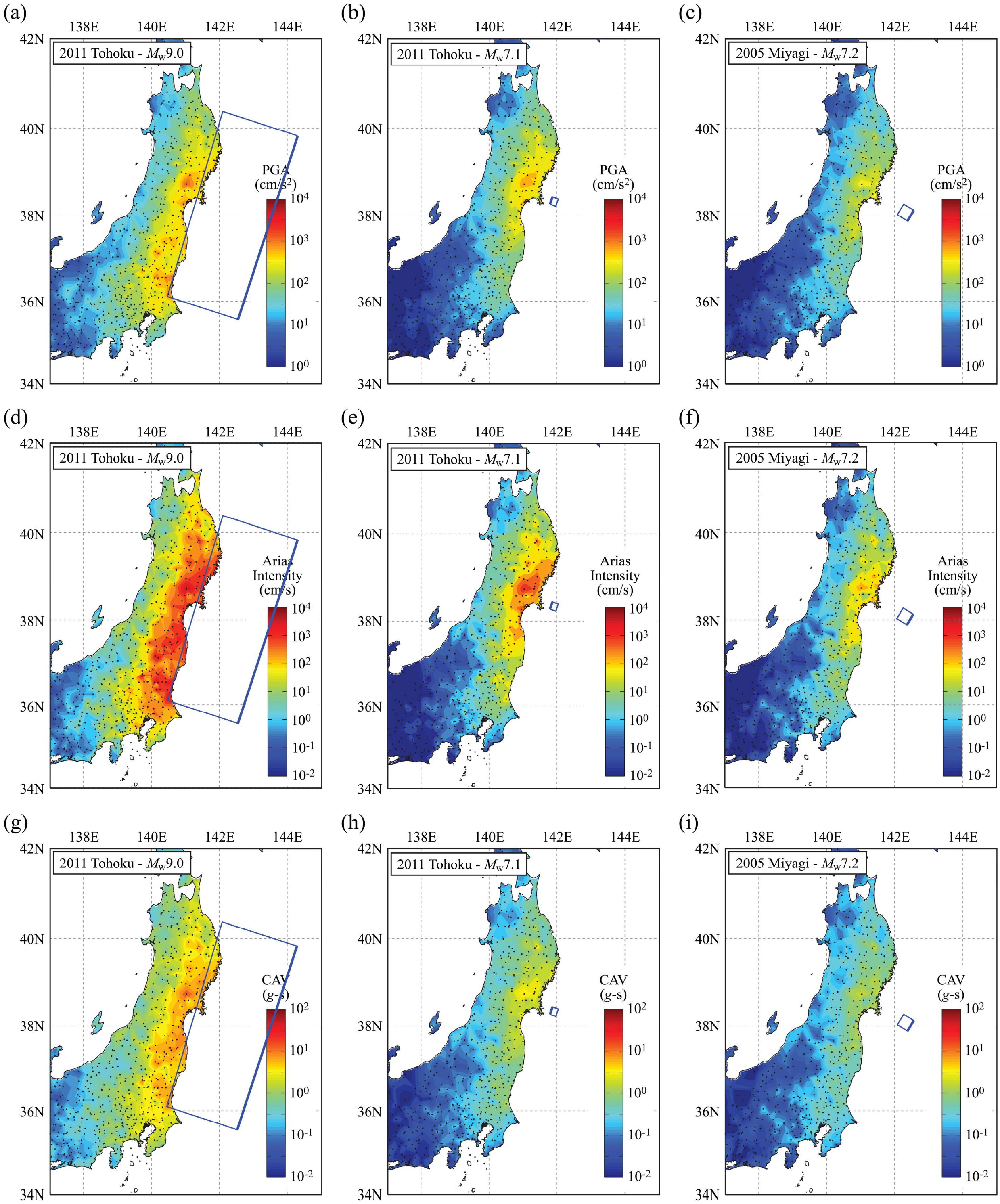

Figure 3. Contour maps of PGA, Arias intensity, and CAV for the 2011 Tohoku mainshock (M_w9.0), the 2011 Tohoku aftershock (M_w7.1), and the 2005 Miyagi-Oki earthquake (M_w7.2): (a-c) PGA contour, (d-f) Arias intensity contour, and (g-i) CAV contour

2. Overall, the Tohoku mainshock did not produce abnormally large PGA values (note: at several sites (e.g. MYG004), very large ground motions were recorded; see Figure 4). This may be explained by noting that peak ground motions are strongly affected by local features and seismic waves generated over a vast rupture area attenuate while travelling the crust. Therefore, a large earthquake size and released energy do not necessarily have significant influence on

peak ground motions, implying that the magnitude scaling effects on peak ground motion parameters are not especially strong for mega-thrust subduction events.

3. The Arias intensity for the Tohoku mainshock is greater than other events. This is due to the long duration of seismic waves, and is particularly noticeable for sites at short distances, where values of Arias intensity reach 2000–4000 cm/s. The magnitude scaling of Arias intensity is more significant than PGA, and this should be reflected in future ground motion prediction equations for Arias intensity.
4. Generally, the above observations for Arias intensity are applicable to CAV. Note that CAV for the Tohoku mainshock reaches 10–15 *g*-s; this seismic intensity level has not been attained in any other events that are considered in this study. The results for Arias intensity and CAV suggest that a mega-thrust subduction earthquake with long duration can be far more destructive than smaller earthquakes.

Lastly, it is insightful to compare time-series data and response spectra of the Tohoku mainshock records, having very large PGA values, with those of significant records from past earthquakes. Figure 4 compares acceleration time-history data and response spectra for three Tohoku ground motions (IBR003, MYG004, and MYG013) with those for the 2004 M_w6.6 Mid-Niigata motions (NIG019 and NIG028) and the 1995 M_w6.9 Kobe earthquake (Takatori). Inspection of Figure 4 suggests that the Tohoku motions have larger PGA values and significantly longer duration, in comparison with those from the Mid-Niigata and Kobe earthquakes. Furthermore, the Tohoku mainshock motions have rich short-period spectral content, while the Mid-Niigata and Kobe motions have rich long-period spectral content. The latter phenomenon is due to near-fault motions (Mavroeidis and Papageorgiou, 2003), where very large velocity pulses with long vibration periods are generated due to forward directivity. The near-fault motions during the Mid-Niigata and Kobe earthquakes caused very destructive effects to structures. The above comparison explains the reason why the Tohoku motions with very large accelerations did not cause much damage/disruption to buildings and infrastructure in the Tohoku region, in comparison with the Mid-Niigata and Kobe ground motions.

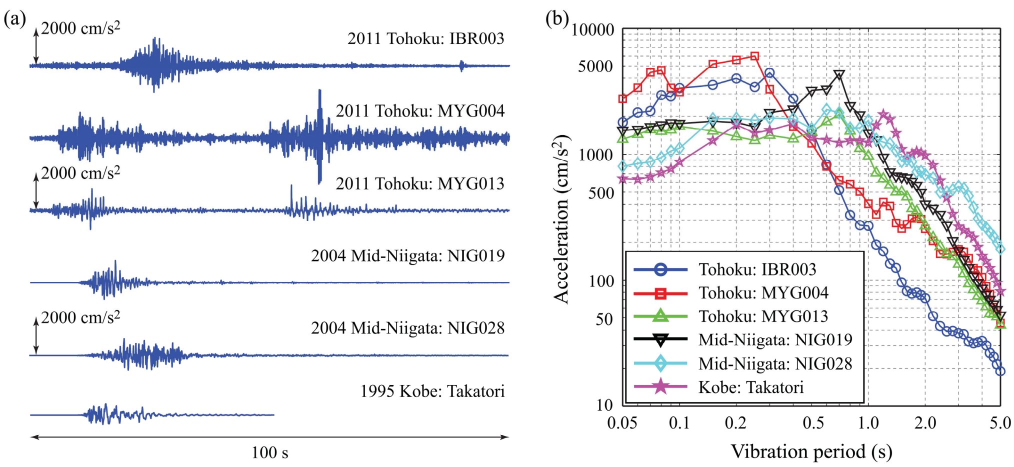

Figure 4. Comparison of acceleration time-history data and response spectra for very significant ground motion records from the 2011 Tohoku earthquake, 2004 Mid-Niigata earthquake, and 1995 Kobe earthquake: (a) acceleration data and (b) 5%-damped response spectra

3. FIELD OBSERVATIONS OF GROUND SHAKING DAMAGE

The Tohoku mainshock and aftershocks caused seismic damage to buildings and infrastructure, including ports, bridges, railways, roads, Sendai airport, electricity grids, power generation plants, water supply/treatment facilities, etc. (AIJ Tohoku, 2011; NILIM and BRI, 2011; EEFIT, 2011). During the EEFIT-Tohoku mission, building damage surveys were conducted in Sendai, Shirakawa, and Sukagawa, where JMA intensity scale of 6+ was experienced. At this ground shaking level, weak structures may be tilted and major building parts may fall, while strong structures may suffer from major cracks in columns/beams/walls. A summary of ground motion parameters observed in Sendai, Shirakawa, and Sukagawa are summarised in Table 1. This section provides a brief summary of field observations for shaking-related damage in these three locations; see EEFIT (2011) for other shaking damage cases.

Table 1. Summary of ground motion parameters in Sendai, Shirakawa, and Sukagawa

Parameters	Sendai (MYG013) NS & EW	Shirakawa (FKS016) NS & EW	Sukagawa (FKS017) NS & EW
Distance (km) & V_{S30} (m/s)	47.1 & 284.1	63.3 & 308.0	56.2 & 265.8
JMA intensity	6+	6+	6+
Arias intensity (cm/s)	1701 & 1128	4094 & 2697	1052 & 1025
CAV (*g*-s)	7.89 & 7.73	12.05 & 10.52	7.27 & 7.04
PGA (cm/s^2)	1329.8 & 799.9	1269.2 & 838.9	658.2 & 490.0
SA at 0.3 s (cm/s^2)	1528.8 & 1312.3	3851.4 & 2398.2	1330.4 & 1253.7
SA at 1.0 s (cm/s^2)	1619.5 & 581.4	528.2 & 288.8	548.5 & 644.6
SA at 3.0 s (cm/s^2)	170.5 & 104.9	77.6 & 54.7	84.5 & 138.6

3.1. Shaking Damage in Sendai

Damage survey was conducted in several districts of Sendai. Shaking damage to buildings and foundation was seen at various locations (e.g. Yamato, Oroshi, Oritate, Taihaku, and Takasago). Typical damage patterns are diagonal cracks on reinforced concrete (RC) wall, scaffolding to mid-/high-rise buildings, roof damage, and falling of cladding materials from wooden houses. Ground shaking observed in Sendai (MYG013; see Figure 1) was intense, containing rich spectral content in the intermediate-period range. This affected many mid-/high-rise buildings in Sendai.

Figure 5 shows three damage cases in Sendai. The first photo is a 2-storey RC office building in Oroshi, which was completely collapsed due to soft storey mechanism. It was constructed in 1969, prior to 1981 when major improvements in seismic provisions were incorporated (Nakashima and Chusilp, 2003). In the surrounding area, several RC buildings were also collapsed or severely damaged. The second photo is a 14-storey residential apartment building, constructed in 1975. This building consists of two structures, connected by expansion joints, and forms L-shape. It suffered from damage during the 1978 Miyagi-Oki earthquake; repairs were done by replacing damaged RC walls with new ones with increased thickness (NILIM and BRI, 2011). During the 2011 Tohoku earthquake, many shear cracks on non-structural walls were observed from ground-floor to upper-floor levels. Furthermore, one of the two structures was tilted by about 2 degrees due to ground settlement (gap between two structures becomes large with height). A common factor for severely damaged structures in this area of Sendai is old RC construction in 1960s and 1970s. In the damaged buildings, several structural deficiencies were noted, such as the use of smooth reinforcement bars and insufficient reinforcement hook length. The third photo in Figure 5 shows a damaged house in Oritate, a hill-side area of Sendai, where several houses were significantly damaged due to slope instability. These houses were relatively new and were built on shallow foundation which displaced significantly due to sliding of surface soil. The affected houses were red-tagged for occupancy. The residential development was built on fill material which is less compacted and is subjected to greater seismic excitation. Houses sited at boundary areas between cut and fill suffered from significant differential strains. To prevent similar slope failure in future large earthquakes, improvements on ground, foundation, and retaining wall are necessary.

Figure 5. Shaking damage in Sendai

Figure 6. Shaking damage in Shirakawa

3.2. Shaking Damage in Shirakawa

Damage survey in Shirakawa was conducted near the Shirakawa City Office, Komine Castle, Shin-Shirakawa train station, and Hanokidaira. Despite the JMA intensity of 6+, major structural damage and collapse were not noticed in downtown Shirakawa during the field survey. Another feature of the shaking damage in Shirakawa is the occurrence of landslides at several locations around Shirakawa. Ground shaking data suggest that the spectral content is particularly rich in the short-vibration period range (reaching 3000-4000 cm/s^2 at 0.1-0.3 s). This might have affected stiff and low-rise structures as well as acceleration-sensitive components/contents significantly.

The first photo in Figure 6 shows the cladding and roof damage to a traditional warehouse near the Shirakawa City Office. Roof damage was seen at several sites near this location. However, there was no clear indication of significant structural damage around this area. Generally, shaking damage in downtown Shirakawa was minor. The second photo shows the collapse of a retaining stone wall at the Komine Castle due to significant out-of-plane force acting on the wall induced by large ground accelerations in Shirakawa (Table 1). In total, the collapse occurred at eight locations, north and south sides of the Castle, noting that ground shaking in the North-South direction was greater than that in the East-West direction. The third photo shows a landslide site in Hanokidaira; 13 people were killed due to this event and several houses at the foot of the slope were destroyed completely. The estimated size of the landslide was about 150 m long and 60 m wide.

3.3. Shaking Damage in Sukagawa

Damage survey in Sukagawa was conducted in the surrounding of the Sukagawa City Office; relatively significant damage occurred in Sukagawa. The damage was concentrated in areas close to the City Office, and this may be partly attributed to soft soil conditions. Overall, major ground shaking damage was noted, and damage to roof, cladding, and traditional warehouse was seen at many places. Although PGA and SAs at short vibration periods in Sukagawa were much smaller than those in Shirakawa, SAs at intermediate and longer vibration periods were greater in Sukagawa (Table 1). Therefore, seismic demand to mid-/high-rise structures in Sukagawa was more intense than that in Shirakawa (note: comparison of shaking damage in Sukagawa and Shirakawa is relevant, because of their geographical proximity).

Figure 7 presents two damage cases in Sukagawa. The first and second photos show the damage condition of the Sukagawa City Office, a 4-storey RC building constructed in 1970 and no seismic upgrading was conducted. Many large diagonal cracks on non-structural walls and shear failures of structural walls/columns were observed. Shear failure of columns occurred at the middle height of the ground floor level. The location of the failure corresponds to the change of (amount of) reinforcement; more reinforcement was placed at joints but less reinforcement was placed in the middle of the column. A similar damage pattern was observed in the 1995 Kobe earthquake. The third photo shows the cladding damage to a traditional warehouse. A simple damage survey was conducted near the City Office; in total, 63 buildings were surveyed; 4 buildings were demolished; 4 buildings were severely damaged; and 11 buildings are partially damaged. These damage survey results are in agreement with quick inspection results in Sukagawa conducted by professional engineers and architects after the 2011 Tohoku earthquake.

Figure 7. Shaking damage in Sukagawa

4. CONCLUSIONS

The mega-thrust earthquake of M_w9.0 along the Japan trench caused tragic loss of many lives and significant damage/disruption to structures and infrastructure, including buildings, foundation and geotechnical structure, highways and railway bridges, road networks, and lifelines. From the ground motion viewpoint, the national strong motion networks in Japan recorded about 1200 high-quality acceleration data. The unique features of the recorded ground motions include: (i) high spectral content in the short vibration period range, (ii) long duration of significant part of ground motions, and (iii) strong effects due to local asperities. The new dataset is an invaluable source of information to further advance the strong ground motion research and provides valuable empirical benchmark on ground motion characteristics of mega-thrust subduction earthquakes.

To gain useful lessons/experiences from this tragic event, shaking-related damage surveys were conducted during the EEFIT-Tohoku mission in Sendai, Shirakawa, and Sukagawa, where JMA intensity of 6+ was recorded there and instrumentally recorded ground motion data were readily available. The field building damage surveys and analysis of observed ground motion data indicate that: (i) many of the damaged/collapsed buildings in Sendai were RC structures, constructed prior to 1981 when a major revision to the Japanese seismic design code was implemented, and (ii) damage to buildings in Sendai and Sukagawa was more severe than that in Shirakawa, which can be explained by inspecting spectral content of the observed ground motions at the three locations. To mitigate shaking damage in future large earthquakes, seismologists and earthquake engineers should incorporate the key lessons from this earthquake.

AKCNOWLEDGEMENT

The EEFIT-Tohoku mission was organised by the Institution of Structural Engineers. This mission was funded by Aon Benfield, Cambridge Architectural Research Ltd., EPSRC grant (EP/I01778X/1), Global Earthquake Model, Institution of Civil Engineers, Sasakawa Foundation, Sellafield Ltd., and Willis Research Network. During the EEFIT mission, generous support was provided by Eri Gavanski, Maki Koyama, Hitomi Murakami, and many other individuals/organizations.

REFERENCES

Architectural Institute of Japan Tohoku Chapter (AIJ-Tohoku) (2011). *Reconnaissance report of the 2011 off the Pacific coast of Tohoku earthquake*. Available at <http://news-sv.aij.or.jp/tohoku/englishportal.html>.

Arias, A. (1970). A measure of earthquake intensity. In: *Seismic Design for Nuclear Power Plants*, MIT Press, Cambridge, MA, 438–483.

Bhattacharya, S., Hyodo, M., Goda, K., Tazoh, T., and Taylor, C.A. (2011). Liquefaction of soil in the Tokyo Bay area from the 2011 Tohoku (Japan) earthquake. *Soil Dynamics and Earthquake Engineering* **31(11)**, 1618–1628.

Earthquake Engineering Field Investigation Team (EEFIT) (2011). *The M_w9.0 Tohoku earthquake and tsunami of 11th March 2011 - a field report by EEFIT*. Institution of Structural Engineers, London, United Kingdom.

Electrical Power Research Institute (EPRI) (1988). *A criterion for determining exceedance of the operating basis earthquake*. *EPRI NP-5930*, Palo Alto, California.

Geo-Spatial Information Authority of Japan (GSI) (2011). *Crustal deformation and fault model obtained from GEONET data analysis*. Available at <http://www.gsi.go.jp/cais/topic110313-index-e.html>.

Kurahashi, S. and Irikura, K. (2011). Source model for generating strong ground motions during the 2011 off the Pacific coast of Tohoku Earthquake. *Earth Planets Space* **63(7)**, 571–576.

Kramer, S.L., and Mitchell, R.A. (2006). Ground motion intensity measures for liquefaction hazard evaluation. *Earthquake Spectra* **22**, 413–438.

Mavroeidis, G.P., and Papageorgiou, A.S. (2003). A mathematical representation of near-fault ground motions. *Bulletin of the Seismological Society of America* **93**, 1099–1131.

Nakashima, M., and Chusilp, P. (2003). A partial view of Japanese post-Kobe seismic design and construction practices. *Earthquake Engineering and Engineering Seismology* **4**, 3–13.

National Institute for Land and Infrastructure Management (NILIM) and Building Research Institute (BRI) (2011). *Quick report of the field survey and research on the 2011 off the Pacific coast of Tohoku earthquake (the Great East Japan earthquake)*. Ministry of Land, Infrastructure, Transport, and Tourism, Tokyo, Japan. Available at <http://www.kenken.go.jp/japanese/contents/topics/20110311/0311quickreport.html>.

Shao, G., Li, X., Ji, C., and Maeda, T. (2011). Focal mechanism and slip history of 2011 M_w9.1 off the Pacific coast of Tohoku earthquake, constrained with teleseismic body and surface waves. *Earth Planets Space* **63(7)**, 559-564.

Tokimatsu, K., Tamura, S., Suzuki, H. and Katsumata, K. (2011). Quick report on geotechnical problems in the 2011 Tohoku Pacific Ocean earthquake. CUEE Research Reports on Earthquake Engineering **118**, 21–47.