# The 2011 Eastern Japan Earthquake: Facts and Reconstruction Recommendations

**H. Kit Miyamoto & Amir S. J. Gilani**
*Miyamoto International, Sacramento, CA, USA*

**Akira Wada**
*Tokyo Institute of Technology, Tokyo Japan*

**SUMMARY**
The magnitude (Mw) 9.0 2011 Sendai Earthquake 9.0 event ids one of the largest earthquakes ever recorded. The earthquake was followed by a large tsunami with waves of up to 30 m inundating an area of 470 km$^2$. This earthquake resulted in over 10,000 fatalities, collapse and damage to over 10,000 buildings, and damage estimated at $US 300B. The water surge topped the tsunami walls, whose design was based on smaller tsunami heights. Following the survey of earthquake and tsunami damage, it was seen that: a) this event covered a large area and for such type of event a more coordinated response is needed; b) ductile detailing used for seismic design also provide protection for tsunami hazard, c) the early earthquake and tsunami warning system saves thousands of lives and this type of approach can be duplicated in other vulnerable parts of the world.

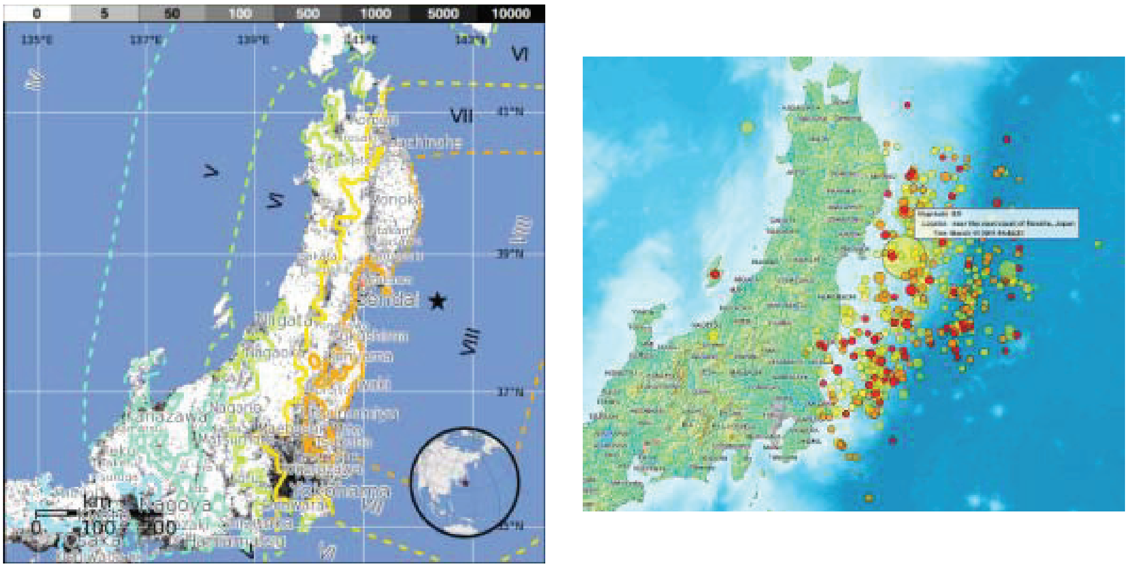
*Keywords: Japan earthquake, damage assessment, Warning system, Tsunami, seismic detailing*

## 1 INTRODUCTION

The magnitude (MW) 9.0 event occurred at 14.46 PM. local time on 11 March 2011, in the western pacific ocean off the coast of Japan. Its epicenter was approximately 130 km from Sendai, Honshu, Japan. As shown in Table 1 (USGS2011) large population of over 2.1 million people was exposed to high earthquake intensity during the event. The main earthquake was preceded by a number of large foreshocks, and hundreds of aftershocks were reported afterwards. The first major foreshock was a 7.2 MW event on 9 March. The main event was followed by hundreds of aftershocks of magnitude 5 or greater. Figure 1 (USGS 2011) presents the intensity and aftershock maps for this event. Japan is one of the world's most earthquake-prone countries, with tremors occurring daily. Major earthquakes and tsunamis have affected this region in 1896 and in 1933. Japan has an extensive array of strong motion sensors. One minute before the earthquake was felt in Tokyo, the Earthquake Early Warning system, which includes more than 1,000 seismometers in Japan, sent out warnings of impending strong shaking. This warning likely prevented further loss of life. The unprocessed strong motion data (see Figure 2 from CGS for example) indicated large accelerations. In the Miyagi Prefecture, approximately 75 km from the epicenter, PGA values as high as 2.7g were recorded in the horizontal direction. The strong motion lasted approximately 90 seconds.

**Table 1.** Population exposure

| City | Population | MMI |
|---|---|---|
| Furukawa | 76k | IX |
| Sendai | 1,038k | VIII |
| Iwaki | 357k | VIII |
| Koriyama | 341k | VIII |
| Hitachi | 186k | VIII |
| Ishinomaki | 117k | VIII |




a. Intensity map

b. Aftershocks

**Figure 1.** Earthquake data (from USGS)

The earthquake was followed by a large tsunami. Waves of up to 29.6 m struck and average 10 meter and some traveled 10 km (6 mi) inland. Smaller waves reached other countries including US and caused damage in excess of several US millions in costal California. The tsunami inundated a total area of approximately 470 km2. An hour after the earthquake the Sendai Airport was flooded with waves sweeping away cars and planes and flooding buildings A 4-m high tsunami hit Iwate Prefecture and Wakabayashi Ward in Sendai was also particularly hard hit Water column height on 11 March 2011 at DART Station, shows the effect of the tsunami (see **Error! Reference source not found.**).

The Japan Meteorological Agency issued a major tsunami warning. The initial estimates indicated the tsunami would have taken 10 to 30 minutes to reach the areas first affected, and then areas further north and south based on the geography of the coastline. This warning allowed hundreds thousands people to escape to higher grounds inland.

The damage by the tsunami was far greater than that of the quake. Some factors contributing to the damage and high death toll were that the large size of the water surge topped the tsunami walls, whose design was based on smaller tsunami heights, and the heights and inland reach of tsunami surprised, many people who thought that they were located on either high enough ground or far away locations inland. The extent of casualties and damage from his event is astonishing; see Table 1 (various news organizations) for data at the time of this report.

**Table 1.**Consequences of the 2011 event (various news organizations)

| Description | Comment |
|---|---|
| Death | 11000+ |
| Missing | 16000+ |
| Injured | 3000+ |
| Building collapse, damage | 120,000+ |
| Transportation (road, bridges,) | Many damaged |
| Lifelines (electricity, water, dams, etc) | Millions without |
| Critical facility | Fukushima Nuclear reactors (I to VI) |
| Total damage | $300B |

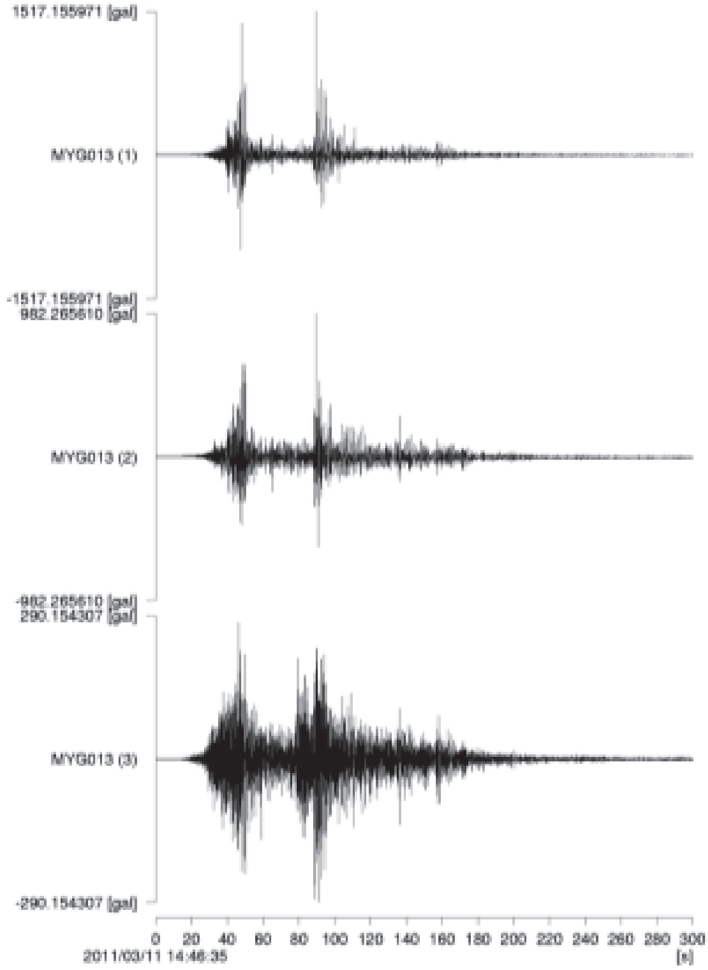



**Figure 2.** Recorded round acceleration (raw data) Station MYG013 in Sendai (CGS)

Shortly after the earthquake, an engineering team from Miyamoto International and Global Risk Miyamoto engineers were on the ground in the affected area, investigating and analyzing the damage, and documenting lessons learned to prevent such catastrophic losses in future earthquakes. The findings on the effects of the earthquake on the people, structures, and the local industry are presented here for various key locations identified in Figure 3.


**Figure 3.** Map of visited sites

## 2 SURVEYED DAMAGE

### 2.1 Arahama

This area experienced tsunami waves of approximately 7 m. the damage was extensive and widespread. Even 5 km from the shore, many houses and structures were destroyed (see Figure 4). Typical Japanese residential housing utilizes wood framing with concrete foundation. This type of construction does not perform well for tsunami surge type of loading. In general the steel and concrete buildings have a much better anchorage to the foundation than the comparable wood construction using silt plates and anchors, which is similar to California construction; see Figure 5. Note in this figure that the superstructure has been washed away.

**Figure 4.** Collapsed houses 10 km from shore

**Figure 5.** Typical wood frame foundation

Many industrial buildings survived the tsunami (see Figure 6). This is partly because these buildings are constructed with steel and concrete and have better foundation anchorage from the super structure. In addition, the industrial buildings have seismic detailing. This seismic detailing provides toughness, system integrity, and strength for both seismic and tsunami surge and impact loading. Steel and concrete buildings performed well. For example, the 4-story concrete school building of Figure 7, located less than 1 km from the ocean, experienced 7-m high waves, and remained undamaged. The damage for the gymnasium structure was due to the water surging in from one side at the bottom floor and bursting from the other side. However, there was no evidence of structural damage. 100% of any building standing had either steel or concrete construction.

Many inlet bridges suffered damage. The bridges parallel to the shore sustained most of the damage being subjected to perpendicular wave forces, while bridges perpendicular to the beach performed better. The tsunami seawall in this area was approximately 2 m tall. The protection for the city is provided by the seawall and row of pine trees planted near the beach.

**Figure 6.** Survived industrial building.

**Figure 7.** Undamaged concrete building

## 2.2 Sendai

Sendai is the capital city of Miyagi Prefecture, Japan, and the largest city in the Tōhoku Region. It has a population of over a million and is a modern city with many new high-rise constructions. Although preliminary reports have indicated large PGAs in this area, there was no evidence of wide spread major earthquake damage; however, some older nonductile concrete buildings experienced damage. There was also no evidence of major liquefaction. However, all commercial buildings were closed (see Figure 8) and residents have to line up for shopping (see Figure 9). There were wide spread shortage of basic food and gas in surround unaffected area, caused by the following factors : a) All eastern ports were damaged, b) Rail system was damaged, c) Tohoku way ( only free way between Tokyo and Tohoku was opened for emergency vehicles only, and d) Over purchase of essentials ( food, gas) by unaffected area such as Tokyo.

The Sendai airport was closed. The facility is located approximately 5-10 km from the ocean and sustained 2-m tall tsunami induced flood. The main structure itself did not sustain much damage; see Figure 10. Many industrial facilities located close to the port were undamaged (see Figure 11). However, financial losses for this sector are large due to business interruptions. The seawall in this area was about 6 m tall; see Figure 12. There was a lot of damage to the wall likely caused by the erosion and landslide as the result of suction as the water goes over the top. There was no damage on the ocean side of the wall; see Figure 13 Note that the dolos stopped at the place where damage to the seawall becomes more pronounced.

**Figure 8.** Closed commercial stores

**Figure 9.** Line for purchasing essential items

**Figure 10.** Sendai airport main building


**Figure 11.** Industrial facility

**Figure 12.** Airport seawall

**Figure 13.** Eroded seawall

## 2.3 Tagajyo

There was major flooding of the main roadway (see Figure 14) and similar shortage of foodstuff and goods similar to Sendai. Transmission towers were damaged; see Figure 15, because the tsunami picked up cars and slammed them to the tower legs.

**Figure 14.** Flooded major roadway

**Figure 15.** Damaged transmission tower

## 2.4 Kesennuma

In this area, almost the entire stock of wood buildings was destroyed in the tsunami affected area but modern concrete structures designed per Japanese seismic code performed well; see Figure 16. Light poles and sign structures experienced bending failure at the base; see Figure 17, due to debris impact.

**Figure 16.** Concrete and wood building,

**Figure 17.** Failed sign structure

The oil container tanks at the bay failed; see Figure 18, oil poured out and ignited, staring a large fire which contributed to destruction. Similarly when the 7-m tall seawall at the Fujikima nuclear power plant was breached, emergency power was lost. A large number of deep ocean ships were washed several km to town; see Figure 19

**Figure 18.** Failed oil tanks

**Figure 19.** Tuna fishing boat washed in town

### 2.5 Minami Sanriku

Many residential (see Figure 20) and industrial buildings (see Figure 21) were destroyed. In this area, almost the entire stock of wood buildings was destroyed in the tsunami affected area but modern concrete structures designed per Japanese seismic code performed well.

The bridge perpendicular to the inlet bay was washed up and only bridge railing and some portion of pier were left behind; see Figure 22. This particular bridge did not seem to have adequate anchorage. Bridges such as the one in the photo near the inlet of narrow bay were subjected to large impact and perpendicular tsunami wave forces. Steel buildings fared well as shown in Figure 23. The moment frames itself were intact and the nonstructural walls were damaged from the force of tsunami.

**Figure 20.** Residential buildings

**Figure 21.** Industrial buildings

**Figure 22.** Destroyed bridge

**Figure 23.** Steel moment frame building

The three-story concrete building shown in Figure 24 did not sustain any damage although located right at the bay. This modern structure was designed and constructed according the current seismic code in Japan. This design provided sufficient strength and ductility for the building to withstand the tsunami forces. This particular building was operational and back in business only one week after the tsunami.

**Figure 24.** Undamaged and operational building

### 2.6 Rikuzen takata

The school building suffered erosion damage at the foundation; see Figure 25. Most of the town 50,000-people was wiped; see Figure 26. Many residential and industrial buildings were destroyed.

**Figure 25.** School building foundation erosion

**Figure 26.** Destroyed wood buildings

The steel truss bridge superstructure over highway 45 was washed about 0.5 km from its original site; see Figure 27. Also note that the concrete pier walls were severely cracked in shear as shown in Figure 28. The river became a focal point of tsunami wave. It increases the tsunami velocity and height substantially. Modern concrete structures; performed well as shown in Figure 29. However, older concrete buildings did not perform well. As seen in Figure 30, this older building did not have confinement steel and used smooth bars and it collapsed.

**Figure 27.** Piers and washed away steel truss

**Figure 28.** Cracked piers

**Figure 29.** Undamaged newer concrete building

**Figure 30.** Damaged older concrete building

## CONCLUSIONS

The 2011 Tohoku Taiheiyo Oki Earthquake caused wide spread significant damage and resulted in more than 11000 deaths. The following observations is made

- Japan has a very extensive and elaborative tsunami warning system. This was communicated via radio, PA, cell, etc and saved hundreds thousands lives. Preparedness and disaster management self-sustainability is critical for post disaster response. It is important for the government agencies and professional organizations to educate the citizens for such events.
- This event differed from the more localized Kobe Earthquake of 1994 and covered over 400 km. A coordinated damage response is required for such a widespread and non-localized event. Limiting Tohoku way to the government authorized emergency vehicles impacted lack of basic necessities in surrounding unaffected area.
- The tall sea walls seem to have slowed down the tsunami velocity in certain areas. However, once water breached them, they were not effective. Emergency and lifeline facilities such as nuclear power plant and gas tanks need to be either relocated to higher grounds or seawalls designed for extreme events be constructed to protect them.
- Seismic detailing such as confinement, system integrity, toughness, and adequate anchorage work well for tsunami loading as well. It is possible to construct tsunami-resistant structures, cost effectively. Multi story steel and concrete frame buildings that have a mechanism for water travel are good candidates.

It is important to note that the observations in Japan were not unexpected. Buildings were designed per code and performed as expected, tsunami warnings were provided and people evacuated, and sea walls up to the design event were constructed. Nonetheless, there was wide spread devastation and loss of life. As a minimum, it is important for professionals, government agencies, and practitioners to educate the public and stakeholders to be aware of such inherent limitation of code design and provide options for more robust design that provide more sustainable structures for disaster resilient communities.

## ACKNOWLEDGEMENTS
The authors acknowledge people in Tohoku disaster area. Despite losing everything, they were determined to have their lives back.

## REFERENCES

U.S. Geological Survey (USGS), 2011.