Proceedings of the International Symposium on Engineering Lessons Learned from
the 2011 Great East Japan Earthquake, March 1-4, 2012, Tokyo, Japan

TSUNAMI DAMAGE IN PORTS BY THE 2011 OFF PACIFIC COAST OF TOHOKU EARTHQUAKE

Takashi TOMITA[1] and Gyeong-Seon YOEM[2]

[1] Research Director, Asia-Pacific Center for Coastal Disaster Research, Port and Airport Research Institute, Yokosuka, Japan, tomita@pari.go.jp
[2] Researcher, Asia-Pacific Center for Coastal Disaster Research, Port and Airport Research Institute, Yokosuka, Japan, yon-g@pari.go.jp

ABSTRACT: The tsunami generated by the 2011 off Pacific Coast of Tohoku Earthquake caused devastated damage in wide areas by not only inundation but also tsunami^-debris. We cannot control generation of earthquake even with state-of-arts technologies. However, we can surely mitigate possible disasters with adequate human responses. To fear tsunamis appropriately and to prepare adequate measure with local characteristics are important to preparing possible tsunamis/

Key Words: Great East Japan Earthquake, tsunami, port, inundation, destruction, debris, estimation, disaster mitigation, disaster prevention

INTRODUCTION

Japan has many experiences of tsunami disasters such as the 1896 Meiji Sanriku tsunami that caused 22,000 dead and missing. Even after improvement of coastal defense systems which have been significantly implemented since the 1960s, the 1983 Nihon-kai Chubu earthquake tsunami (the Japan Sea tsunami) killed 100 persons, and 1993 Hokkaido Nansei-oki earthquake tsunami (the Okushiri tsunami) caused 230 dead and missing including casualties by the seismic damage. In the case of Okushiri tsunami, many residents in Okushiri Island escaped to hills soon after the earthquake shock and saved their lives, because the residents had a disaster experience of the 1983 Japan Sea tsunami which hit and inundated the southern part of the island and caused two missing persons. However, the Okushiri tsunami came several minutes after the earthquake: for example, tsunami arrived the northern part of the island 5 minutes or less because it was near the epicenter. Some residents, therefore, did not have enough time for evacuation. In the 2003 Tokachi-oki earthquake tsunami, two anglers were missing in the mouth of a river. Since the 2003 tsunami tsunamis have caused no dead or missing in Japan. However, the 2011 Off the Pacific Coast of Tohoku Earthquake generated a higher tsunami (the 3.11 tsunami) than the tsunami level determined for tsunami disaster management in communities such as the 1896 Meiji Sanriku tsunami. As the result, the number of dead and missing reached about 20,000 people.

The 2011 Off the Pacific Coast of Tohoku Earthquake occurred in the subduction zone where the Pacific plate subducts beneath the North American plate or the Okhotsk plate. The magnitude of earthquake was Mw 9.0. The earthquake-induced tsunami was high and caused devastating disasters along the coast in the Tohoku and Kanto regions. According to the National Police Agency (NPA), as of 30 December 2011, the confirmed death was 15,844 persons and the missing was 3,451, the number of completely-damaged houses was 127,185. Further, 84,537 people were in 1,328 refuges as of 13 June 2011, according to NPA. The Fishery Agency reported 25,008 fishing boats were damaged.

TSUNAMI HEIGHT

Offshore Tsunami

Buoys with a GPS sensor off the coast in the Tohoku region successfully measured the tsunami propagating to Japan in the Pacific Ocean. Figure 1 indicates a profile of the 3.11 tsunami measured off the Port of Kamaishi with a GPS-installed buoy. Even in the water of 204 m deep, the maximum tsunami of 6.5 m high was measured, which appeared in the first tsunami wave. This high tsunami in the offshore region is furthermore enlarged due to wave transformation in shallower water depth.

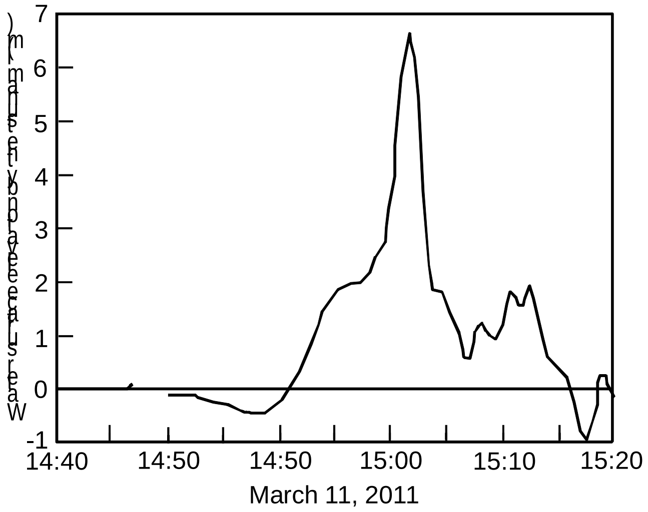

Fig. 1 Tsunami profile measured with a GPS-installed buoy off the Port of Kamaishi (Kawai et al., 2011)

Tsunami Trace Height

Many teams have conducted field surveys to measure heights of tsunami trace and understand tsunami damage. The tsunami inundation and runup heights have been measured at more than 5,000 points and are summarized in a web page of the 2011 Tohoku Earthquake Tsunami Joint Survey Group (http://www.coastal.jp/ttjt/). Figure 2 indicates tsunami trace heights measured by teams dispatched to damaged major ports by the Port and Airport Research Institute of Japan. In the figure, (I) and (R) indicate inundation height and runup height, respectively. These values are height above the estimated tide level at the time of tsunami arrival. Records of the historical tsunamis (Watanabe, 1998) are also indicated in the figure.

In the Sanriku coast from Kuji to Kesen-numa, which is formed by a series of inlets, tsunami inundation and runup heights were greater than those of Hachinohe and the southern part from Ishinomaki which lie on plains. The maximum inundation and runup heights in damaged areas so far were broken by the 3.11 tsunami. The maximum runup height among the measurements of the 2011 Tohoku Earthquake Tsunami Joint Survey Group is about 40.0 m in Ofunato city. Even in Ishinomaki and Sendai where the tsunami records were 5 m or less, the inundation height by the 3.11 tsunami was more than 10 m.

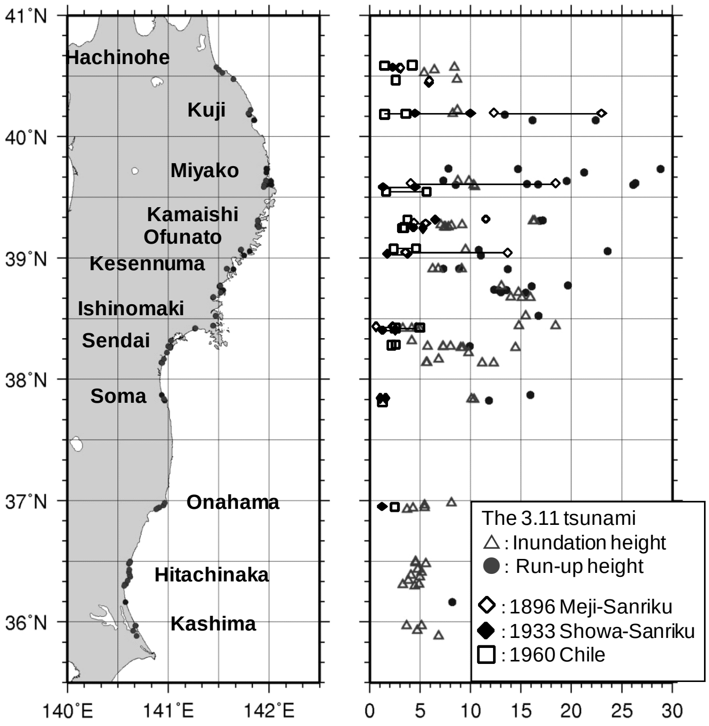

Fig. 2 Heights of tsunami trace measured in major ports

TSUNAMI DAMAGE

In the Port of Hachinohe, inundation heights are 5.4 to 6.4 m (2.5 to 2.9 m in the inundation depth above the ground surface) at points behind breakwaters. On the contrary, they are 8.3 to 8.4 m at the points directly facing the Pacific Ocean. The difference of the inundation heights indicates an effect of breakwater to reduce tsunami. Boats were moved and landed by tsunami action, as shown in Fig. 3, because the inundation depth is deeper than draft of the boats. Boats and ships with deeper draft were not able to be landed but moved on the sea surface in the port, following the tsunami flow.

Even in the outside of the protected area by the breakwater, inundation height of 6.0 m was measured behind a coastal green belt consisting of pine trees. The green belt also mitigated tsunami flooding and further caught boats to prevent them from hitting houses as shown in Fig. 4.

Fig. 3 Boats landed on a wharf in Port of Hachinohe

Fig. 4 Boats caught by a coastal green belt in Hachinohe

Among the North Hattaro Breakwater of 3,504 m long, caissons of total 1,437 m long were moved and submerged, as shown in Fig. 5. In the figure many caissons are moved and submerged, and parts of wave-absorbing blocks installed in front of caissons can be seen above the sea surface. Figure 6 shows the tsunami overtopping the breakwater. According to the depth survey around the breakwaters after the event, parts of mound of the breakwater were scoured. Therefore, the breakwater may be damaged by not only the tsunami forces induced by difference of the water surface level in the front-side of the breakwater from that of rear side but also lack of stability of caisson induced by foundation failure due to the overtopping tsunami.

Significant seabed scours were also measured around a corner of a reclaimed island in the port as well as opening sections of breakwaters. The scoured depth there was about 11 m.

Fig. 5 Breakwater damaged in the Port of Hachinohe

Fig. 6 Tsunami overtopping a breakwater (Courtesy of Tohoku Grain Terminal Co. Ltd.)

In the Port of Kuji the tsunami overtopped a line of tide protection wall of 3.6 m high, and flooded residential area with inundation depth of 4.4 m. Furthermore, the tsunami push oil tanks over sideways as shown in Fig. 7. The depth of water mark on the upright standing tank, which is at the center of the figure, indicates inundation depth of 4.4 m. In another city of Kesen-numa, 21 oil tanks were also damaged, floated and moved by the tsunami. The estimated amount of oil leaking from the damaged tank was 12,810 m^3, according to a report of City of Kesen-numa. The oil was one of causes of fire in the city.

Fig. 7 Oil tanks damaged in the Port of Kuji

In the Port of Kamaishi, the tsunami inundation heights were 7.0 and 8.1 m (5.7 m and 3.5 m in inundation depth respectively) near coasts. The deep tsunami on land floated and crushed wooden houses, as shown in Fig. 8, which was a scene of the video taken by the Kamaishi Port Office of MLIT. Reinforced concrete (RC) buildings and large-scale grain silos were also damaged but not collapsed. Many vehicles together with debris from the destroyed houses filled roads, as shown in Fig. 9.

Fig. 8 Destruction of houses in Kamaishi

Fig. 9 Tsunami debris in Kamaishi

An offshore breakwater installed in the mouth of the Kamaishi Bay, which protected residential and industrial area in the bay together with seawalls along costal lines against the tsunami whose height was the same as the 1896 Meiji Sanriku tsunami, was damaged by the tsunami as shown in Fig. 10. Caissons were moved and submerged by horizontal force caused by the difference of the water surface levels in the front-side of the breakwater from that of the rear side (Takahashi et al., 2011). Photo analysis indicates that the water surface rose up to T. P. +11.8 m at least and overtopped the breakwater whose crown height was T. P. +5 m, in which T. P. is the datum of altitude in Japan.

Fig. 10 North offshore breakwater damaged in the Port of Kamaishi

Fig. 11 Tsunami overtopping the north offshore breakwater in the Port of Kamaishi
(Photo courtesy of Japan Coast Guard)

Tsunami inundation heights were almost same in the Miyako bay, as shown in Fig. 12. The tsunami of 10 m high overtopped a protection dike along the coast and inundated residential areas as shown in Fig. 12. Boats were landed on wharfs in the Port of Miyako. Logs and vehicles were also floated and impacted houses, as shown in Fig. 13.

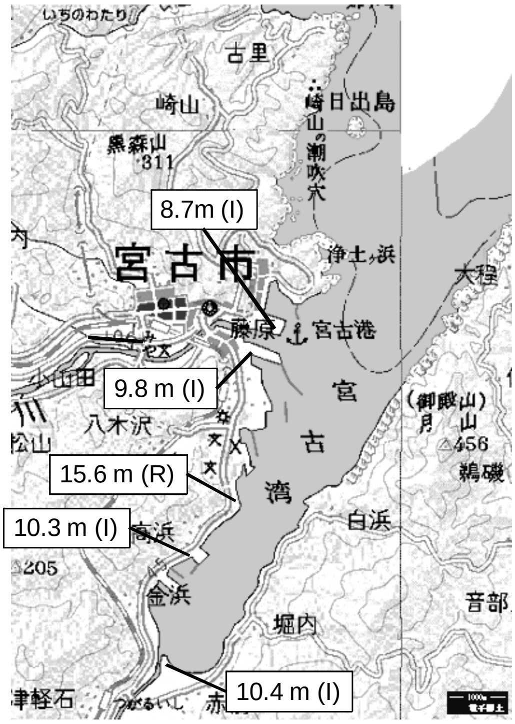

Fig. 12 Tsunami heights in Miyako Bay

Fig. 13 Destruction of residential area behind a protection dike

Fig. 14 Debris impact

Tsunami debris is not only vessels, automobiles, oil tanks, logs but also shipping containers. In the Port of Sendai-Shiogama, many containers were scattered by the action of tsunami, as shown in Fig. 15. In the Port of Hachinohe, about 700 containers were also floated and moved, as shown in Fig. 16.

Fig. 15 Scattered containers in the Port of Sendai-Shiogama

Fig. 14 Floated containers in the Port of Hachinohe (Courtesy of Tohoku Grain Terminal, Co. Ltd.)

NUMERICAL SIMULATIONS ON THE TSUNAMI IN KAMAISHI

The tsunami propagation and inundation is calculated with the model of STOC (Tomita et al., 2007) with the eighth nested grid system in which the smallest grid size of 12.5 m is allocated in the Port of Kamaishi. The tsunami source is basically estimated with the fault model proposed by Fujii et al. (2011), but the fault dislocation is 1.5 times original amount so as to fit the calculated first peak of the tsunami to the the measured one offshore the coast of Kamaishi with a GPS-mounted buoy, as shown in Fig. 15.

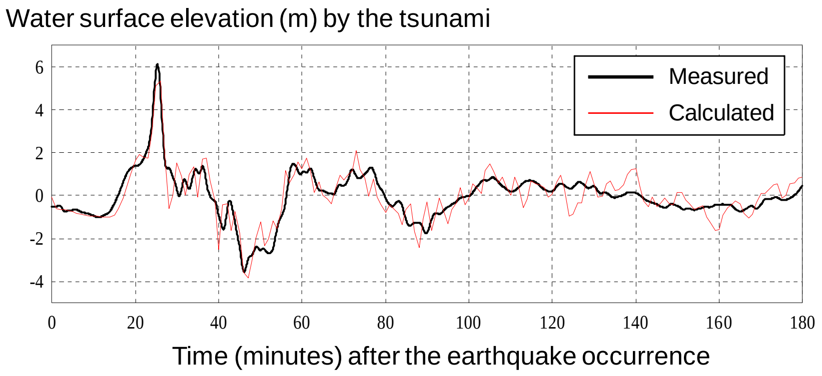

Fig. 15 Comparison of the calculated tsunami to the observed one offshore the coast of Kamaishi

Figure 16 indicates the distribution of the maximum inundation height in the case of no-damaged breakwater. The values in the figure indicate the measured inundation depth in the field survey and the calculated one at the same points. In this case, the function of breakwater to reduce the tsunami is slightly strong in the calculation. On the contrary, in the case of breakwater damaged initially, the tsunami reduction due to the breakwater is smaller than actual reduction, as shown in Fig. 17, because the calculated inundation heights are greater than the measured. Therefore, the breakwater may be functional until around the time of the first and largest peak of the tsunami hitting. In the case of no breakwaters showed in Fig. 18, the inundation depth is greater than that of case with the breakwater. Especially, at the point with the measured inundation depth of 8.1 m, residents escaped a three-stories building. If there are no breakwaters, the tsunami surely overtops the building and the escaping people may be exposed to danger to lose their lives.

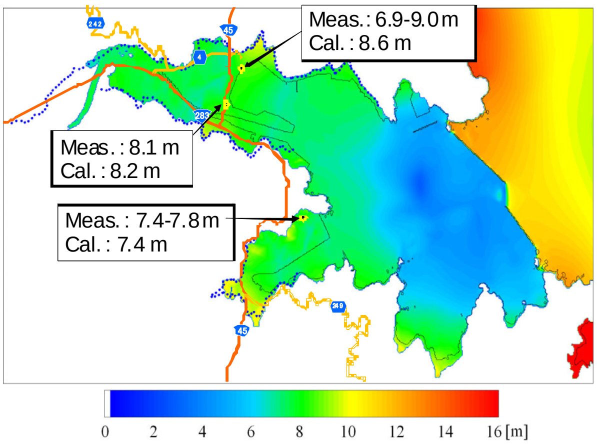

Fig. 16 Distribution of the calculated maximum inundation height in the case of no-damaged breakwaters

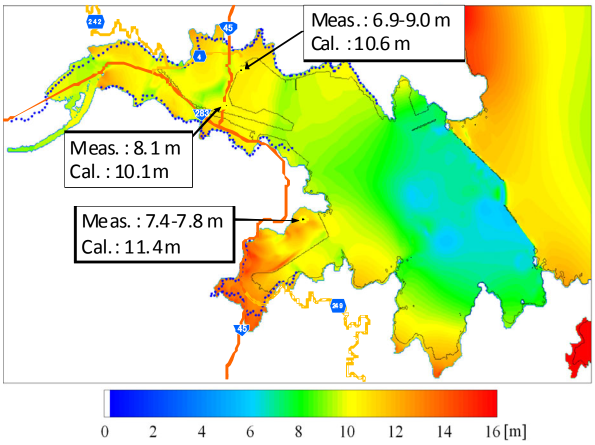

Fig. 17 Distribution of the calculated maximum inundation height in the case of the breakwater damaged before the tsunami attack

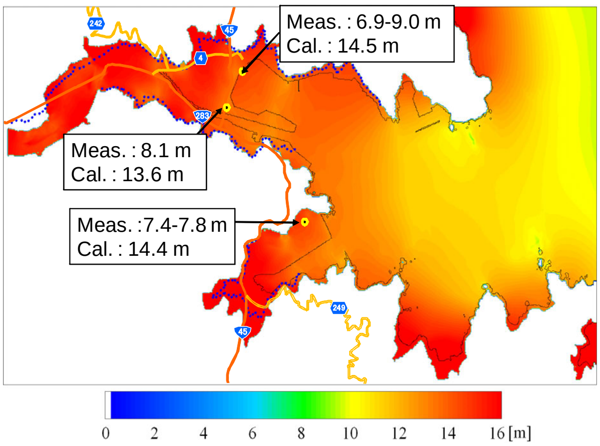

Fig. 18 Distribution of the calculated maximum inundation height in the case of no breakwaters

LESSONS LEARNT FROM THE MARCH 11 TSUNAMI

From the devastating and cruel tsunami disaster on March 11, 2011, the following three concepts are pointed out to prepare possible tsunamis.

The first is to fear possible earthquakes and tsunamis appropriately. At the event of the 3.11 tsunami, inundation was reduced behind areas of infrastructures such as breakwaters, seawalls and highly-mounted roads. On the contrast, the large tsunami overtopping or breaking such an infrastructure caused deadly inundation. Thus, we should predict possible earthquakes and tsunamis with various sciences and technologies. At least, we should understand the maximum level to attain no casualties. A useful way to find out the maximum level of tsunami is investigation of paleo-tsunamis with tsunami descriptions in archives and tsunami depositions under the ground. This level may be inconformity with the design level of infrastructures such as a seawall.

After the estimation of possible tsunamis, to image its-induced damage in an objective area is important to fear the tsunamis appropriately. To enhance images of tsunami damage, physical and mathematical simulations are available as well as experiences of the past disasters. These tools provide virtual reality experiences that we undergo in a virtual field. Base on such an image, to mitigate tsunami disasters with no causalities, we can adequately integrate structural measures like a seawall and non-structural measures like an evacuation plan.

The second is risk communication. It is essential that all stakeholders at levels of the nation, region, province, municipality and resident share correct knowledge and damage image. The disaster risk will be fully able to be reduced if many related persons correctly understand disaster risk and its management measures.

The third is to live with the sea. A tsunami is a hazard originated in the sea. However, people have lived with the sea and received many benefits from the sea such as fishery, marine traffic and rich coastal environment. We cannot live without the sea. Thus, some people have to have their activities near the sea to continue our livelihoods. To save their lives, we should develop the way to mitigate tsunami disasters taking the living with the sea into consideration.

CONCLUSIONS

Tsunami-resilient communities and people should be built through integration of town/city planning, public education including evacuation drill, tsunami disaster mitigation structures, warning system and evacuation system including arrangement of emergency shelters. Regarding tsunami reduction structures such as breakwaters and seawall, they should have a function that prevents lives and properties from being lost by a certain level of tsunami or lower. Even for the maximum level of tsunami, systems and measures should be enhanced and developed to attain no casualties and to make its-induced damage be as little as possible. We should also have systems and measures to restore and rehabilitate damage easily if the damage occurs. To implement them, it is important to estimate possible tsunamis and their-induced damage, and share knowledge and damage image among stakeholders in all levels.

Finally, I would like to express my deepest sympathy to victims of the 2011 Great East Japan Earthquake

REFERENCES

Kawai, H, Satoh, M., Kawaguchi, K. and Seki, K. (2011). *"The 2011 off the Pacific Coast of Tohoku Earthquake Tsunami Observed by GPS Buoys." Journal of Japan Society of Civil Engineers, Ser. B2 (Coastal Engineering*, Vol. 67, No. 2, I_1291-I_1295 (in Japanses).

Takahashi S. et al. (2011). *"Urgent Survey for 2011 Great East Japan Earthquake and Tsunami Disaster in Ports and Coasts." Technical Note of PARI*, No. 1231.

Tomita, T., Honda, K. and Kakinuma, T. (2007). *"Application of three-dimensional tsunami simulator to estimation of tsunami behavior around structures," Proceedings of 30th International Conference on Coastal Engineering*, ASCE, 1677-1688.

Watanabe, H. (1998). *"List of Damaging Japanese tsunami (2nd edition)."* Tokyo University Publishing (in Japanese).