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DAMAGE DUE TO THE 2011 TOHOKU EARTHQUAKE TSUNAMI AND ITS LESSONS FOR FUTURE MITIGATION

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ABSTRACT: The Tohoku region in Japan was hit by a gigantic earthquake of M=9.0 subsequently followed by a huge tsunami which occurred off the Pacific ocean. Both of them have caused huge damage on the eastern coast of Japan, having a huge inundation area more than 500km^2 with the attack of destructive wave forces. There are several issues why this tragedy occurred, and what unrecognized factors contributed to the high vulnerability of the area, and how the risk at each region in the future earthquake and tsunami.

Key Words: Heisei Tohoku earthquake and tsunami, historical tsunamis, damage due to a tsunami, mitigation

INTRODUCTION

The 11 March 2011 Heisei Tohoku earthquake tsunami disaster devastated the Pacific coast of northeastern part of Japan, Sanriku, Miyagi, Fukushima and Ibaragi, where the earthquake followed by tsunamis have took place in the past. The magnitude of the 2011 Tohoku earthquake was estimated to be 9.0 or 9.1 and occurring at N38.1, E142.9 with a magnitude of 9.0 and a depth of 24 km (JMA, 2011), which is the largest in our Japanese history. The earthquake was ranked as the fourth largest in the world following the 1960 Chile (M9.5), 2004 Sumatra (M9.3) and 1964 Alaska (M9.2) earthquakes. The earthquake had a long period (about three minutes with the largest slip found to be approximately 30 m) (USGS, 2011). The maximum recorded earthquake intensity was 7, the maximum level on the Japanese scale (JMA, 2011). The earthquake early warning system was issued 8 seconds after the detection of a first P-wave. A tsunami warning was issued 3 minutes after the earthquake and revised several times after getting real time seismic and tsunami data. The after shocks in the source region off the Pacific region have still continued to happen around the earthquake source. The devastating tsunami with a maximum height of 39 m (The 2011 Tohoku Earthquake Tsunami

Joint Survey Group, 2011). The large number of casualties more than 19,500, which is the worst in Japan after World War II, and several types of tsunami impact such as inundation in a large area more than 500km^2, destructive force damaging houses, buildings, infrastructures, road, and railways, and change of topography due to the erosion and deposition are also reported to be severe.

THE REGION AND TSUNAMIS IN THE PAST

Along the Sanriku coast, there are many picturesque gulfs and capes with a saw-toothed coastal line which contributs to the local amplification of the tsunami, with heights exceeding 10 m. The Sanriku coast has been attacked by a series of tsunamis since the first historical record in 869 (M~8.6), 1611 (M~8.1), 1896 (M~8.5) and 1933 (M~8.1), as shown in Table 1. In the 1896 Meiji-Sanriku Tsunami, it is known that the tsunami ran up to the height of 38.2 m, killing more than 22,000 people. Before the 2011 event, a possible Miyagi-oki earthquake with magnitude ranging from 7.5 to 8.0 had been estimated as 99% within 30 years, the highest earthquake risk in Japan. Along this coast, tsunami countermeasures have been extensively explored and built. On the other hand, the Sendai plain had been considered to be low tsunami risk compared to those at Sanriku coast. For instance, the 1933 Showa-Sanriku tsunami caused maximum runup of 28 m, but only 3.9 m in Yamamoto. The 38.2m maximum runup height from the 1896 tsunami was recorded in Ofunato, but less than 5 m was recorded in Sendai (Sawai et al., 2008). As a result of focusing on a 7.5-8 Miyagi-oki earthquake, tsunami countermeasures in the Miyagi prefecture were not sufficient for the 2011 M=9.0 Tohoku tsunami.

Table 1 Historical and major tsunamis in the Sanriku area and their resulting damage

Date	Name	Magnitude	Damage
9 Jul 869	Jogan tsunami	8.3-8.6	More than 1,000 deaths
2 Dec 1611	Keicho Sanriku	8.1	More than 5,000 deaths
15 Jun 1896	Meiji Sanriku	8.5	21,959 deaths and > 10,000 houses destroyed
3 Mar 1933	Showa Sanriku	8.1	3,064 deaths and 1,810 houses destroyed
11 Mar 2011	Heisei Tohoku	9.0	19,295 deaths and 359,073 houses destroyed

Sendai as example of effected area is a castle town controlled by the powerful feudal lord Date Masamune who built and constructed Sendai Castle (Aoba Castle) in 1601. Because of considerations for the castle's defense, Masamune selected to location of his fortifications on Mount Aoba, 100 meters above the town below. In 1611 Keicho, the Sendai Castle was damaged by the earthquake followed by the tsunami. According to the chronology of the collapse of the stone walls of the Sendai castle is recorded six times throughout the Edo period (1611, 1646, 1668, 1717, 1835 and 1855). Moreover, there were some events that damage to the castle town was recorded in 1731, 1736, 1793 and 1861. There was a record of somewhat large damage in 1897 and small damage in 1896 and 1900. After In the aftermath of the 2011 Tohoku earthquake, the 869 Jogan and 1611 Keicho earthquakes, which have had been known regarded as the largest historical event that caused a large-scale tsunami in Northeast Japan, which has attracted more attention from researchers and the public [Normile, 2011]. One historical document and another twenty-five 25 traditions of the Jogan tsunami have been found on the coasts of Miyagi, Fukushima and Ibaraki prefectures [Watanabe, 2001]. The Distributions of the historical records are comparable to the area devastated by the 2011 tsunami. The occurrence of and damages by the Jogan earthquake tsunami is known from the historical document, named known a s called Nihon-Sandai-Jitsuroku, which was compiled by the ancient Japanese government. According to the document, the Jogan tsunami flooded the coastal plain of Sendai extensively and drowned over 1,000 people. Most of the traditions describe earthquake- or tsunami-associated episodes, such as situation at the time of tsunami attack, and the provenance of particular places locations that can could be correlated with the tsunami. No historical information is known so far that can quantify the height of or the inundation area by due to the Jogan and Keicho tsunamis.

FIELD SURVEY OF THE TSUNAMI

The 2011 Tohoku Earthquake Tsunami Joint Survey Group was conducted to measure the tsunami traces along the shore and inland, which are essential to estimate the tsunami magnitude and to discuss the mechanism and the reasons why the devastating damaged have been occurred. The field surveys as well as satellite image analysis with ground truth data are managed to obtain the data of the tsunami and its disaster, and identify extent of tsunami inundation and land use change.

The Inundation area of the 2011 tsunami was initially estimated preliminary by the Geospatial Information Agency, based on satellite imagery and aerial photographs (available from the Geospatial Information Authority of Japan, http://www.gsi.go.jp/common/000060133.pdf). We conducted a field survey to determine inundation limits and to measure tsunami heights in the Sendai Plain. The post-tsunami field survey was carried out from the middle of March 2011 to the beginning of April, 2011. The survey was planned as a part of the Joint survey, and the measurement data is have been integrated into a single result (available from the 2011 Tohoku Earthquake Tsunami Joint Survey Group, http://www.coastal.jp/tsunami2011/). Because there are was almost no rainfalls and less little progress of in land -clearing work during the survey period, traces of the tsunami height inundation and heights were clearly recognized in the field.

Figure 1 shows the distribution of tsunami runup heights measured along the coast are ranging the 7-15 m in Sendai and Fukushima with the simple beach geometry and the 10-30 m in Sanriku with the complex one of a coast. Maximum run-up heights of up to 39 meters m were reported from the Sanriku region, where the saw-toothed coast is characterized by narrow V-shaped bays and steep coastal geomorphology. Tsunami heights near the coastlines of the flat coastal plains facing to Sendai Bay reached around or more than approximately 10 m, and run-up distances (i.e., inundation area) in these coastal lowlands extended more than 4 kilometers km. In our survey, we also observed that inland heights of March 11, the 2011 tsunami was almost same or 1.5 as large as those of the 1896 Great Meiji tsunami. It could be mentioned that the tsunami death toll of 11 March 2011 tsunami is lower in relative terms compared to the population size. Hence tsunami protection and mitigation measures and public education could be effective in reducing loss of life, which should be discussed more detail in later with the available data.

The period of waves in the 2011 Tohoku Tsunami can be estimated at about 60 minutes by using a size of a tsunami source and its water depth. As the tsunami waves shoaled in shallow, combined with reflected waves on the coast and breakwater and soliton fissions at the shallow water region, components of short wave period could be generated. Tsunami waves propagated through narrow and long bays and focused energy amplified the wave in the shallower regions in front of settlements at the bottom of bays. The waves overtopped tsunami walls, caused massive damage by very strong currents in inundation zone and runup along the rivers as well. The tsunami inundated up to 5 km distance in Sendai plain. The in-situ tsunami surveys revealed that the tsunami flow was reached to supercritical conditions in most of the areas and therefore caused significant damage.

The photo, videos and witness to record and report the tsunami attacking the coastal area, which should be compiled to know its feature. Although the observation system of tsunami were heavily damaged along the coast, some available data recorded by the tidal gages, GPS buoy one, and deep sea pressure sensors.

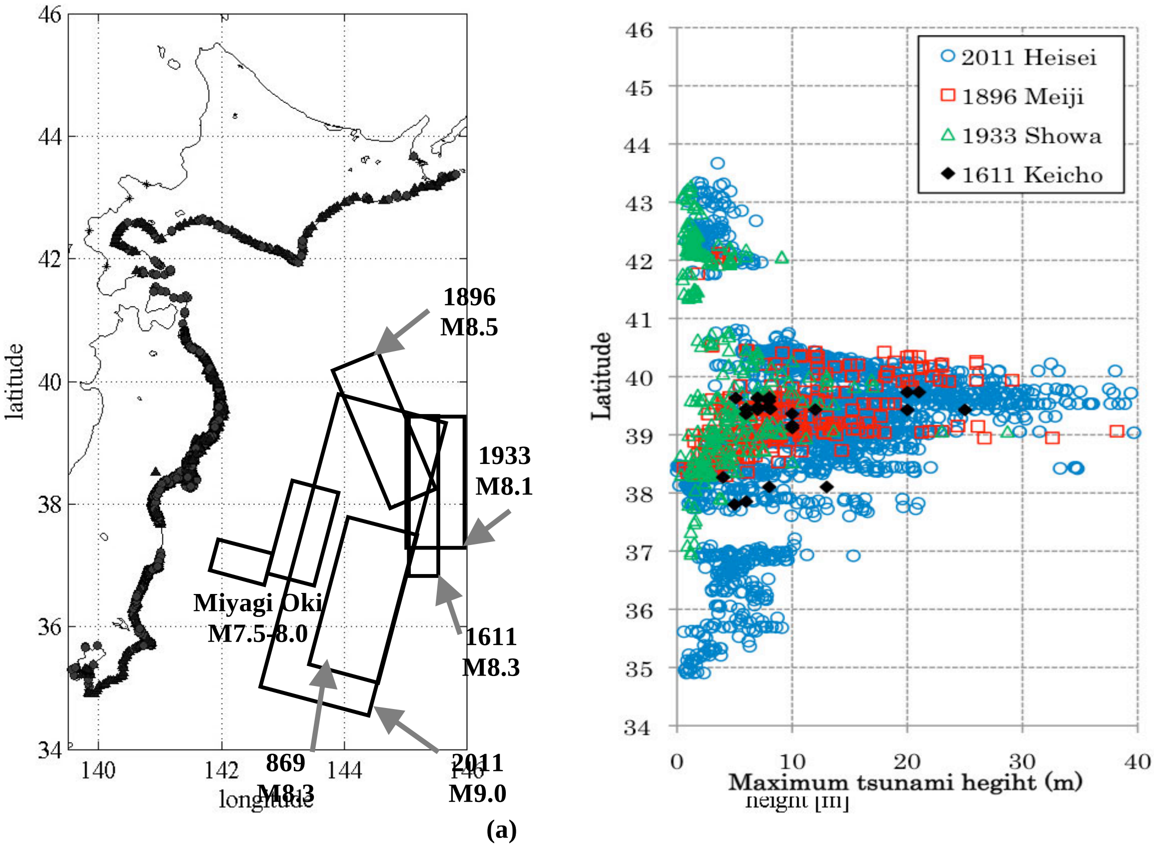

Figure 1 Left: Major historical tsunamis and the expected Miyagi-Oki earthquake and location of the main shock; Right: tsunami height distribution of the 2011 Great East Japan tsunami (the 2011 Tohoku Earthquake Tsunami Joint Survey Group, 2011) and of the historical 1611 Keicho, 1933 Showa-Sanriku and 1896 Meiji-Sanriku tsunamis (Tsunami Engineering Laboratory, 2011)

TSUNAMI WARNING AND EVACUATION

Japan Meteorological Agency (JMA) is in charge of issuing the tsunami warning and advisory or not within a short time whenever an earthquake occurs in Japan and other area, with the quantitative information of tsunami heights and arrival time by using the data-bases for tsunami forecasting system. On 11 Match 2011, JMA recorded seismic waves up to 22 seconds before the earthquake was felt in other locales, i.e., before the arrival of the P waves. In the first TV broadcast, the magnitude was initially stated as 7.9. Two minutes later, the JMA determined to issue a tsunami warning that was broadcasted. Three minutes after rupture initiation of the main earthquake, tsunami warning announcing a 6m in Miyagi and 3m in Iwate and Fukushima was broadcasted, whereas 28 minutes post-earthquake, the wave amplitude was recalculated and announced as 10m (JMA,2011).This last message, however, could not possibly have been disseminated to the people on the coast successfully due to damage to communications infrastructure. Although corrected later, the initial tsunami warning underestimated the actual tsunami's height, which possibly affected people's evacuation behavior. Because the estimated tsunami height were lower than the level of sea wall and break water in Sanriku and other area.

Even though the people receiving the tsunami warning tried to evacuate to the safety area, they met the several difficulty to reach there because of heavy traffic jam on the roads and at the intersections and bridges damaged by the quake and so on. And some of the tsunami shelters and evacuation places designed for the target tsunami on the coast were flooded by the tsunami so that especially the peoples on the ground or lower floors were washed away. And the tsunami struck areas outside the potential danger zones indicated on hazard maps, underlining the in-sufficient of the predictions. On the other hand, community-based preparedness could save lives despite the failure of coastal defense and the warning system. Well-prepared evacuation planning through regular drills should led to the prompt evacuation (immediately after the earthquake) of some locals who did not wait for evacuation calls.

DAMAGE MAINLY RELATED THE TSUNAMI

Overviews of damage and effects along the coast

The degree and extent of damage caused by the earthquake and resulting tsunami were enormous, with most of the damage being caused by the tsunami. Video footage of the towns that were worst affected shows little more than piles of rubble, with almost no parts of any structures left standing. Estimates of the cost of the damage range well into the tens of billions of US dollars; before-and-after satellite photographs of devastated regions show immense damage to many regions. Although Japan has invested the equivalent of billions of dollars on anti-tsunami seawalls which line at least 40% of its 34,751 km (21,593 mi) coastline and stand up to 12 m high, the tsunami simply washed over the top of some seawalls, collapsing some in the process. Large tsunami breakwaters had been constructed at the entrance of Kamaishi and Ofunato Bays at 62m and 22m depth respectively, which both did not withstand due to the strong tsunami forces. Upper concrete blocks, caisson, were moved but settlements were less exposed to protect the tsunami attack.
Table 2 shows damage due to the 2011 Tohoku earthquake as of 2010 August and tsunami compared with the estimated in Miyagi-oki and Meiji Sanriku by Cabinet office (2007 and 2011), indicating that the damage is extensive much more than estimated those in the previous estimation with the scenario in Tohoku region. In the 2011 tsunami, almost all wooden structures were destroyed by debris impact as well as strong currents with increasing inundation depth. The criteria of housing damage could be a inundation depth of more than 2 m according to the measured data by MLIT(2011).

Table 2 Summary of the damage due to the 2011 Tohoku earthquake (as of 2010 August) and tsunami compared with the estimated in Miyagi-oki and Meiji Sanriku by Cabinet office (2007 and 2011)

	The estimated damage		The actual damage
	Miyagi-oki	Meiji Sanriku	2011 Tohoku
Housing damage by earthquake and tsunami	21,000	9,400	112,703
Housing damage by tsunami	2,900	9,400	
Debris (ton)	1,400,000	950,000	22,633,000
Fatality by earthquake and tsunami	290	2,700	20,444
Fatality by tsunami	280	2,700	

Effects at each area

After the 1896 Meiji and 1933 Showa Sanriku events, costal structures such as tsunami seawalls were constructed along the coastlines in Sanriku to prevent and reduce tsunami inundation, which walls were concrete structures ranging in height from 5m to 15m. Only the 15m high gate in the Fudai protected the settlements behind it and prevented loss of life. The 2011 tsunami was 17 m high at the gate, it overtopped it but only further inundated a few hundred meters inland from the gate. However, sea walls at Taro in Miyako, Otsuchi and Yamada were collapsed or the tsunami overtopped them, resulting huge flooding on the land where tsunami inundation depth was as high as the first or two floors of these buildings.

Concrete buildings were used for vertical evacuation and saved lives, however in some cases buildings designated as suitable for vertical evacuation were not high enough and people were drowned. And a few building were turn over because their foundations become weak during the strong ground motion and liquefaction, and air trapped between the ceiling and door and window frames increased the bouyancy of structures, so that they may be uplifted and moved laterally or overturned. Large scale erosion was observed around the concrete structures due to strong and long lasting currents and in some cases causing overturning. Scouring occurred as expected during tsunami attacks. Green belt such as pine tress as coastal control forestation was one of Japan’s tsunami mitigation strategies. However a destructive tsunami attacked them and severely damaged. For example, 4000 pine trees were planted in Rikuzentakata city, Sanriku, between the settlements and the sea. Only one single pine tree survived. The field survey suggested that the roots of them planted at low land were so short that the tsunami easily pulled out them however, those at higher land were long and survived.

An estimated 230,000 automobiles and trucks were damaged or destroyed in the disaster. As of the end of May 2011, residents of Iwate, Miyagi, and Fukushima prefectures had requested deregistration of 15,000 vehicles, meaning that the owners of those vehicles were writing them off as unrepairable or unsalvageable.

Photo 1 Damage on the forest control area due to the tsunami at Sendai

Transport of JR, airport and port

JR East train lines suffered damage to some degree in the worst-hit areas, 23 stations on 7 lines were affected or washed away by the tsunami, with damage or loss of track in 680 locations. And the 30-km radius around the Fukushima I nuclear plant be not allowed to access. Four trains on coastal lines were reported as being out of contact with operators; one, a four-car train on the Senseki Line, was found to have derailed, and its occupants were rescued shortly after 8 am the next morning. Train washed away uphill from Onagawa Station

Sendai airport is located in Natori city, Miyagi prefecture near the Pacific Ocean coast on center of south part of Miyagi prefecture. The airport is about 20 km south from the Sendai port with protected by sandy coast and control forest ;pine tree, all along the coast. The airport stopped their service due to the damaged at the first floor by the tsunami on around 11,000 people were stranded within the terminal until 13th March 13 2011, when they were evacuated. The airport was clean up with support from the US army until 4th April 4 and re-opened with a limit number of flight on 13th April 2011.

Photo 2 Sendai international airport before and after the 2011. The first floor was inundated c
Ports causing serious damage on the operation system

The ports at Hitachinaka, Hitachi, Soma, Shiogama, Kesennuma, Ofunato, Kamashi and Miyako were also damaged and closed to ships. All 15 ports reopened to limited ship traffic as of 29 March 2011. A total of 319 fishing ports, about 10% of Japan's fishing ports, were damaged in the disaster. Photos 3 and 4 show the damage at the port and its surrounding area, caused by the tsunami. Not only direct tsunami effect but also floating material such as the debris and boats and fire cause the secondary damage.

Photo 3 Damage on the residential and fishery area due to the tsunami attacks and floating debris such as cars and ships at Kesennnuma

Photo 4 Ships moved by the tsunami and fire at the residential area at Kesennnuma

In 1964, there was a plan to construct a new industrial city around the Sendai port region, which was started to build by digging the sand for the purpose of forming an industrial area coastal to lowland swamp and surrounding the site of Navy. It was opened in 1971 providing function as a commercial port and also later has become a distribution center in the Tohoku region, Miyagi Prefecture and Sendai City area or the outer harbor. Sendai Port was also used for international beach volleyball competitions. As one of a few ports in the northeast region, Sendai port can handle a 40ft container including crude oil, automobiles, fuel oil as cargo handling various types of products and liquefied petroleum gas. In 2006, the port handling capacity of about 37 million tons and 7,024 vessels were entered. The port is also served for passengers by ferry between the Port of Nagoya and Tomakomai Port in Hokkaido.

Photo 5 Damage due to the tsunami followed by fires at Sendai port

LESSONS LEARNED FROM THE 2011 TOHOKU TSUNAMI

After the 2011 earthquake and tsunami, several meetings and committee were hold to discuss the issues for recovery and reconstruction, and future mitigation. An expert panel to the Central Disaster Prevention Council recently issued an interim report on future countermeasures. It pointed out the limitations of previous approaches, which relied mainly on prediction-based technology-oriented solutions and it stressed the necessity of putting greater priority on residents' evacuation planning and land use. This is a clear transition from the previous approach to a more balanced approach, involving comprehensive measures that incorporate land use and evacuation plans. Such comprehensive measures to facilitate immediate evacuation are crucial in preparing for a once-in-a-millennium tsunami because it is not feasible to predict accurately the maximum possible magnitude of tsunamis, even though predictions are useful in the protection against such tsunamis.

Another of them is Committee for Technical Investigation on Countermeasures for Earthquakes and Tsunamis Based on the Lessons Learned from the “2011 off the Pacific coast of Tohoku Earthquake” in the Cabinet office, which final report indicates the Principle for future tsunami hazard assumptions for developing tsunami countermeasures requires two levels of tsunamis; (1) Level 1 Tsunamis that occur frequently but cause major damage despite the relatively low tsunami height. Development of coastal protection facilities from the point view of protecting human life and the assets of residents, stabilizing the regional economy and securing efficient industrial bases. And (2) Level 2 Largest-possible tsunamis with extremely low possibility of occurrence but devastating once they occur. Place protection of people’s lives as the first priority and establish comprehensive tsunami countermeasures embracing every possible instrument, while placing evacuation of residents as the core.

The following are the main part of the report;

Table 3 Two levels of tsunamis for the countermeasure after the 2011 Tohoku Tsunami

Tsunami		Performance	Frequency
Level 1	Tsunamis envisaged on the basis of constructing coastal protection facilities	Reducing the damage of human, housing, property, and economic activity	50-150 years
Level 2	Largest-possible tsunamis envisaged on the basis of developing comprehensive disaster management measures	Saving the lives. evacuation of local residents as the main pillar.	ultra-long-term more than 150 years , several thousands years

Level 1 ; Principles for countermeasures using coastal protection facilities against frequently occurring tsunamis

The coastal protection facilities that have been constructed were based on a scenario of tsunamis that occur with relatively high frequency, and they have achieved certain results in preventing damage. However, since the tsunami height in this disaster far exceeded the tsunami height that these facilities were designed for, while they were effective to a certain extent in terms of lowering water levels, delaying the arrival of the tsunami and maintaining the coastline, most of the coastal protection facilities were damaged and the land behind these facilities suffered enormous tsunami damage.
In preparing for largest-possible tsunamis, raising considerably the designed tsunami height for the coastal protection facilities is not realistic from the standpoint of the financial requirements for construction of such facilities, and the potential impact on the coastal environment and its use. Therefore, coastal protection facilities must continued to be constructed for relatively frequent tsunamis with a certain level of tsunami height from the point of view of protecting human life and the assets of residents, stabilizing the regional economy and securing efficient industrial bases.
With regard to coastal protection facilities, it is also essential that progress be made in the promotion of technical developments of structures that will rigorously withstand tsunamis that are higher than

those for which they were designed.

Level 2 ; Principles for countermeasures against largest-possible tsunamis

The occurrence of a mega tsunami and the devastating damage experienced in this disaster revealed that there were problems with disaster management measures that depended too much on such measures as coastal protection facilities. It is essential that tsunami countermeasures be developed by accounting for the tsunamis experienced in the ―2011 Tohoku Earthquake‖ or the largest-possible tsunamis, and while placing protection of people‘s lives as the first priority, it is needed to ensure sustaining of minimum required social and economic functions such as governmental functions and hospitals regardless of what sort of disaster occurs. For this, it is necessary to establish comprehensive tsunami countermeasures embracing every possible instrument, which place evacuation as the core and combine land use planning, evacuation facilities and disaster management facilities.

CONCLUSIONS

The paper aims to review the damage due to the tsunami mainly and introduce the lessons from them. Now rapid and proper recovery and re-construction are under-taken and also discussed for long term safety. Then observation and documentation of the tragedy with several viewpoints; natural, social and human sciences are important to discuss the effects of the countermeasure before the 2011 and identify the limitation. Evaluation of the past countermeasures to identify the issues to solve the problems is essential. And, we should also pay attention to the necessity of learning from this terrible disaster for the primary mitigation of future tsunamis. In order to save lives from tsunamis, identifying vulnerable groups and area should lead to practical and effect evacuation plans including the routes for the shelters and safety place. Interdisciplinary science integrating health science, human-behavior science, social science, civil engineering, architecture and urban planning is required to support the planning at each area.

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