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Damage and reconstruction after the 2004 Indian Ocean tsunami and the 2011 Great East Japan tsunami

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ABSTRACT

The 2004 Indian Ocean tsunami was one of the world's worst tsunamis and caused devastating damage in many Asian countries. Then, in 2011, Japan was hit by a tsunami that was generated by the greatest earthquake in the country's history. This paper discusses the damage caused by these tsunamis and subsequent reconstruction. Introduced first are the experience gained and lessons learned for future tsunami mitigation, such as tsunami awareness, proper evacuation building and the memorial parks created in the countries affected by the 2004 tsunami (Indonesia, Sri Lanka and Thailand). Second, the damage by the 2011 tsunami to structures designed to protect against tsunamis is summarized. Most of these structures could not withstand and protect from the tsunami because they were not designed for such a large tsunami. Human casualties and building damage are discussed using fatality ratios and fragility curves, respectively. These analyses show that experience and awareness help reduce human casualties in the Sanriku area, and wooden houses damaged by the 2011 tsunami fared better than in previous historical events. Finally, examples of ongoing reconstruction in Japan are introduced. Most reconstruction efforts were planned after considering the lessons learned from the tsunami's impact, and the towns in question are now strengthening their disaster prevention-related plans to be better prepared for future tsunamis.

Keyword: The 2004 Indian Ocean tsunami, the 2011 Great East Japan tsunami, reconstruction, disaster reduction, disaster mitigation

1. INTRODUCTION

The 2004 Indian Ocean earthquake and tsunami occurred on December 26th, 2004. It was the first instrumentally and historically recorded major earthquake and tsunami in the region. The earthquake's magnitude was estimated at 9.3, which shocked most scientists at the time. The estimated rupture area reached approximately one thousand kilometers, the longest rupture ever recorded. A tsunami was generated, and the maximum tsunami height of approximately 50 m was measured in the Banda Aceh region of Indonesia. The tsunami caused wide-ranging damage in 15 countries and approximately 230,000 deaths. Seven years later, on March 11th, 2011, a massive earthquake of magnitude 9.0 occurred off the Pacific coast of Tohoku (in the northeast region of Japan) and was followed by a devastating tsunami that again shocked many scientists with its magnitude. This time, the rupture length was estimated at 500 km, with a large slip of more than 30 m. A maximum tsunami height of approximately 40 m was measured, and approximately 20,000 deaths in Japan and one death each in the United States and Indonesia were reported. A comparison of the two tsunamis is shown in Table 1 (NOAA, 2011). In general, both tsunamis were generated from a massive M9-class earthquake with a large rupture area and resulted in a large tsunami of 40-50 m in height. One difference between the two events is the ten-fold difference in the number of casualties due to the earthquake and tsunami source locations, which can often lead to a difference in the number of affected countries.

This paper will introduce examples of successful reconstruction based on experiences in the 2004 Indian Ocean tsunami-affected countries, namely Indonesia, Sri Lanka and Thailand. The number of deaths in these three countries were reported as 150,000, 35,000 and 8,000, respectively. Section 2 will introduce tsunami-related structures such as a tsunami memorial park, museum and evacuation building, as well as stories related to tsunami awareness and self-evacuation. Several damage field surveys of the 2011 Great East Japan tsunami conducted in Iwate and Miyagi prefectures will also be presented. In section 3, damage to structural countermeasures and buildings will be discussed using survey data, and human casualties will be discussed using statistical data. Japan is well known for its tsunami countermeasures and evacuation preparedness. Nevertheless, very heavy damage was observed on the Sanriku Coast, a 600-km-long shoreline that extends northwards from Sendai and into the Miyagi, Iwate and Aomori prefectures. Many structural and non-structural facilities had been constructed along the coast as tsunami countermeasures. In the present study, the effectiveness of these measures during the 2011 tsunami is discussed, showing examples of breakwaters, tsunami gates, seawalls, control forests and highland residences. Tsunami damage to communities will be discussed in two ways: in terms of human casualties, using the fatality rate as a metric, and in terms of building damage, using a fragility curve and comparing the data with results obtained from historical tsunami events. The present reconstruction status observed during field surveys of tsunami-affected areas in Sendai is introduced. The discussion will include ideas for and efforts toward the construction of a tsunami memorial for the future tsunami disaster prevention in the Tohoku region (Fig. 1). There are ten possible locations for these memorials: Miyako, Rikuzen-Takata, Kesennuma, Minami-Sanriku, Onagawa, Ishinomaki, Shiogama-Matsushima, Sendai, Natori and Iwanuma, and some interesting ideas, such as the “Sakura Line 311” in Rikuzen-Takata, the “Overturned Building” in Onagawa and the “Hill of Thousand Year Hope” in Iwanuma, will also be described in detail.

2. EXPERIENCES FROM THE 2004 INDIAN OCEAN TSUNAMI

2.1 Banda Aceh region, Indonesia

Unlike in Japan, which has a long history of tsunami disasters and implemented countermeasures, the word “tsunami” was not commonly heard in Indonesia before the 2004 Indian Ocean tsunami. Therefore, it is not surprising that the tsunami of 2004 destroyed 120,000 homes and heavily damaged 70,000 more,

Table 1. Comparison between the 2004 Indian Ocean tsunami and the 2011 Great East Japan tsunami

Item	2004 tsunami	2011 tsunami
Earthquake magnitude	9.3	9
Size of rupture (km^2)	1,000*150	500*200
Max. tsunami height (m)	50.9	40.5
No. of death	230,000	20,000
No. of affected country	15	Mostly in Japan

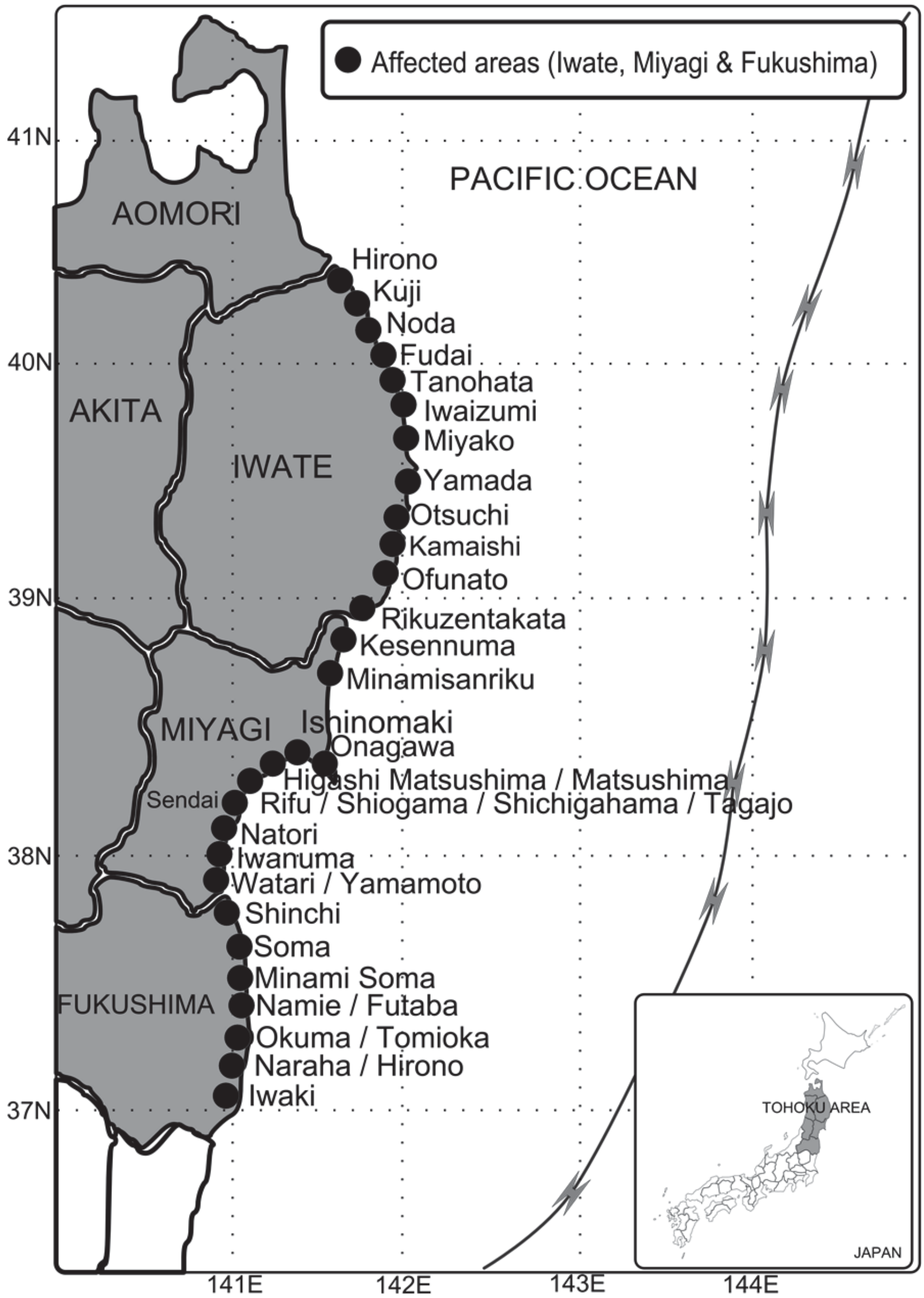

Figure 1. Map of tsunami-affected areas in Iwate, Miyagi and Fukushima prefectures

destroying 3,000 government buildings (including hospitals and schools) and 14 seaports. Nearly 3,000 km of roads in this region was damaged, and 150,000 people lost their lives. Overall, 800 km of coastline with an average width of 1.6 km was affected by the tsunami.

Because of the breadth and scale of the disaster, the Indonesian government established a special agency called the Agency for Reconstruction and Rehabilitation in Aceh and Nias (BRR Aceh-Nias) to conduct reconstruction activities in Banda Aceh and the surrounding areas. This agency began to operate effectively in mid-2005. With only a four-year tenure, reconstruction activities focused on the development of housing (2005 to mid-2007), development of public infrastructure (2005 to 2008), institutional and social development (2005 to mid-2009) and economic development (2005-2009). The agency's overall reconstruction expenses were 6.7 billion USD, which came from the Indonesian government (37%), bilateral and multilateral donors (36%), and national and international non-governmental organizations (27%).

The redevelopment of areas in the Aceh region was conducted through a community participatory method at the village level. For instance, a community would decide whether their area would be built with the employment of land consolidation or as it was. Along with these village-level reconstruction efforts, facilities and infrastructure for future tsunami mitigation were also prepared at a higher level. Buildings for vertical evacuation are now ready for use in Banda Aceh (Fig. 2a), and evacuation routes have been tested in national and international tsunami drills such as the IO-wave (Indian Ocean wave of 2009) in which all countries affected by the 2004 tsunami performed the drills. Recognizing that experiencing of the enormity of a tsunami is important, the media employed to spread the tsunami-related experiences of 2004 to the next generation come in various forms. A tsunami museum (Fig. 2b) is now established in Banda Aceh along with 85 tsunami poles indicating the height of the tsunami that hit the area. Other forms of memorial evidence such as ships, including a large diesel power plant vessel that was carried approximately 3 km inland, were left in place as a memorial to the next generation.

The case of Simeulue Island is one example that illustrates the importance of understanding, awareness and future mitigation of tsunami hazards. This island is located 50 km south of the epicenter of the December 26, 2004, M9.3 Sumatra event. A tsunami struck the west side of this island in 1907, and the experience taught the inhabitants that inundation from the sea (called “smong” in the local language) can cause extensive loss of life and property damage in and around coastal villages. Since the 1907 event, the people of this area have been acutely aware of the motion of the sea after earthquakes. In 2005, the Governor of the Island, Buphati Dr. Darmili, noted that the people of Simeulue all fled the shoreline after feeling the earthquake, and of the island’s 78,000 inhabitants, only 8 died (Yalciner et al., 2005).

2.2 Galle District, Sri Lanka

Because the island nation of Sri Lanka is quite far from any active faults, earthquakes and earthquake-induced tsunamis were not considered a major natural threat before the 2004 Indian Ocean Tsunami. Hence, damage to human life and property was a thousand times more prolific due to the lack of awareness surrounding the event. One of the most devastating natural catastrophes in Sri Lankan history, the tsunami struck an extremely long (about two-thirds of the total coastline) coastal area of Sri Lanka, covering thirteen districts and resulting in over 35,000 casualties and damage to more than 130,000 houses.

Galle became a well-known district after the tsunami because noteworthy damage occurred along its entire coastline. A total of 4,200 deaths were reported from the tsunami, with over 500 missing, almost 130,000 persons displaced, and approximately 11,500 houses either partially or completely damaged in the district (end of January 2005, Department of Census and Statistics). In addition, severe damages to the Galle port, Galle bus terminal, fishery harbors such as Galle, Dodanduwa and Hikkakuwa, and the International Cricket Stadium were major reconstruction challenges left to the community after the tsunami.

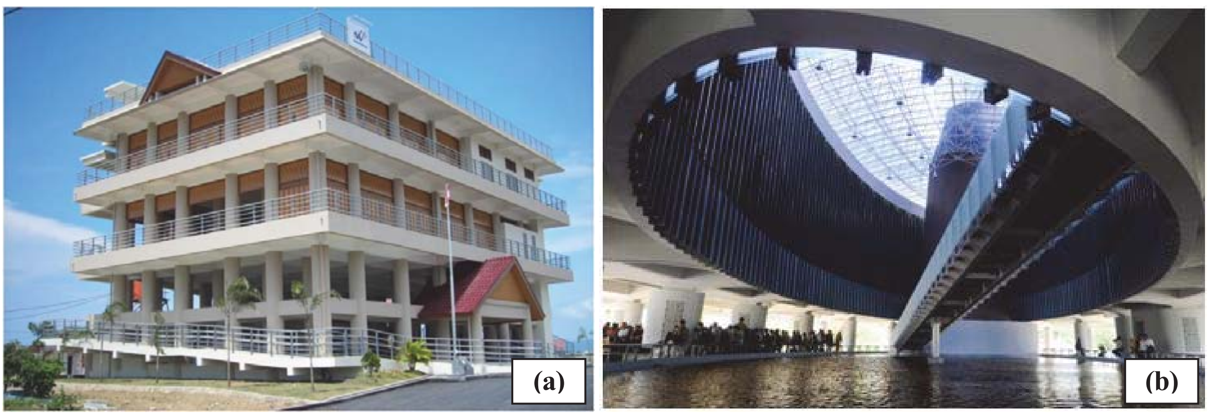

Figure 2. (a) Evacuation building in the Banda Aceh region in 2009 and (b) tsunami museum in the Banda Aceh region in 2009

However, the most noteworthy damage was that near Peraliya, where the tsunami surge overturned and submerged a Galle-bound train, killing over one thousand people. Galle International Stadium, which is considered to be one of the most picturesque cricket grounds in the world, is situated near the Galle fort and surrounded on two sides by the Indian Ocean. The Stadium was destroyed (Fig. 3a) in the 2004 tsunami but was rebuilt and hosted international matches again in 2007. The Galle bus terminal was totally destroyed in the tsunami, claiming thousands of lives. A temporary bus stand was built after the calamity as a temporary measure, and work on a new modern bus stand commenced in October 2010 and was handed over to the public in July 2011 (Fig. 3b).

Peraliya, the most devastated area in the Galle district, is now considered a memorial site for the Indian Ocean tsunami. A number of tsunami memorials were constructed in this area to sustain the memory of this event and to educate the younger generation who have never experienced a tsunami. Figure 4a shows a memorial built in this fashion, located at the site of the train accident that resulted in the worst human disaster in Sri Lankan history. A tsunami photograph museum at Telwatta, shown in Figure 4b, tells thousands of stories related to the event to show future generations what happened.

2.3 Phang Nga province, Thailand

Tsunami awareness is the most important factor to increasing survival rates in countries with no massive tsunami countermeasure structures. Thailand, for example, has a lower tsunami risk than Japan in terms of both size (maximum height of 15 m) and return period (M9.0 every 600 years). The 2004 Indian Ocean tsunami was the first tsunami in Thailand to be instrumentally recorded, and more than 8,000 deaths were reported. However, most of the Moken population who live in the Surin Islands of the Phang Nga province survived. They live near the Andaman Sea, and the first floors of their houses are open spaces. They use wooden boats for aquaculture, and their ancestors taught them about the importance of early evacuation following artificial and natural warning signs (such as earthquakes and abnormal tides).

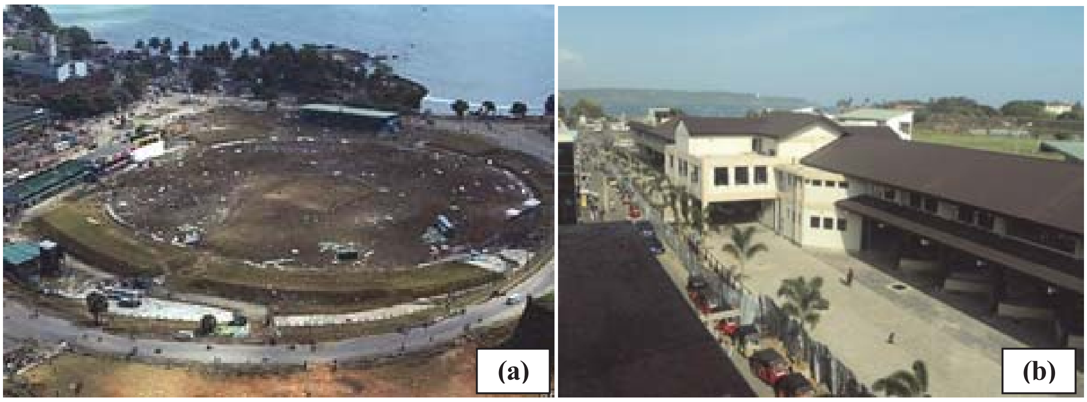

Figure 3. (a) Galle International Stadium (29/12/2004) and (b) Galle bus terminal (7/2011)

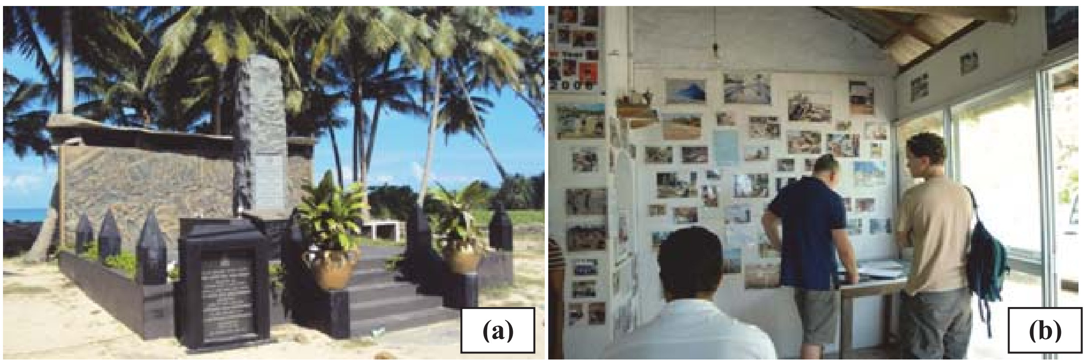

Figure 4. (a) Tsunami memorial in Galle (27/4/2010) and (b) tsunami photo gallery in Galle (11/2008)

In 2004, a maximum tsunami height of 15 m attacked Nam Khem village, which had no breakwaters, seawalls or control forests. As a result, the maximum tsunami inundation distance was almost one kilometer, causing Nam Khem to become the most devastated village in Thailand, with casualties exceeding 1,000. Consequently, many awareness activities are now being conducted in this area, and residences have very high readiness and awareness compared to those in other areas of Thailand. Two evacuation drills were conducted, and residents learned about problems they could encounter during nighttime and rainy evacuations. Evacuation team members are separated for their duties during evacuation periods and must know how to protect themselves without support from the government. Sea observation teams check the receding of a wave if they receive a warning. Patrol teams look after residents' belongings. Traffic teams enforce rules during an evacuation, having pedestrians keep to the left and vehicles keep to the right without opposition. Rescue teams check houses for abandoned or disabled individuals. Nursing teams standby with first aid materials.

Nam Khem now has many good strategies to promote tsunami recognition and awareness among residents during tsunami events. A school was chosen as the local evacuation shelter, and its location was moved higher above sea level and farther from the coast in response to lessons learned from the tsunami. The evacuation route is the main two-lane village road for vehicles. Two fishing boats that were carried 500 m inland, killing many residents and causing more housing damage, were left in place as a tsunami memorial. A memorial park was also constructed next to the beach for recreation (Fig. 5a), and a memorial gallery (Fig. 5b) was erected inside the park with information on tsunamis, evacuation procedures and historical damage at Nam Khem.

In Pakarang Cape, Phang Nga, an evacuation shelter near the beach (Fig. 6a) was constructed in 2010 in accordance with shelter regulations stating that the distance to a safe zone must be greater than 1 km when there is no greenbelt to dissipate tsunami energy. In Khao Lak, the patrol boat that was in charge of protecting the royal family on their vacation was brought approximately 2 km inland by the tsunami (Fig. 6b). That boat was also kept in place as a symbol of the tsunami, and a small tsunami gallery was built nearby.

3. THE 2011 GREAT EAST JAPAN TSUNAMI

3.1 Performance of tsunami countermeasures

Tsunami breakwaters: Ofunato city

Ofunato Bay is a long bay that is resonant to long-period tsunamis such as the 1960 Chilean tsunami. After the Chilean tsunami, breakwaters composed of two parts measuring 290 m and 250 m were constructed at the bay's entrance, leaving an opening 200 m wide. Just after its completion, the 1968 Tokachi-oki earthquake tsunami hit and the breakwaters worked successfully. However, the 2011 tsunami overtopped the breakwaters, inundating 3 km of the bay's bottom area and reaching 23.6 m in height. The broken breakwaters were still submerged in June 2011.

Figure 5. (a) Tsunami memorial park in Phang Nga (19/3/2009) and (b) tsunami memorial gallery in Phang Nga (19/3/2009)

Figure 6. (a) Tsunami evacuation building in Phang Nga (5/11/2009) and (b) patrol boat from the 2004 tsunami in Phang Nga (19/3/2009)

Seawalls: Taro village, Miyako city

Taro is a typical example within the areas hit hardest by tsunamis in 1611, 1896 (15 m high) and 1933 (10 m high) (Fig. 7a). In 1934, the town constructed two lines of seawalls 10 m high above mean sea level with a total length of 2.4 km. In the 1970s, the village constructed another two lines of seawalls 10 m high to accommodate the increasing population. Both sets of walls were designed considering only the 1933 tsunami. The actual purpose of the seawalls was not to totally stop a tsunami similar to the event of 1896 but to mitigate such a tsunami. The population's tsunami awareness went down when the second line of seawalls was constructed because the inhabitants felt more secure behind the double construction. The seawalls worked very well during the 1960 Chile tsunami, and the village became famous as the best tsunami disaster prevention area in Japan. However, the 2011 tsunami overtopped these two-line seawalls, and the eastern part of the new seawalls deteriorated (Fig. 7b). The main reasons why the seawalls were destroyed were that the two seawalls were crossed in an X shape, which concentrated the tsunami at the center of the seawalls; the foundations were weak and unstable because they were located near the river; and the seawalls were not maintained properly or adequately connected to one another (Suppasri et al., 2012c).

Figure 7. (a) Height records of historical tsunamis in 1896 (15 m) and 1933 (10 m) in Taro village (9/11/2011) and (b) destroyed seawalls (9/11/2011)

Tsunami gates: Fudai village, Shimohei district

Fudai was developed along the Fudai River, and it suffered during the 1896 and 1993 tsunamis, which flooded this river. In 1984, tsunami gates 15.5 m high were constructed to close the river mouth in case of a tsunami. The 2011 tsunami was 17 m high at the gate and overtopped it but inundated only a few hundred meters of land behind the gate (Fig. 8a). The majority of Fudai village, including its evacuation shelters (located in primary and secondary schools), was protected and no loss of human life was reported (Fig. 8b).

Control forest: Rikuzentakata city

This city is well known for its Takata-Matsubara region, a 2-km stretch of shoreline that was lined with approximately seventy thousand pine trees. In 1940, it became a designated cultural property of Japan. Such a control forest could withstand a tsunami up to 3-5 m, but the measured height of the 2011 tsunami was 19 m. As a result, only one tree, 10 m tall and two hundred years old, remained and the city behind the forest was completely destroyed (Fig. 9). This tree became the city's symbol of reconstruction.

3.2 Human casualties and the fatality ratio

One way to compare human casualties in each area is to calculate a fatality ratio. The fatality ratio in this study is defined as the number of reported deaths and missing persons divided by the total population for historical tsunamis (Yamashita, 2008) and by the estimated population in a tsunami inundation area for the 2011 Great East Japan tsunami (Statistics Bureau, 2011). Here, data from historical tsunamis that affected the Sanriku area (1896 Meiji, 1933 Showa), the 2004 Indian Ocean tsunami and the 2011 Great East Japan tsunami are compared (The 2011 Tohoku Earthquake Tsunami Joint Survey Group, 2011 and Suppasri 2012a). The relationship between the maximum tsunami height and the fatality ratio is shown in Fig. 10a. In general, the fatality ratio increases rapidly when the tsunami height is larger than 2 m and can be up to 30% when the tsunami height reaches 3 m. It is clear that the characteristics of the fatality ratio in the Sanriku plain area in question are similar to those during historical events. However, the fatality ratio on the Sanriku ria coast is nearly identical to that of the plain, even though the tsunami height reported on the coast is much higher. The fatality ratio for historical events reached more than 20-50% when the tsunami height was greater than 20 m but only approximately 10% during the 2011 event on the coast. Though it is difficult to compare tsunami events, one of the possible reasons for the low fatality ratio could be due to the effective evacuation. Coastal residents on the Sanriku ria coast had more tsunami experience (in 1611, 1869, 1933 and 1960) and awareness than in the Sendai plain area (no severe tsunami damage since 1611).

3.3 Building damage and the fragility curve

During the survey, it was observed that the structure of a wooden house was damaged when the tsunami inundation depth was greater than 2-3 m, while no damage occurred to reinforced concrete (RC) build-

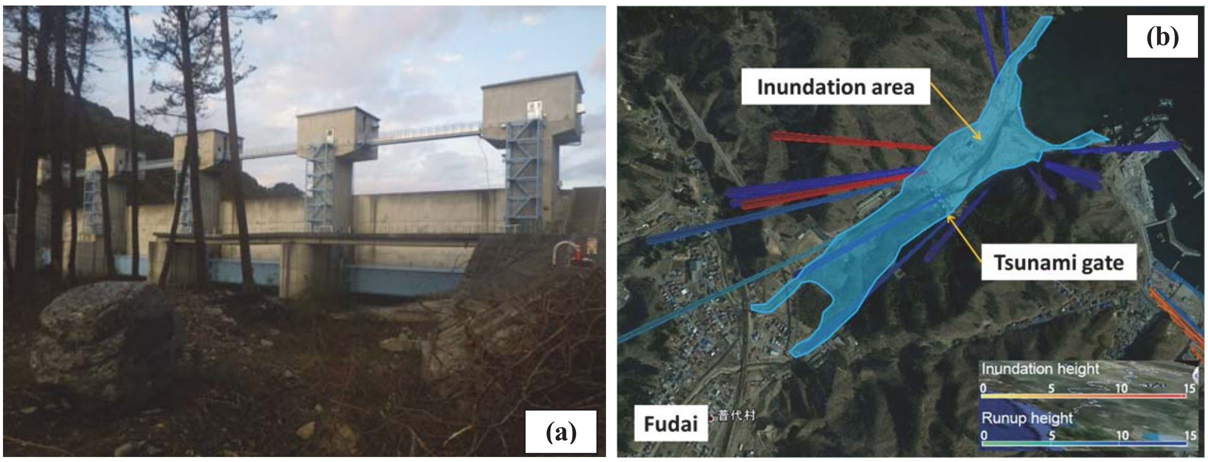

Figure 8 . (a) Tsunami disaster prevention memorial (rock on the lower left) behind the tsunami gate in Fudai village (9/11/2011) and (b) location of Fudai, its tsunami gate and tsunami inundation area

Figure 9 . (a) The only pine tree remaining of the 70,000 trees in Rikuzen-Takata (a) after three months (1/6/2011) and (b) after one year (29/4/2012)

ings at this depth. In general, one good example of the impact of tsunamis on three different house types is shown in Ishinomaki city (Suppasri et al., 2012b). Although three houses were inundated at the same depth of 4 m, the damage to each house is totally different. The RC two-story office had broken windows but no structural damage. The two-story wooden house had damage to some walls and columns. The one-story wooden house totally collapsed. The tsunami fragility curve developed from previous tsunamis shows that the possibility of damage at a 4-m inundation depth to an RC house, a mixed RC and wooden house and a wooden house is 0.3, 0.7 and 0.9, respectively, as shown in Fig. 10b (Suppasri et al., 2011).

4. RECONSTRUCTION STATUS AFTER ONE YEAR IN SENDAI CITY

4.1 New tsunami hazard map

As in other locations in Miyagi prefecture, Send-

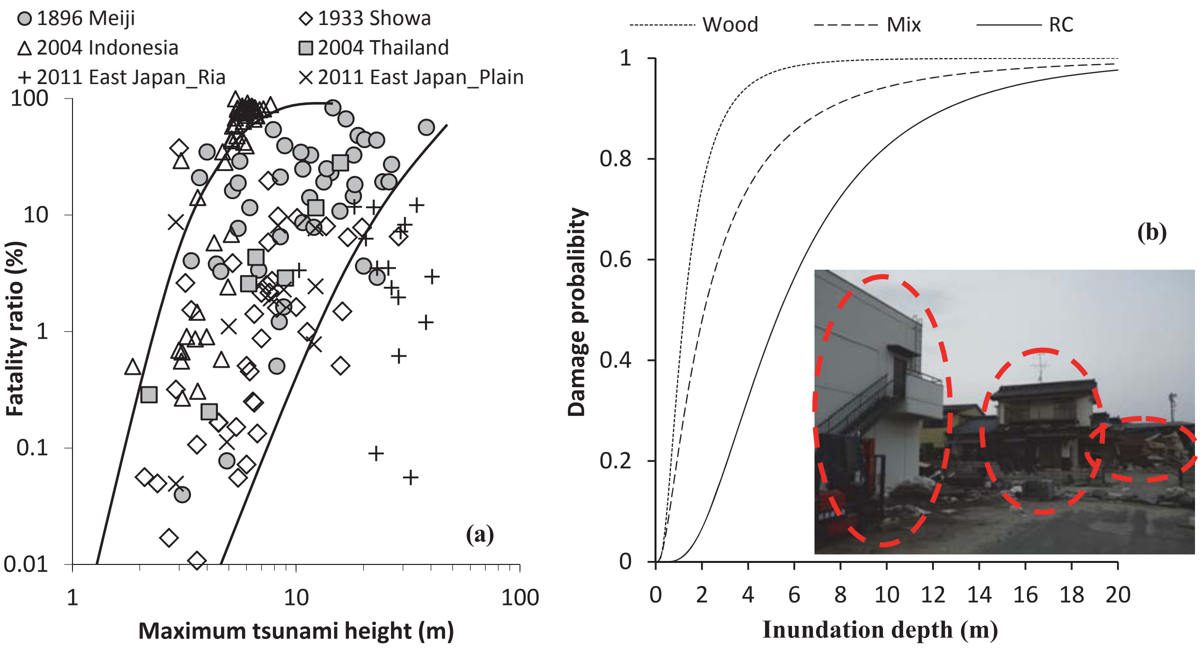

Figure 10 . (a) Comparison between the tsunami fatality ratio from this event and from other historical events in Japan and the 2004 Indian Ocean tsunami and (b) damaged condition of an RC building, two-story wooden house and one-story wooden house under the same inundation depth of 4 m in Ishinomaki (26/4/2011)

ai city had high tsunami awareness due to the Miyagi earthquake, which had an estimated magnitude of approximately 7.5-8.0. Many tsunami countermeasures, such as evacuation drills and hazard maps, were implemented among coastal residents. Arahama primary school was the only tsunami evacuation building near the Sendai coast before the 2011 tsunami because the estimated tsunami inundation area was located only around the Tenzan canal, extending approximately 500 m inland. However, the 2011 tsunami generated by the M9.0 earthquake caused a larger tsunami height and wider inundation area than expected. The tsunami inundated an area reaching approximately 5 km inland, causing a wide range of damage to Sendai. The Sendai-East expressway helped to protect against the tsunami by chance in some areas because the expressway was situated perpendicular to the tsunami inundation direction. After the tsunami, the city created a new tsunami evacuation map separating the region into two areas (Fig. 11). The first area, situated from the coast to the prefecture road, is being raised to 6 m above ground level, and the second area extends over the inundation area of the 2011 tsunami (Sendai city, 2011). Sendai's new tsunami hazard map is shown in Fig. 11. The older tsunami hazard map based on the Miyagi earthquake, which was located next to Arahama beach, was found after the 2011 tsunami with the damage shown in Fig 12a. A paper saying "Please do not remove this" was later attached to the map, indicating a need to maintain it as a memorial, but the sign was finally removed during a site visit in late March 2012. A memorial for tsunami victims was later constructed near the seawall and the old tsunami hazard map at Arahama beach (Fig 12b).

4.2 Arahama primary school

The changes to the condition of Arahama primary school over several visits are shown in Fig. 13. The first visit to Arahama primary school was on April 16th, about one month after the tsunami. At that time, large amounts of debris were found below the second floor, including sandy soil from around the school. Small changes were observed during a visit on May 29th as the asphalt was revealed and some of the debris removed. On July 25th, most of the debris inside the school had been removed and the interior was being cleaned. Open space in front of the school was now being used as a temporary space for damaged motorcycles that the government could not demolish before obtaining permission from the motorcycles' owners.

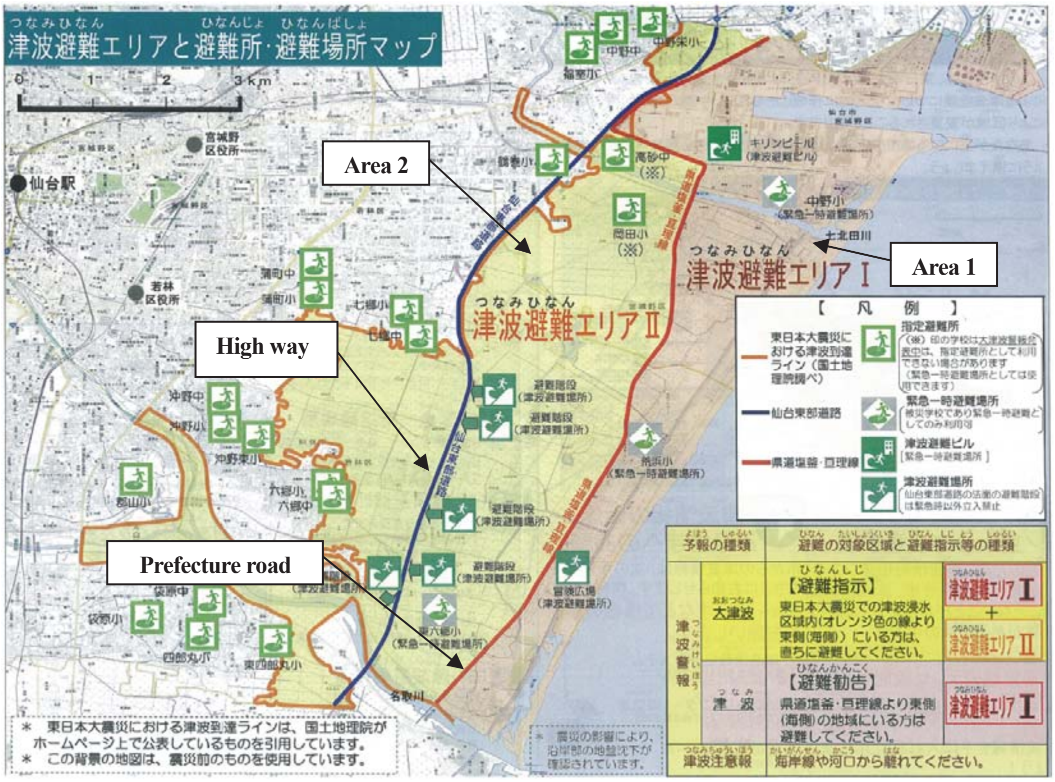

Figure 11. New tsunami hazard map in Sendai

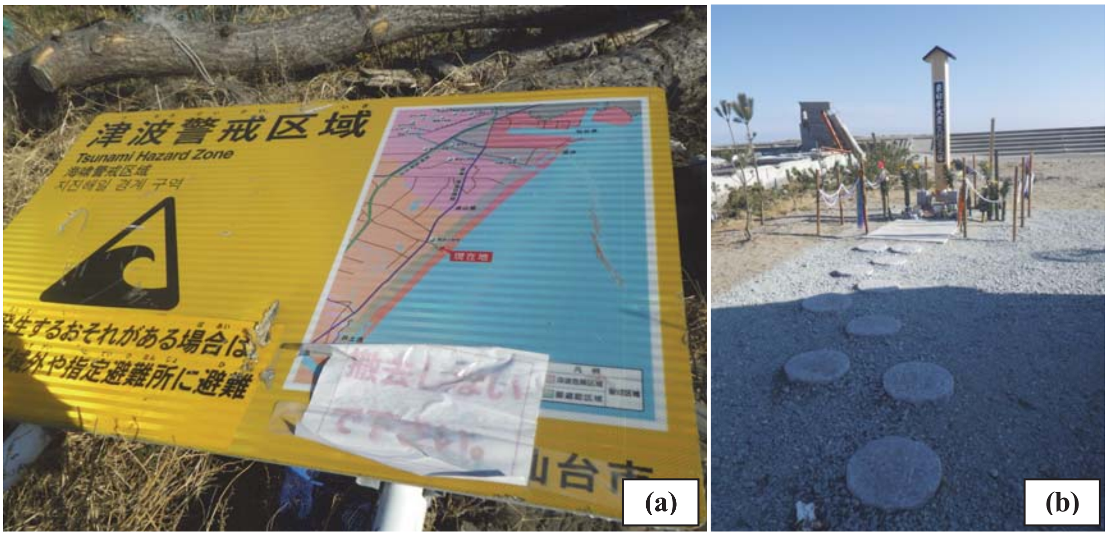

Figure 12. (a) Coastal adventure park office (18/1/2012) and (b) Namiwake shrine (18/1/2012)

Figure 13. Arahama primary school on April 16th (upper-left), May 29th (upper-right), July 25th (lower-left), and September 2nd (lower-right)

A message saying, "Thank you for your large afford" was also found in the fourth floor. On September 2nd, fences were erected in front of the school prohibiting people from entering the school grounds.

4.3 Wakabayashi ward

A coastal adventure park in this ward is now part of a tsunami evacuation area in the ward's newly revised tsunami evacuation map because the 2011 tsunami did not reach the top of the park. Information about the tsunami's inundation was gathered inside the tourist information office of the park, including the inundation line, the tsunami's height around the park and pictures before and after the tsunami (Fig. 14a). A nursing home that evacuated all of its elderly residents to the primary school before the tsunami was demolished. The Namiwake shrine gained fame after the 1611 tsunami because the tsunami stopped just in front of the shrine's original location. Due to a large number of visitors after the 2011 tsunami event, the shrine finally posted a sign in August 2011 giving information about the shrine's legend (Fig. 14 b).

4.4 Other areas

Concrete stairs were built along the Sendai-East expressway, which is located approximately 5 km from the sea, because many people survived by climbing onto the expressway during the tsunami (Fig. 15a). New electricity lines have been observed near the Sendai airport (Fig. 15b). A park in the Sendai port with an elevation of 10 m survived the 5-m-high tsunami. The park grounds were being used for the construction of temporary houses for disaster-affected residents during a visit in April 2011. However, the grounds were then covered in debris in January 2012 (Fig. 16). One of the reasons for this is that disaster-affected residents did not want to live near the sea and had transportation problems when living in this area. An example of an area affected by multiple disasters is Matsushima town (Fig. 17). The water mark from the 2011 Great East Japan tsunami in March was located approximately 0.4 m from ground level. Another water mark was found at the same location from the Roke typhoon (Typhoon No. 15) that attacked most prefectures in central and northeast Japan on September 22nd, 2011. Coastal residents evacuated

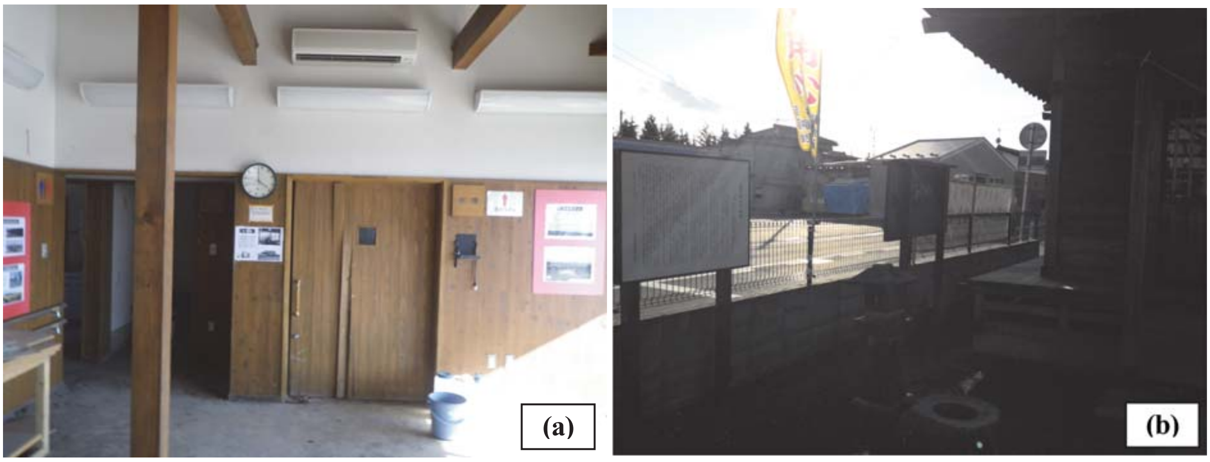

Figure 14. (a) Coastal adventure park office (18/1/2012) and (b) Namiwake shrine (18/1/2012)

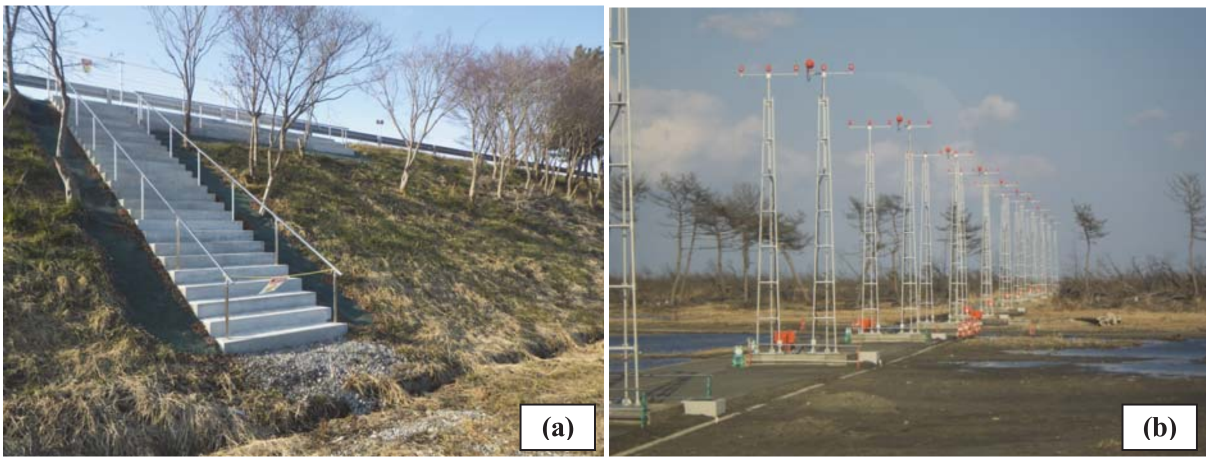

Figure 15. (a) Staircase built for access to the surface of the Sendai-East expressway (25/1/2012) and (b) new electricity line (26/3/2012)

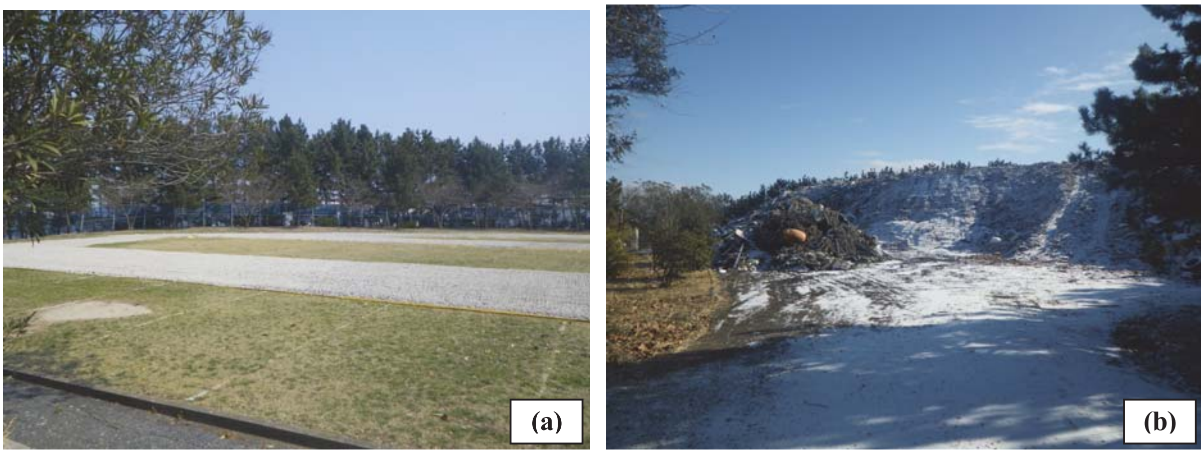

Figure 16. Condition of the elevated park at Sendai port (a) after one month (14/4/2011) and (b) after 10 months (25/1/2012)

Figure 17. Water mark of the Great East Japan tsunami on March 11th, 2011 and Typhoon Roke (Typhoon No. 15) on September 22nd, 2011 (20/11/2011)

a second time just half a year after the great tsunami. Heavy rainfall also caused landslides in the tsunami-affected areas near temporary shelters on high ground or near mountains. This experience taught researchers that more than one disaster may occur at the same time, and integrated disaster mitigation and management of future events is crucial.

5. FUTURE TSUNAMI DISASTER MEMORIAL ALONG THE TOHOKU COAST

5.1 Tsunami boulder: Taro-Settai area, Miyako city

After the tsunami, a massive boulder was found approximately 750 m inland. A 28-m-high tsunami overtopped and destroyed a water gate near the sea and transported numerous tetrapods inland, including the boulder mentioned (Fig. 18). This boulder is 3.5 m high, 6 m long, 4 m wide and weighs approximately 143 tons. According to the local news, the boulder, which was originally located near the water gate (approximately 300 m from sea), destroyed 6 out of 7 houses it hit and killed 3 out of the 6 people in its path (Iwate Nippo, 2011).

5.2 Sakura line 311: Rikuzen-Takata city

Rikuzen-Takata city was famous for its "Takata-Matsubara" or coastal pine tree forest. The 2011 tsunami severely destroyed the stand of approximately 70,000 pine trees, and only one tree survived. The uprooted trees also became floating debris, increasing damage to the city. Rikuzen-Takata has a plan to

Figure 18. Massive boulder that was moved approximately 450 m by the tsunami in the Taro-Settai area (9/11/2011)

replant the pine tree as its city symbol in a memorial park. Another interesting project is called "Sakura line 311" (Sakura line 311, 2011), which consists of planting Sakura trees every 10 m along the 1.7-km-long inundation line (Kahoku Shinpo, 2011). Approximately 17,000 trees will be required and will become a new symbol of the city to promote tourism and show people a clear image of the tsunami hazard map at the same time. The reconstruction plan for the city also includes a disaster memorial park.

5.3 Stranded fishing boat and tsunami inundation mark: Kesennuma city

This city was damaged significantly, not only by the fluid force of the 2011 tsunami but also by the many fishing boats that became debris and the explosion of an oil tank that lit the city on fire for a few days. Kesennuma organized a contest to collect ideas from universities, companies and individuals about the city's reconstruction. After one year, the city has a plan to keep one large stranded fishing boat as a memorial of the 2011 event (Fig. 19a). The tsunami inundation mark was also recorded in the tsunami evacuation building one year later (Fig. 19b) next to the tsunami evacuation mark that had already been there before the 2011 event. The city's fish market has already recovered after one year.

5.4 Disaster memorial park: Minami-Sanriku town

Minami-Sanriku was one of the most tsunami-aware communities in the Tohoku region. The town suffered from many historical tsunami events in the past, including the 1896 Meiji-Sanriku, 1933 Showa-Sanriku, and 1960 Chile tsunamis, so massive structures including tsunami gates and seawalls were already in place. However, the 2011 tsunami was too large and destroyed all of the town's disaster facilities. Minami-Sanriku has a plan to construct new disaster prevention facilities on two levels. The first

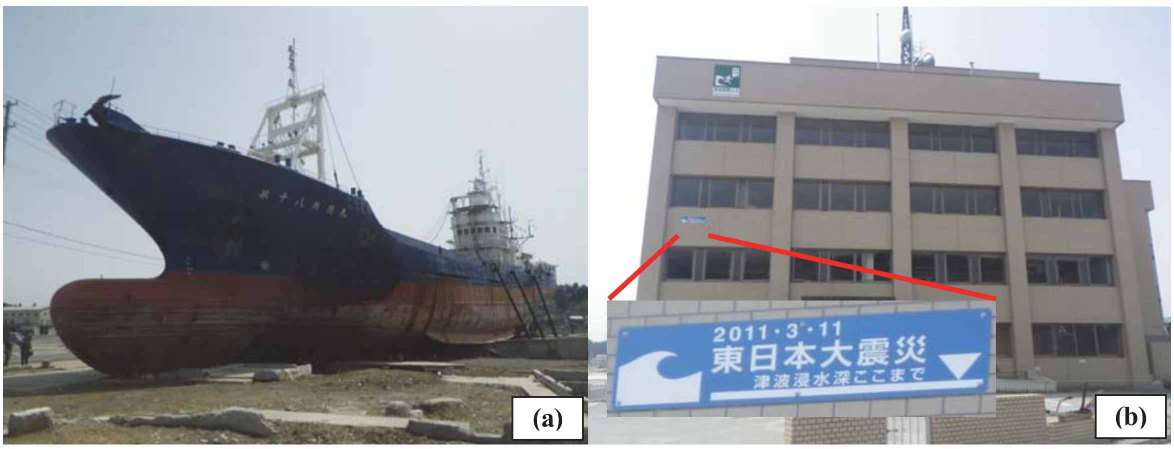

Figure 19. (a) Large fishing boat transported inland by the tsunami in 2011 (29/4/2012), and (b) 2011 tsunami inundation mark that was put in a damaged tsunami evacuation building (29/4/2012)

level is for the events with short recurrences, similar to historical events in the town's memory, and the second level is for large tsunamis with long return periods, such as the 2011 tsunami (Minami-Sanriku town, 2011). For this reason, one of the town's projects is to spread lessons learned and folklore, which includes the founding of a prayer and memorial park, museum, disaster record, disaster prevention day and the employment of a storyteller.

5.5 Overturned building memorial and tsunami inundation mark: Onagawa town

Memorable damage from the 2011 tsunami included the overturned buildings in Onagawa. Six 2-4 story reinforced concrete (RC) buildings with pile foundations collapsed (Fig. 20). This type of structural damage is uncommon during tsunami events in such buildings, and has become a topic of study for the structural design of RC and/or evacuation buildings. The town would like to preserve some of those buildings as a memorial to educate people about a tsunami's power and its massive impact on the town (Onagawa town, 2011). At present, the town has decided to keep three buildings: the police station, a commercial building and an organization building. After one year, the tsunami inundation mark was recorded in front of the Onagawa hospital (Fig. 21a), and the fish market is now recovered (Fig. 21b).

5.6 Large fish oil tank: Ishinomaki city

Unlike communities along the Sanriku coast, Ishinomaki had comparatively low tsunami damage from historical tsunamis. Thus, many factories located in Ishinomaki city did not have proper mitigation plans, and most of them were seriously affected by the tsunami. Among these, a giant fish oil storage tank 11 m high and 9 m in diameter was moved approximately 300 m from its original location by the tsunami (Yomiuri Shinbun, 2011), as shown in Fig. 22a. The tank can be clearly seen by people passing through the area, but it has been moved to a different place because it was blocking traffic. Some residents would like to preserve it as a monument to remind the community of the tsunami, and the city has a plan to make it a disaster memorial. In late March, it seemed that the city was planning to incorporate it in a memorial park (Fig. 22b)、however apparently the idea was not fully supported by residents and finally the city decided to remove the tank.

5.7 New seawall construction and tsunami inundation mark: Shiogama city and Matsushima town

Most of the tsunami-affected areas designed higher seawall after the tsunami. Some have a plan to increase the height to be equal to the height of the 2011 tsunami, while others do not and some are changing the seawalls less drastically. Shiogama city

Figure 20. (a) Area map of Onagawa and location of its six overturned buildings A through F (6/4/2011), and (b) example of an overtopped building being saved for a memorial park (Building C) (29/3/2011)

Figure 21. (a) Tsunami inundation mark (16/3/2012) and (b) fish market in Onagawa (16/3/2012)

Figure 22. Large fish oil tank in Ishinomaki (a) after one month (15/4/2011) and (b) after one year (26/3/2012)

and Matsushima town are located inside a bay area and were protected by almost 300 small islands in the water. As a result, only 4-m and 2-m tsunamis were observed in the two locations. The sign in Fig. 23a on the left shows the planned height of 2.7 m for a new seawall in Shiogama. Markings at 3.3 m and 4.3 m are also shown to give citizens some idea of other tsunami heights. Matsushima is famous as a sightseeing area due to the above mentioned islands, and tsunami inundation marks at 2.1 m were built in some areas over the original 1-m-high seawall (Fig. 23b).

5.8 Disaster memorial shrine and tsunami inundation mark: Yuriage village

Yuriage, located in Natori city, was one of the populated areas in Miyagi prefecture where tsunami videos and damage were reported just after the event. A small 6-m-high hill was situated in the flat plain of this fishing village. A shrine built at the top of the hill was washed away by the approximately 8-m-high 2011 tsunami (Fig. 24a). A warning message about tsunamis after earthquakes and a memorial for the 1933 Showa Sanriku tsunami (saying that the tsunami arrived after 40 min with a height of 3 m) was found below the shrine (Fig. 24b). The city has plans to reconstruct the shrine as a memorial symbol of the disaster, as well as other projects such as records of the damage, lessons learned and a new exchange program for volunteering, research or study focusing on disaster prevention (Natori city, 2011). A tsunami inundation mark was placed on a column in a pedestrian bridge that saved many lives during the tsunami (Fig. 25)

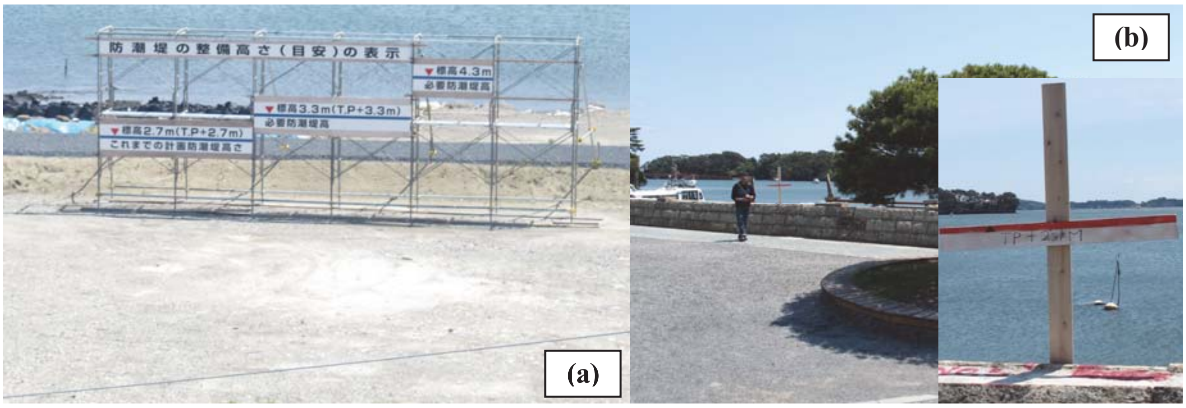

Figure 23. (a) Sign showing new seawall level to be constructed in Shiogama (12/5/2012) and (b) tsunami inundation mark in Matsushima (12/5/2012)

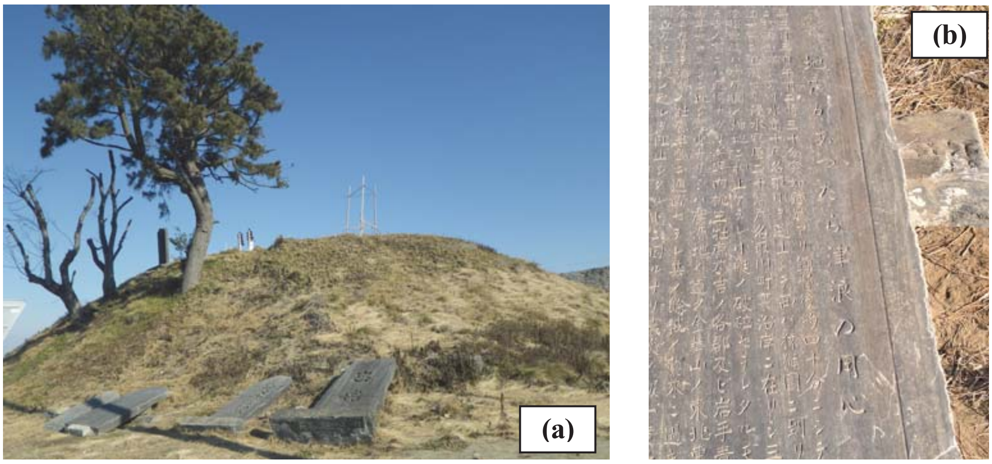

Figure 24. (a) Small shrine preserved as a disaster symbol in Yuriage (18/1/2012), and (b) tsunami memorial stone saying "If earthquake happens, beware of tsunami" (18/1/2012)

Figure 25. (a) Pedestrian bridge that saved many lives in Yuriage (30/5/2012) and (b) tsunami inundation mark approximately 2.1 m above ground level (30/5/2012)

5.9 Tsunami inundation mark: Sendai airport

The Sendai airport covers area in Natori and Iwanuma cities and is located about one kilometer from the coast. Though the airport was protected by coastal seawalls and a 10-m-high control forest, these measures were insufficient and the tsunami inundated the first floor of the airport terminal. The airport was reopened one month after the tsunami for a limited number of domestic flights. There are two marks showing the inundation depth of the 2011 event on a first floor column, and some tsunami-related activities are on display near the arrival lobby (Fig. 26a). In addition, the Sendai airport train line reopened its service after seven months and used space near its entrance to present pictures of the earthquake and tsunami damage to the train lines and stations (Fig. 26b). Unfortunately, the displays were removed by late March.

5.10 Hill of thousand years hope: Iwanuma city

Iwanuma was one of the cities with a coastal pine tree forest along its coast linked from the northern part of Miyagi prefecture. However, the greenbelt was heavily damaged, and the city has plans to replant it. Iwanuma's seawall was also severely damaged, and a temporary seawall was constructed using innumerable sand bags (Fig. 27a). The city has an idea to construct an artificial hill, the height of which varies from 10-15 m, using tsunami debris (Fig. 27b). The purpose of the hill, called the "Hill of thousand years hope," is to create a memorial park and evacuation site for future tsunamis (Iwanuma city, 2011). This hill will also help the new seawall to reduce a tsunami's energy before it reaches the populated area behind it. The town has plans to use solar energy on a large scale as part

Figure 26. (a) Tsunami inundation mark in the Sendai airport and (b) display of tsunami damage in the Sendai airport train station (25/1/2012)

Figure 27. (a) Temporary seawall (25/1/2012) and (b) management of debris (25/1/2012)

of an eco-compact city project.

6. Conclusions and recommendations

M9.0-class earthquakes occurred twice in the last seven years: in 2004 in the Indian Ocean and in 2011 off the Pacific coast of the Tohoku region in Japan. Both of these earthquakes resulted in huge tsunamis but had different impact scales. The 2004 tsunami was a near-field and far-field tsunami that propagated to all 15 countries located along the Indian Ocean coasts. This paper introduced examples of tsunami recovery from the 2004 Indian Ocean tsunami in Indonesia, Sri Lanka and Thailand. Because it was the first historically and instrumentally recorded event in the region, many tsunami activities have been performed since it occurred. Some of these include the construction of tsunami evacuation buildings, tsunami memorial parks and tsunami museums. On the other hand, the 2011 near-field tsunami caused devastating damage concentrated in Japan and had a comparatively small impact on other countries in Pacific coastal areas.

Recent technology has made it possible to build massive structures such as breakwaters and seawalls that can fully protect against 500-1,000-year return period tsunamis, but these structures are impractical in terms of budget and time. Nevertheless, the scale of damage and loss can be reduced by implementing proper structural design and land use management techniques. New design methodologies for stronger and more stable coastal structures should be developed. However, these structures may reduce the tsunami awareness of residents by leading them to believe that the structure fully protects them rather than simply reducing damage; an example of this thinking occurred in Taro town. The scenery of an area should also be considered when contemplating the construction of high seawalls.

Some locations, such as Iwanuma city and Rikuzen-Takata city, decided to replant their damaged control forests. However, although there are plans for replanting the control forest in Rikuzen-Takata as a memorial park, there are still issues to be considered, such as the budget and organization of those in charge, and there is some opposition to this idea because the forests increased tsunami damage impact when they turned into debris flow during the 2011 event.

It is clear that experience and evacuation helped reduce tsunami death rates in the coastal areas along the ria coasts of Miyagi and Iwate prefectures. This shows the importance of educating for disaster prevention because people who live along the Sanriku coast have a higher tsunami awareness and better evacuation strategies than other populations. Overturned buildings in Onagawa could be an example of a tsunami memorial park that would help warn people in future generations about major tsunamis with return periods much longer than a human lifespan. The selection of proper tsunami evacuation locations should be reconsidered in some locations because the experiences in Minami-Sanriku town and Onagawa town show that about half of the tsunami evacuation shelters in those locations were inundated, leading to a great loss of life.

Another important issue raised by the 2011 tsunami was the loss of many firefighters working on the call of duty when closing tsunami gates. The sea observation team, as introduced in the case of Thailand, could be an interesting alternative. However it might be risky for the team members since tsunami phenomena does not always start by receding waves. It is possible that the first phase of tsunami would be the positive wave and immediately attack the coastal area. Consequently, such sea observation teams are not a highly recommended alternative; instead the same outcome can be obtained through surveillance cameras near the coast.

RC structures are still preferable for protecting against tsunamis. It is necessary to find a balance between a light structure such as wood to reduce shear forces due to earthquakes, and a stronger structure such as RC that can resist hydrodynamic forces from a tsunami. One suggestion from the survey results is that because a wooden house is fragile at inundation depths of 2-3 m, the best house to build along the coast in the future is probably a structure with RC in the lower floor to protect against tsunami forces and wood in the upper floors to protect against earthquake forces.

Japan is well known for its advanced tsunami disaster prevention knowledge, but it also suffered great losses from the 2011 Great East Japan tsunami. Similar to the countries affected by the 2004 Indian Ocean tsunami, Japan has plans to construct memorial parks and museums using floating debris and damaged structures as symbol to recall events and advocate tsunami awareness among coastal residents. Other ideas, such as the "Sakura line 311" plan for planting Sakura trees along the tsunami inundation line and the "Hill of thousand years hope" that will make use of tsunami debris to build an artificial tsunami escape hill, lead Japan toward the next stage of tsunami disaster prevention. A major difference setting Japan apart from other countries is that it has a longer and richer history of tsunami experience and culture than, for example, Southeast Asian countries.

A good example of this culture is a festival in the Wakayama prefecture that celebrates a real story called "Inamura no Hi." The story originated from the Nankai tsunami in 1854. The town leader, Hamaguchi, knew that it would be difficult to convince people to evacuate away from the tsunami. Therefore, he set fire to his own rice straw and asked people to help him extinguish the fire (in Japanese, "inamura" means rice straw and "hi" means fire). All of the town residents came to help him and were saved from the huge tsunami that destroyed the rest of the village. Hamaguchi became a hero in the village and spent his own money to construct a seawall, which later helped protect the town from the 1944 Tonankai and 1946 Nankai tsunamis. In memory of this event, local residents, especially children, help pile dirt on the seawall's earthen embankment and strengthen their tsunami awareness every year. Japan can adapt its own knowledge, for example, by using shrine as a tsunami storyteller, employing cutting-edge technology to construct a massive structural countermeasure and creating media to promote awareness, such as tsunami videos, numerical simulations and hazard maps. These measures will help Japan reconstruct towns affected by tsunamis and also be ready for the next tsunami. In addition, because of this vast knowledge which is updating with number of tsunami event, Japan could play an important role as a leader of tsunami preparedness and awareness country

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