

Lessons Learned from the 2011 Tohoku Tsunami

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Introduction

On 11 March, 2011 a devastating tsunami accompanied by a M9.0 earthquake struck the northern Pacific coast of Japan, and completely destroyed many coastal communities, particularly in the Iwate, Miyagi, and Fukushima prefectures. The total area affected by the tsunami was estimated as 561 km² along the Pacific coast of Japan (Geospatial Information Authority of Japan, 2011). The tsunami run-up height reached 40 m (The 2011 Tohoku Earthquake Tsunami Joint Survey Group, 2011).

As of 10 September, six months after the event, Japan's National Police Agency reported 15,781 dead (4656 in Iwate, 9456 in Miyagi, 1603 in Fukushima and 66 in other prefectures) and 4086 still missing. 115,151 buildings and/or houses collapsed or were washed away by the tsunami. The economic impacts have been estimated at 16 - 25 trillion yen (Cabinet Office, 24 June, 2011), compared to a FY2010 national budget of 92 trillion yen (Ministry of Finance, February, 2010).

Having passed six months since the event, the devastated areas have started moving forward to recover and reconstruct, or, in other words, renovate their communities. Approximately 82,000 residents who lost houses have moved from shelters to temporary houses (52,000 units were supplied) and rental housing (Ministry of Land, Infrastructure, Transport and Tourism, 2011). Eight-nine percent of an estimated 23 million tons of tsunami debris has been removed (Ministry of Environment, 2011). Though the recovery process continues, local governments have completed draft reconstruction plans that include infrastructure design, transportation, land use management, urban design, relocation, economic and industrial outlooks.

This paper will report on efforts to identify the impact of the 2011 Tohoku tsunami disaster and the lessons learned from this event, in the hopes of promoting the safety of schools and children within tsunami-resilient coastal communities.

Causes of Tsunami Generation

Tsunami is a Japanese term derived from the characters *tsu* (meaning harbor) and *nami* (meaning wave). The term is now widely known. A tsunami is defined as a series of water waves caused by the sudden displacement of a large volume of water, usually in an ocean or in large lakes. Due to the tremendous volumes of water released at high energy from its source, a tsunami can devastate coastal

regions. Earthquakes, underwater explosions such as volcanic eruptions, landslides, underwater landslides and large mass movements (meteorite ocean impacts or similar impact events) all have the potential to generate a tsunami. For example, the 1883 Krakatau volcanic eruption generated a devastating tsunami that reached 38 m above sea level, killing thousands of people and destroying coastal villages.

Most tsunamis are generated by earthquakes that occur in a **subduction zone**, the area where an oceanic plate is subducting beneath a overriding plate. The friction between the subducting plate and the overriding plate causes stress to build up between plates. Usually, stress accumulates in the interface between plates (inter plate) over a long period of time, such as decades or centuries. Finally the stress accumulated between the plates reaches its limit and is suddenly released, as a fault rupture. This sudden motion occurring in shallow crust within ocean depths becomes the cause of the tsunami, because the sea floor deformation--such as uplift and subsidence--pushes up or draws down the overlying water, causing a sudden displacement of a large volume of water body

(Figure 1).

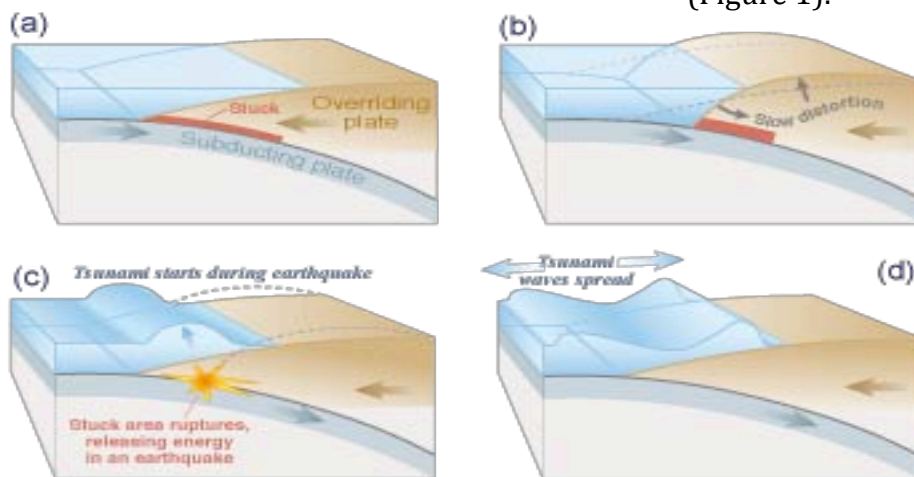


Figure 1 --- The process of stress accumulation between the plates and generation mechanism of tsunami (Atwater et al., 1999). (a) Subduction of oceanic plate underneath continental plate, (b) Accumulation of stress between the plates, (c) Energy release by fault rupture to cause sea bottom deformation and tsunami generation, (d) Tsunami propagation and coastal inundation.

Mechanisms of the 2011 Earthquake off the Pacific coast of Tohoku

The March 11 Tohoku earthquake was caused by thrust faulting on the plate boundary between the Pacific and North American plates. There, the Pacific plate moves westwards at a speed of 8.5 cm/year and is subducting beneath the North American plate at the Japan Trench. Earthquake source studies imply that the fault rupture occurred with a slip amount of 30 m, over an area approximately 450 km by 150 km (Figure 2).

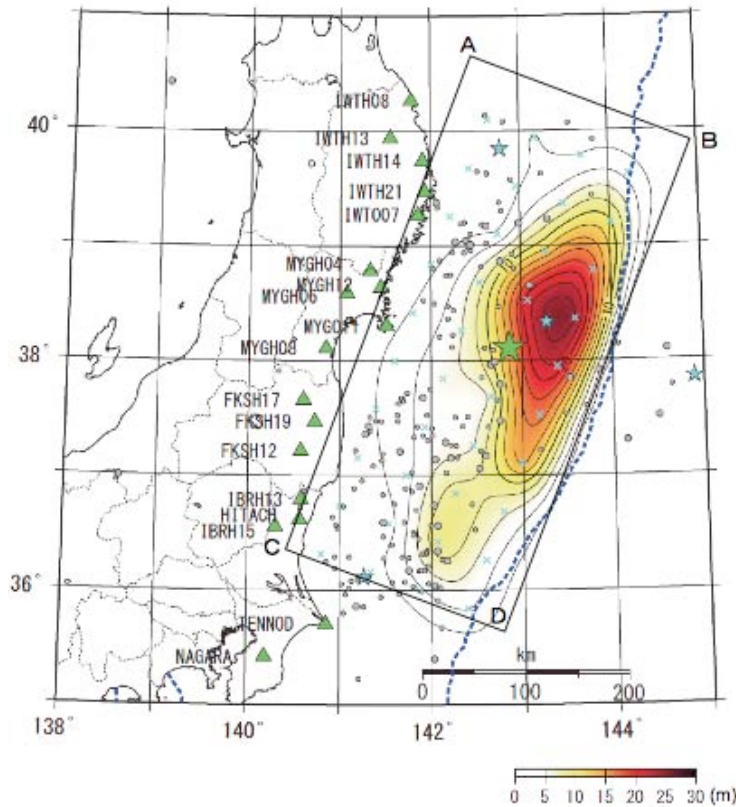


Figure 2. Rupture of the 2011 earthquake off the Pacific coast of Tohoku (Meteorological Research Institute, 2011).

Since 1973, nine earthquakes M7 or greater have occurred in the Japan Trench subduction zone (USGS, 2011). The largest one was M 7.8 (the 1994 offshore Sanriku earthquake) and occurred approximately 260 km north of the March 11 earthquake's epicenter. The Sanriku earthquake caused three fatalities and more than 700 injuries. In June 1978, a M 7.7 earthquake 35 km southwest of the March 11 epicenter caused 28 fatalities. Large offshore earthquakes occurred in the same subduction zone in 1611 (Keicho era), 1896 (Meiji era) and 1933 (Showa era), generating devastating tsunamis on the Pacific northeast coast of Japan (Sanriku).

The Sanriku coastline is particularly vulnerable to tsunamis, because it has many V-shaped bays that cause tsunami energy to converge and amplify. For example, the 1896 Meiji earthquake (M7.6) generated a tsunami as high as 38 m, which resulted in a reported death toll of 22,000. The 1933 Showa earthquake (M 8.6) tsunami reached as high as 29 m on the Sanriku coast and caused more than 3000 fatalities. Few earthquakes larger than M 8.0 have occurred along the northern part of the Japan trench and Kuril trench (off north Miyagi to Hokkaido), excepting the 869 (Jogan) and 1611 (Keicho) earthquakes.

The 2011 Tohoku Tsunami

To describe the overland flow of a tsunami, we define quantities as shown in Figure 3 (see page 4). Important quantities include the tsunami flow depth, tsunami inundation height, the run-up height and the inundation distance. Run-up height is the maximum ground elevation inundated by the tsunami on land. Flow depth is the depth of the tsunami flood over the local ground height, while the inundation height is the total elevation of the water free surface (water mark) above a reference datum, which is usually defined as the tide level under normal conditions.

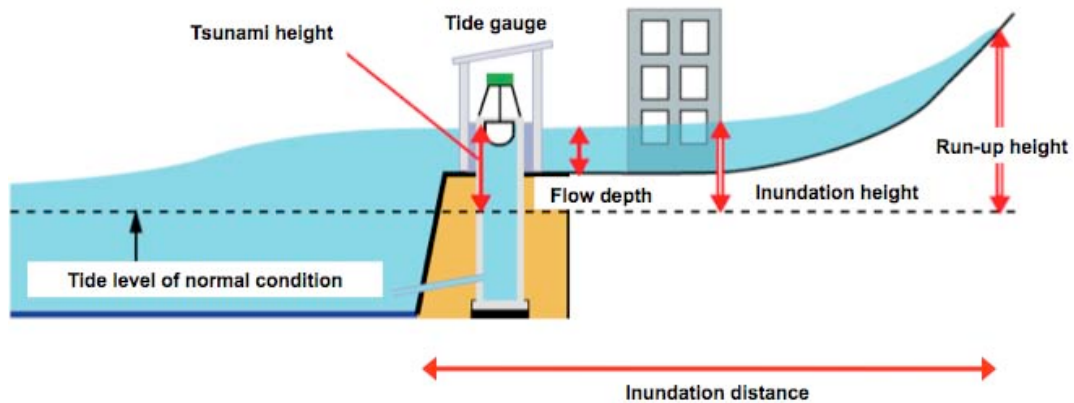


Figure 3 Definition of tsunami height (After Japan Meteorological Agency).

Figure 4 (see page 5) illustrates the measured tsunami inundation and run-up heights (2011 Tohoku Earthquake Tsunami Joint Survey Group, 2011), with plots of historical tsunami heights included (1611 Keicho Sanriku, 1896 Meiji Sanriku, and 1933 Showa Sanriku earthquake tsunamis). Northeast of Tohoku, the maximum run-up height in this event was similar to the events of both 1896 and 1933, especially of the 1896 Meiji Sanriku tsunami. However, the affected area of this event was much more extensive than in those historical events. In this sense, the 11 March 2011 event was the largest known tsunami event in Japan. In addition, a significant feature of the 2011 tsunami was the wide extent of the inundation zone; for example, on the Sendai plain, the tsunami inundated more than 5 km inland, causing devastating damage to populated areas and rice fields (Figure 5, page six).

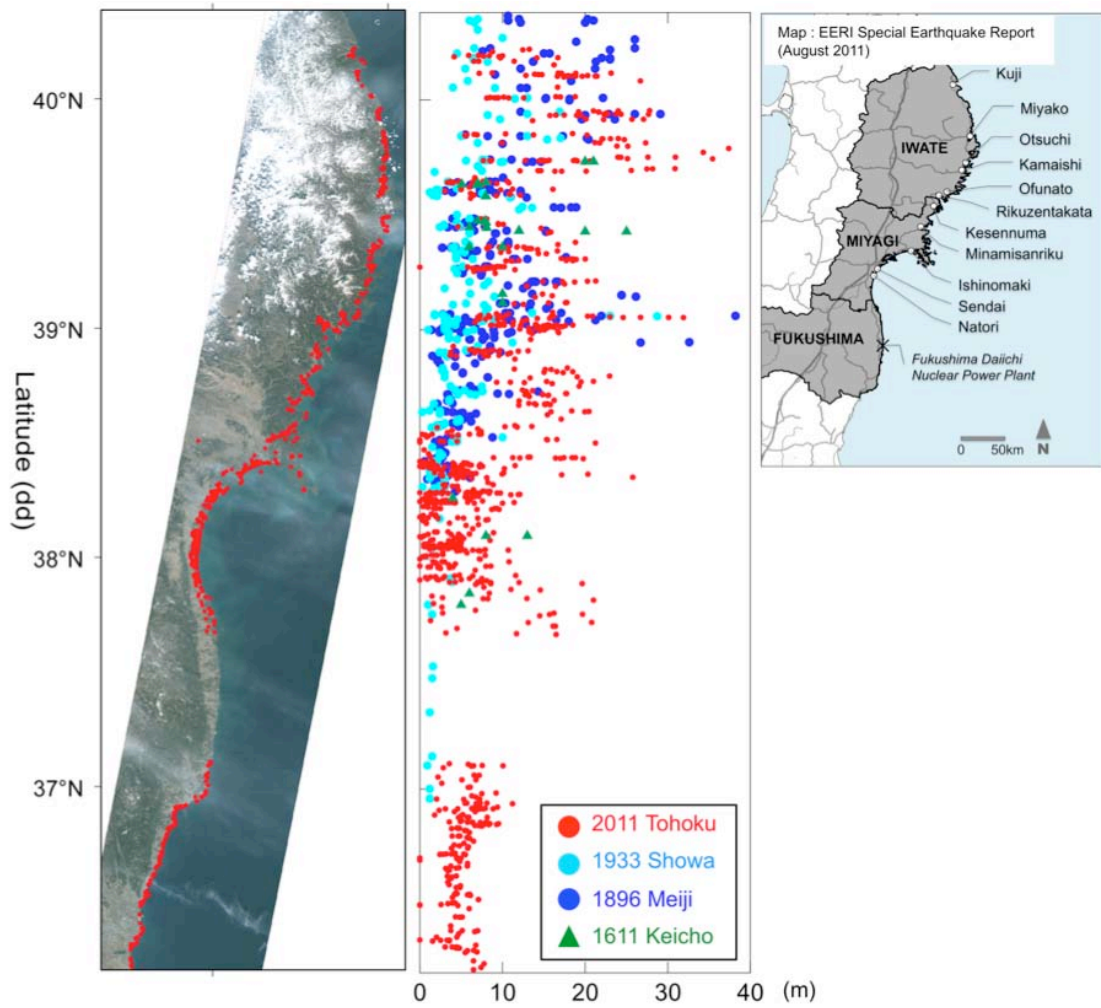


Figure 4 The measured heights of the 2011 Tohoku tsunami and historical Sanriku earthquake tsunamis (1611, 1896 and 1933 events).

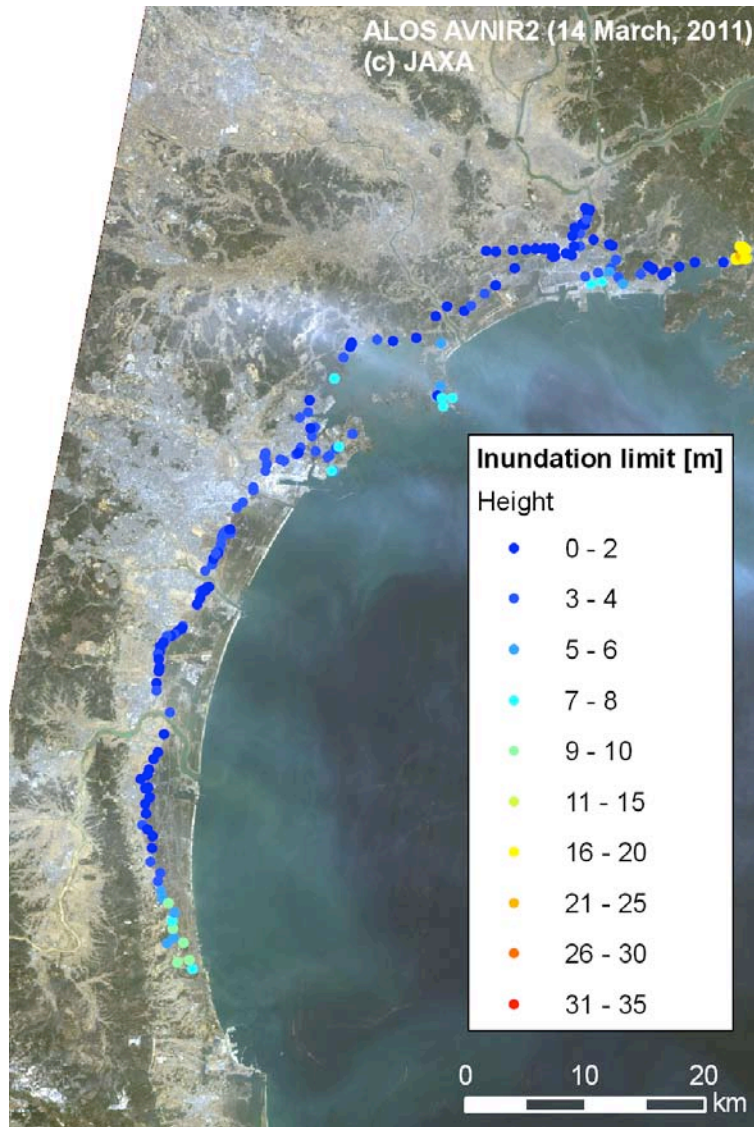


Figure 5 Inland limit of tsunami penetration on Sendai plain, Miyagi prefecture. The colored dots represent the position and the ground height of the inland limit of tsunami inundation.

Tsunami Propagation and Coastal Inundation

A tsunami is categorized as a “long wave” in water surface waves, which has much longer wavelength (L) than the water depth (h). When h/L of a water surface wave (train) is smaller than $1/20$ --in other words, when a wavelength is 20 times longer than the water depth (often hundreds of kilometers long, whereas normal ocean waves have a wavelength of only 30 or 40 meters), it has the characteristics of a long wave. Consider the moment that a tsunami is generated offshore at depths of several thousand meters by a sudden sea bottom deformation. Assuming the wavelength of a tsunami as a hundred kilometers and the initial height of the sea surface as several meters or even 10 meters, the horizontal scale of that tsunami is much larger than the vertical scale of sea surface movement. In this sense, tsunamis generally travel unnoticed in the deep sea, and ships are hardly aware of the wave’s passage.

Simply, how fast a tsunami travels in the ocean can be described by the formula, $c = \sqrt{gh}$, where c (m/s) is the speed of the tsunami (travel speed of long wave), g is the gravitational acceleration ($=9.8 \text{ m/s}^2$), and h is the local water depth (m). Thus, the speed of tsunami propagation only depends on the water depth; a tsunami travels faster in the deeper ocean and slower in shallower sea waters. When we assume $h=4000 \text{ m}$ as an approximate average water depth in the Pacific Ocean, c is calculated as $198 \text{ m/s}=713 \text{ km/h}$. This is almost the same order of speed as the cruising speed of a jet plane. However, when a tsunami propagates near shore area or in a bay entrance (e.g. $h=30 \text{ m}$, c is as $17 \text{ m/s}=61 \text{ km/h}$), its traveling speed is equivalent to the speed of a car. Finally, when a 5 m tsunami reaches a coast, c is reduced to $7 \text{ m/s}=25 \text{ km/h}$, comparable to the speed of a small motorcycle. (Considering that a 5 m tsunami travels as fast as a motorcycle, going to a harbor or beach to watch a tsunami is suicide!)

As the tsunami approaches the coast and the water depth becomes shallower, reducing the tsunami’s traveling speed, wave shoaling (the effect by which surface waves entering shallower water increase in wave height) compresses the tsunami, and its amplitude increases significantly (Figure 6 on page 8).

When fishermen who had not noticed a tsunami’s passage, while they were at sea fishing, came back to shore, they could find their harbor and village devastated by a huge wave. This is why the term “tsunami” means “harbor wave”.

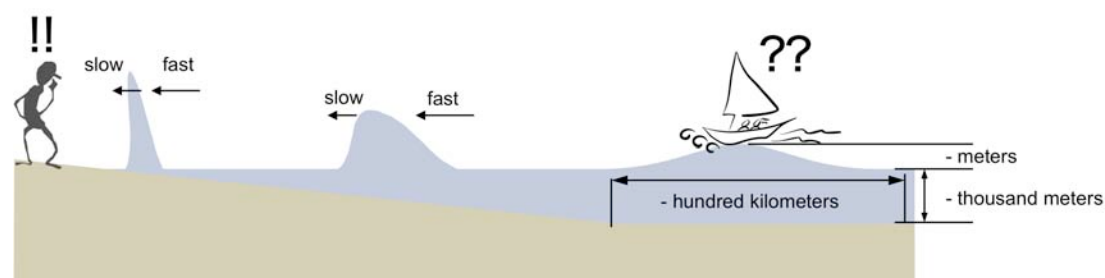


Figure 6. Schematic explanation of tsunami wave shoaling.

Tsunamis Have No Border

The tsunami threat is not contained to the coast facing the fault rupture area. Sometimes a tsunami travels across the ocean as a so-called “tele-tsunami” or far field tsunami. A tele-tsunami is defined as a tsunami from its source more than 1000 km away from area of interest.

In 1960, a gigantic earthquake of M 9.5 occurred off the coast of south-central Chile and generated a tsunami that was devastating to the entire Pacific. The tsunami propagated across the Pacific Ocean, striking the Hawaiian islands with 10.5 m tsunami height, causing 61 fatalities and \$24 million USD in economic losses (National Geophysical Data Center), and then reaching all the way to Japan as an over 6 m tsunami, where it killed 142 people (Figure 7 on page 9).

In recent years, the 2004 Sumatra-Andaman earthquake tsunami (known as the Indian Ocean Tsunami) and the 2010 Chilean earthquake tsunami affected many countries. Similarly, the 2011 Tohoku tsunami traveled across the Pacific, sank several boats in harbors along the coasts of Oregon and California (two states in the western U.S.), swept away four people who were later rescued, and killed a man who was taking photos of the tsunami waves. As previously mentioned, going to the beach to watch a tsunami when a warning has been issued is suicide.

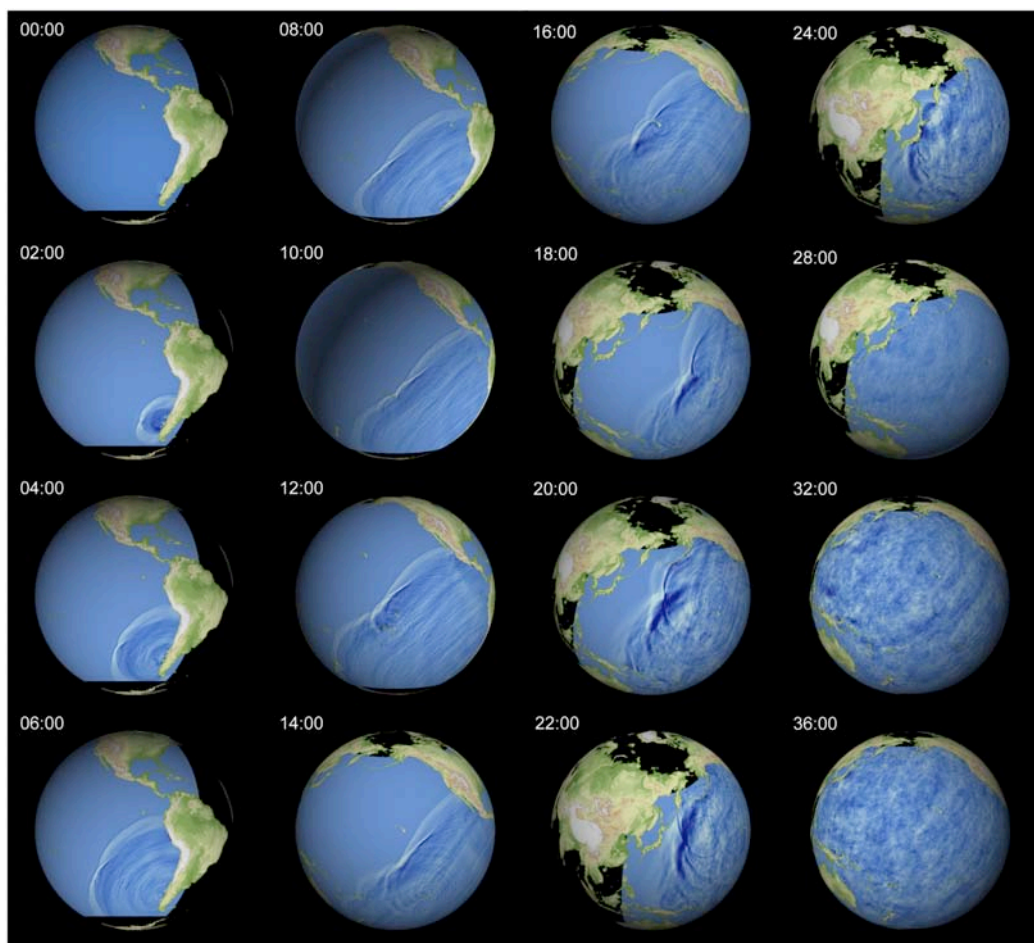


Figure 7 The 1960 Chilean tsunami simulation traveling across the Pacific, where it would cause severe damage to the Hawaiian islands and Japan.

Tsunami flow velocity

When a tsunami reaches the coast, its characteristics change significantly, from that of a water wave to a strong inundation flow. The hydrodynamic forces of a strong inundation flow cause damage to infrastructure, buildings and people. Measuring the flow velocities of tsunami inundation on land was historically quite rare, and it was difficult to understand what had really happened in a devastated area and to identify the cause and mechanisms of structural destruction by tsunami inundation flow. However, in recent years, many tsunami survivors have attempted to capture the moment of the tsunami's assault on their communities using a videocamera or cell phone and have then uploaded their footage onto the Internet. (Note again that taking photos or videos of a tsunami should only ever be done from a position uphill, never from a beach.)

Applying a video analysis technique, the tsunami flow velocity can be determined. Here, the author presents one example from Onagawa town, in Miyagi Prefecture (which had a population of 10,014 before the earthquake), which was devastated by the 2011 Tohoku earthquake tsunami. The author's investigation determined that at least six reinforced concrete or steel construction buildings were found overturned or washed away. The tsunami attacked the town of Onagawa (Figure 8) at 15:20 (35 minutes after the earthquake occurred), causing 816 fatalities. One hundred twenty-five people are still missing. The video from which this still was taken was filmed by a resident who evacuated to the top of a reinforced concrete building in Onagawa harbor (see arrow indicator in Figure 8).



Figure 8. An overview of Onagawa town, Miyagi Prefecture. Photo taken by PASCO Corporation. The red arrow indicates the point where the survivor video was taken.

Figure 9 (on page 11) is a still shot taken from the video, capturing the moment when houses are being washed away. Using this video, the author analyzed the time series of flow depth by measuring the height of the water level on withstanding buildings shown in the video. By also focusing on the movement of

drifting objects, the flow velocity was estimated at the moment when the houses were washed away. Consequently, the flow velocity of the tsunami inundation was estimated as 6.3 m/s, at a flow depth of approximately 5 m. This 6.3 m/s of inundation flow caused approximately 10 tons of force per meter of wall. This hydrodynamic force easily destroyed houses.

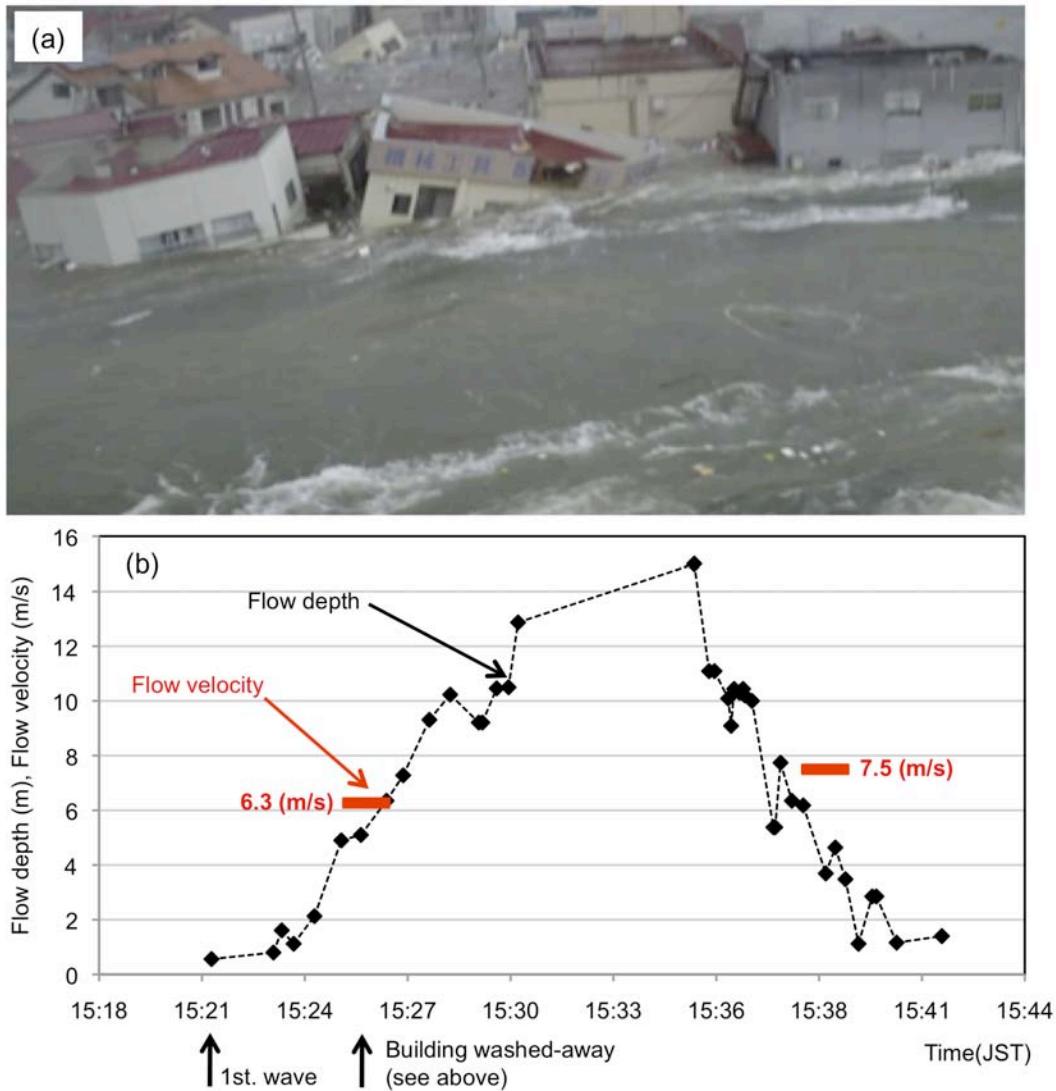


Figure 9 (a) A snapshot from the video taken by a survivor (Yomiuri Shinbun, 2011) capturing the moment when houses were washed away. (b) Time series of tsunami flow depth and current velocities, interpreted based on study of the video.

Tsunami Preparedness in Coastal Communities

Tsunami countermeasures in Japan

In 1997, Japan's central government council, which consists of seven ministries, issued a guideline for comprehensive tsunami countermeasures that should be taken as part of regional tsunami disaster prevention. In those guidelines, three basic concepts of tsunami countermeasures were recommended: (1) Building seawalls, breakwaters and flood gates to protect lives and properties. (2) Urban

planning to create a tsunami-resilient community through effective land use management and arrangement of redundant facilities to increase the safe area, such as vertical evacuation buildings. (3) Disaster information dissemination, evacuation planning and public education. The 2011 Tohoku event provided the first real test of the various technologies and countermeasures that Japan is using to protect people in tsunamis. Some probably worked well, while others appear to have failed (March 11, 2011, by Andrew Moore, Special to CNN).

Coastal Protection Infrastructure

In Miyagi Prefecture, north of Ishinomaki, the coastline becomes rugged and steep forming a V-shaped bay, with potential to amplify a tsunami. Since the 1896 Meiji Sanriku earthquake tsunami that killed 22,000 people, and since the more recent 1960 Chilean earthquake tsunami, Japan has developed a coastal protection infrastructure of seawalls and breakwaters. Especially in Iwate Prefecture, 10 m high seawalls have been built along the coast to protect communities that have been devastated many times throughout history.

The Kamaishi tsunami breakwater (Figure 10 on page 13), which is in the Guinness World Book of Records as the deepest tsunami breakwater at nearly 63 m deep, was designed to protect the densely populated area in Kamaishi city, which is located at the bottom of the bay. Its construction started in 1978 and was completed in 2006, requiring an investment of almost 30 years and 120 billion yen. But even this barrier could not protect citizens from the 2011 tsunami, although it earned them a six minute delay before the tsunami penetrated to Kamaishi city. One can understand how, with this huge concrete breakwater, people in Kamaishi city would feel well protected, and yet the 2011 tsunami caused 1253 fatalities.

The lesson is that even great seawalls can fail. Seawalls should be designed with the assumption of overtopping and destruction, and we should not rely so heavily on coastal infrastructure.

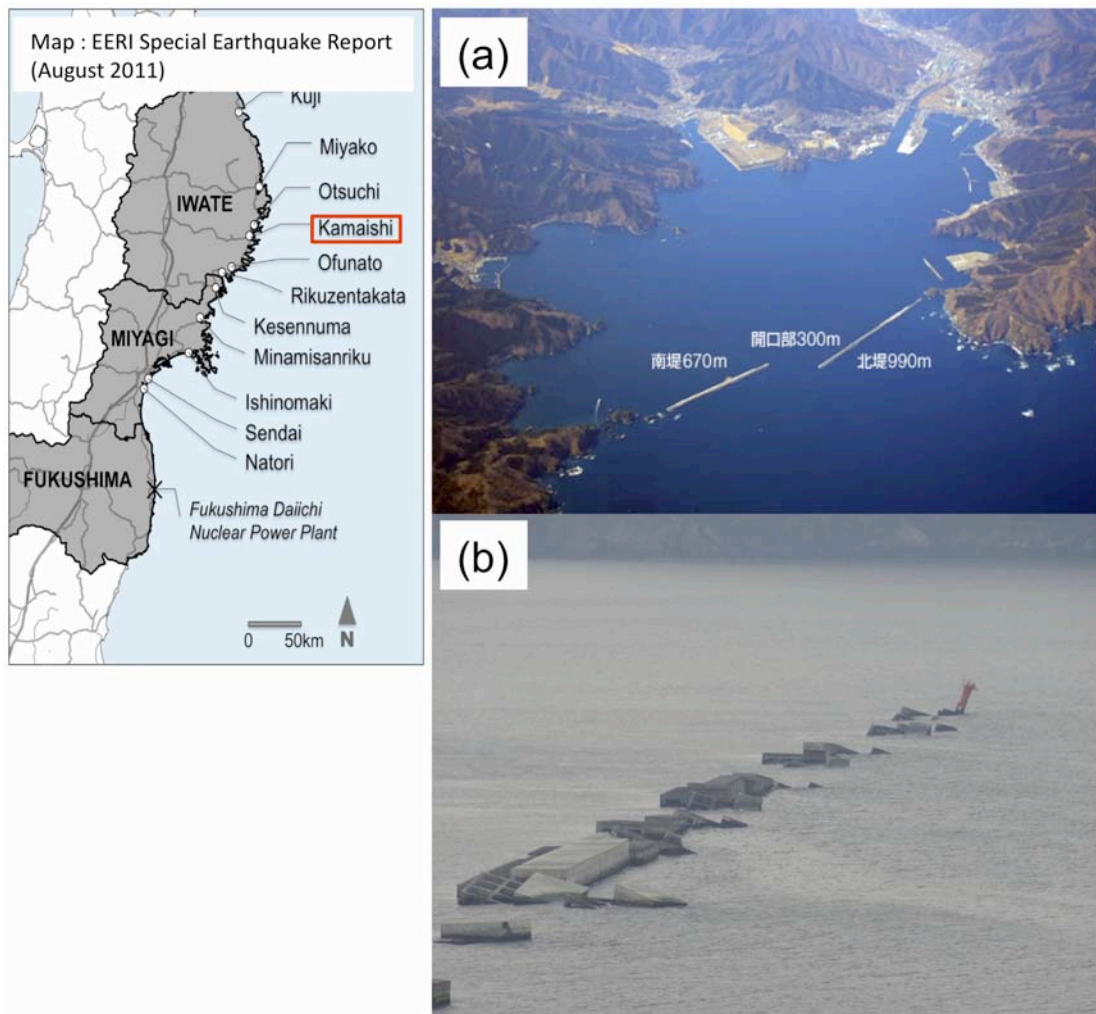


Figure 10 (a) Tsunami breakwater in Kamaishi city, Iwate Prefecture. (b) Damaged Kamaishi tsunami breakwater (northern part).

Hazard Maps

It was widely believed that Japan was one of the most prepared countries in the world for a tsunami event. Was this belief correct? If so, then why were so many people killed in this catastrophic March 11 event?

In one sense, the belief **was** right. The 2004 Sumatra-Andaman earthquake tsunami (Mw9.0-9.3) killed 220,000 people, while the 2011 event (Mw 9.0) caused approximately 20,000 fatalities, if we include those who remain missing. Both events are geologically similar with regard to the size of the earthquake and the height of the tsunami. One reason for the striking difference in the number of fatalities could be the level of preparedness.

Coastal cities and towns in Japan had prepared tsunami hazard maps with estimated inundation zones, the list of shelters where people could evacuate and instructions on how to survive a tsunami. In many coastal communities, people have conducted very regular evacuation drills and have held workshops to learn which areas are at risk, by referring a hazard map prepared by the local government. Figure 11 contrasts one hazard map for Kesenuma city, in Miyagi

Prefecture, with the actual extent of inundation in the 2011 tsunami. Most readers will agree that the maps are quite similar in terms of the tsunami inundation extent.

In addition, in Sanriku coastal communities, people were taught the lesson or phrase of “tsunami tendenko,” which means that “people should run without taking care of others, even family members.” This phrase encourages people to escape by relying on everyone’s individual decision and responsibility: each individual’s effort increases the surviving possibility.

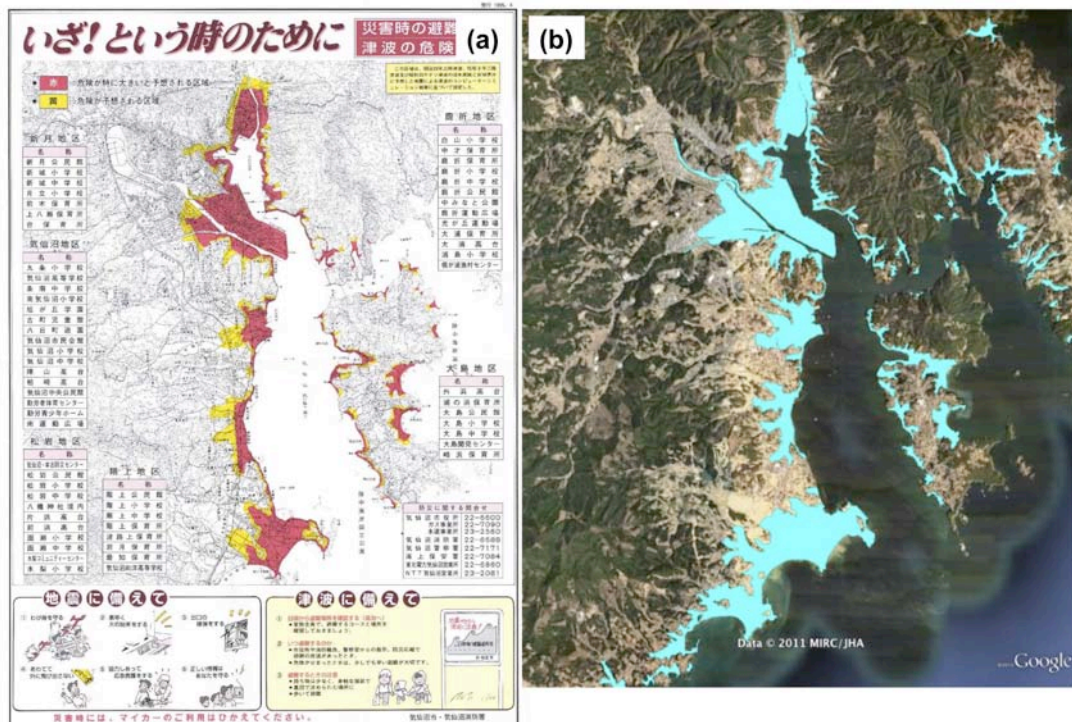


Figure 11 (a) Tsunami hazard map published in Kesenuma city, Miyagi Prefecture, and (b) the map of tsunami inundation extent in the 2011 event. The tsunami caused 1,467 dead or missing even in this well-prepared community.

At the same time, in some coastal regions, the 2011 tsunami was far more extensive than had been expected. Figure 12 (on page 15) shows a comparison of the expected tsunami inundation zone in Sendai city’s hazard map, with the state-of-the-art computer simulation assuming M8.0 earthquake scenarios off Miyagi Prefecture, and the 2011 tsunami inundation extent. The 2011 tsunami caused much more inundation than had been estimated by the computer simulation. The lesson learned is that computer simulations cannot paint the whole picture of any disaster.

Hazard maps have two functional aspects. One is to tell people that they are at-risk. It is through such opportunities to *know* their risk that people learn that they must try to escape an at-risk area as soon as possible, when they feel strong ground motion or hear the tsunami warning or evacuation order issued. On the other hand, a hazard map can function to assure residents living outside of the expected inundation zone that their area is NOT at risk. This is one negative aspect of relying too completely on a hazard map. In the 2011 event, hazard

maps failed to offer accurate predictions in some areas and may have increased the number of fatalities, as people believed that they did not have to evacuate immediately—this although the maps indicated the uncertainty of estimations based on computer simulation.

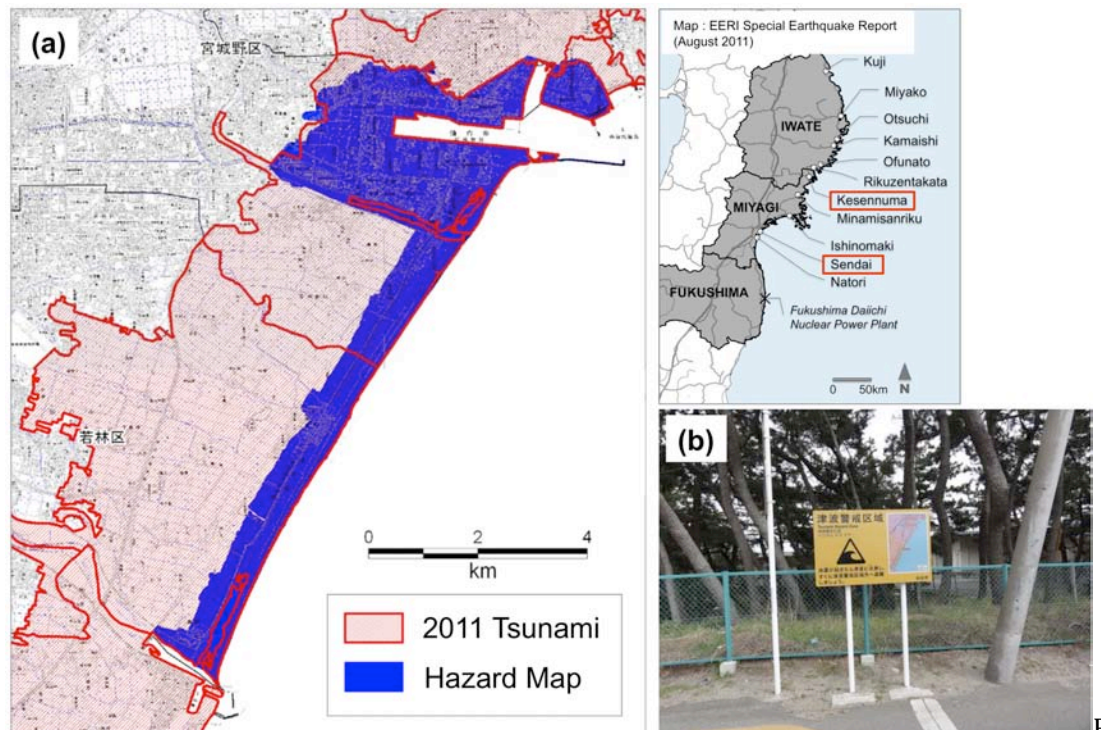


Figure 12 (a) Tsunami hazard map published in Sendai city, Miyagi Prefecture. The 2011 tsunami inundation extent is also on the map for basis of comparison. (b) Tsunami sign and instruction were put on the beach to warn residents and visitors to evacuate. The tsunami left 755 dead or missing in Sendai city.

Tsunami Warnings in Japan

The Japan Meteorological Agency (JMA), which is responsible for issuing tsunami warnings and for estimating tsunami height, employed a new system in 1999 and updated it using Earthquake Early Warnings (EEQ) in 2006. Japan believed that JMA's tsunami warning system was using the most advanced technology in the world. In fact, its tsunami forecasting technologies and numerical models were exported to many foreign countries that needed support. JMA prepared a pre-calculated tsunami database for over 100,000 earthquake scenarios around Japan. The contents of the warning were classified into 3 categories, according to the estimation of tsunami height: "Major tsunami" (as warning, more than 3 m of estimation), "Tsunami" (as warning, 1 or 2 m of estimation) and "Advisory" (0.5 m or less).

When the 2011 event occurred at 2:46 PM on 11 March (JST), JMA's initial estimate of the magnitude (M_j) was 7.9, using the nationwide seismic records that were not saturated. Based on the initial estimate of magnitude 7.9, three minutes after the quake, JMA issued a tsunami warning to the coasts of Iwate, Miyagi and Fukushima Prefectures with the estimates of 3 m, 6 m, and 3m,

respectively. After the tsunami was observed at offshore tsunami buoys, JMA revised the contents of the warning with estimates of 3 m, 6 m, over 10 m, 6 m, 4 m to the coasts of Aomori, Iwate, Miyagi, Fukushima, Ibaraki and Chiba Prefectures (see Figure 13). Receiving the tsunami warning from JMA, some residents claimed that they thought they were safe based on the 3 m estimation; they did not feel that they had to evacuate, since they felt safe behind a 10 m seawall. Even worse, in several communities, the radio or speaker system did not work because of the blackout caused by the earthquake.

Now, JMA has started planning to expand its seismic/tsunami monitoring network by installing broadband seismometers and offshore tsunami monitoring system, to increase its capability for quicker and more accurate estimation. However, there are limitations on the reliability of science and technology that can be used in such a limited amount of time. Tsunami warning information can inform people that they are in danger, but it cannot guarantee people's safety. The most important lesson is that one should not wait for official information to act: strong ground shaking is the first alert to take action, in order to survive.

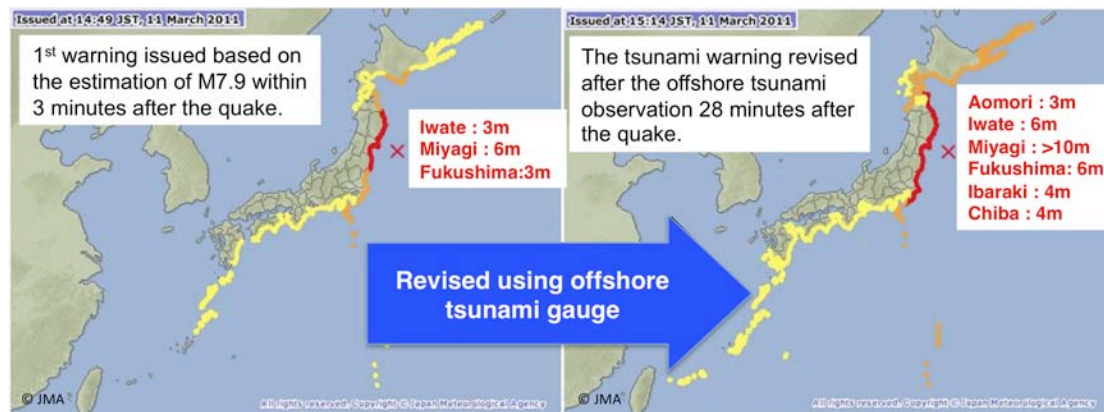


Figure 13 The JMA tsunami warning issued and revised in the aftermath of the 2011 Tohoku earthquake.

Structural Vulnerability to Tsunamis

Structural vulnerability to tsunamis is a critical issue in planning for tsunami-resilient communities. Figure 14 (on page 18) shows the result of mapping building damage in Ishinomaki city by interpreting aerial photos that the Geospatial Information Authority of Japan acquired of the devastated area. By mapping the structural damage and overlooking its spatial distribution, not only the impact of tsunami, but also the protective effect of coastal infrastructure and vegetation can be seen.

Integrating structural damage mapping with field survey data, such as flow depths (Figure 15 on page 19), produces a new measure of structural vulnerability to tsunamis, as a form of tsunami fragility curve or tsunami fragility function. A tsunami fragility curve is defined as the structural damage probability or fatality ratio with particular regard to the hydrodynamic features of tsunami inundation flow, such as flow depth, current velocity and hydrodynamic force. The tsunami fragility curve is preliminarily obtained as

shown in Figure 16 (on page 20). The fragility curve shown in the figure indicates the damage probabilities of structural destruction equivalent to the flow depth. Structures in Miyagi Prefecture were especially vulnerable when the local flow depth exceeded 2 m, while a 6 m flow depth would cause everything to be washed away. This finding can inform land use planning (zoning), so that residential areas will not be inundated more than 2m.

Figure 15 shows a spatial distribution of flow depths measured in the tsunami inundation zone. Spatial interpolation of measurement data (point data) to obtain raster data is combined with the structural damage mapping (e.g. Figure 14).

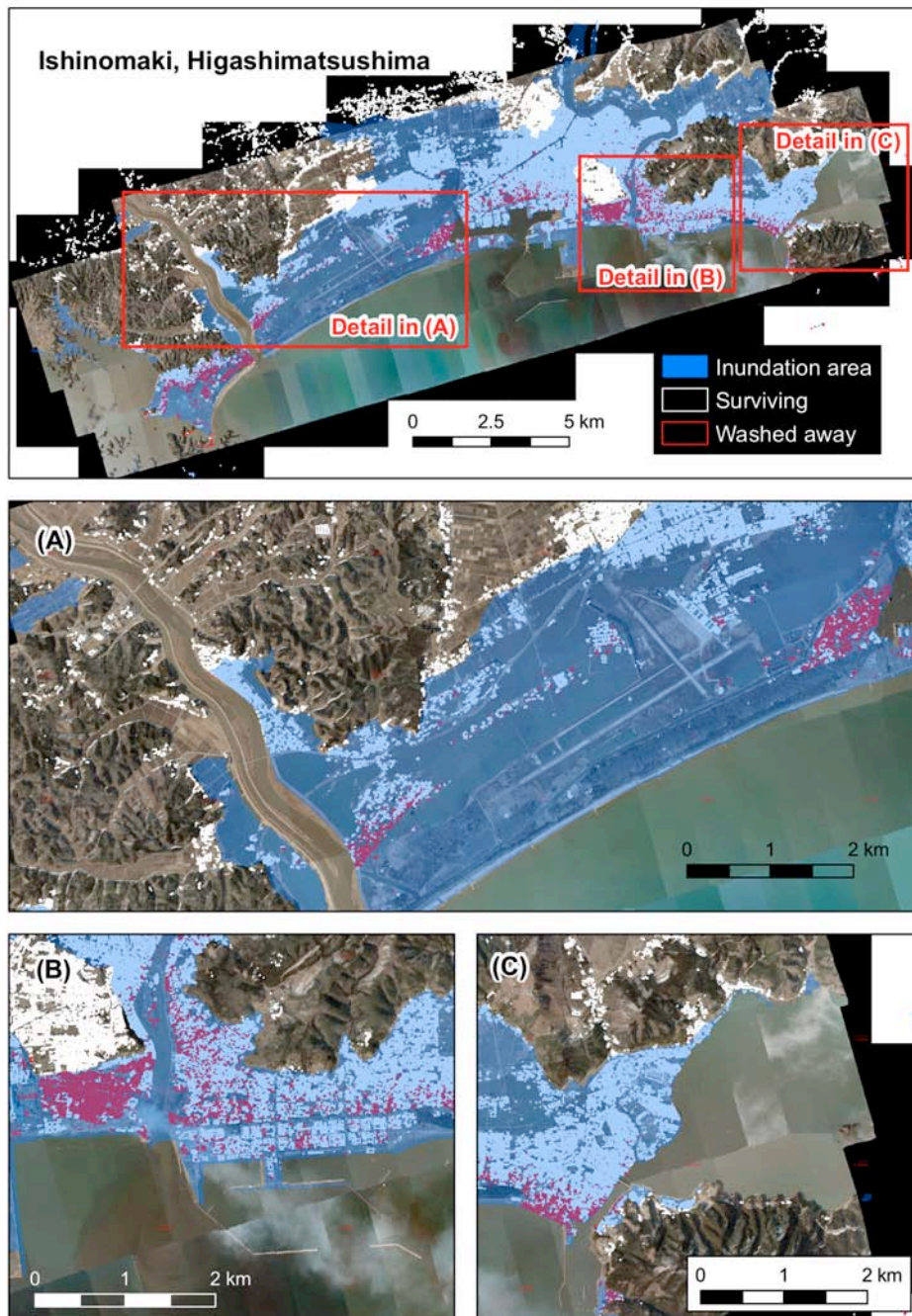


Figure 14 Mapping building damage by inspection of post-event aerial photos.

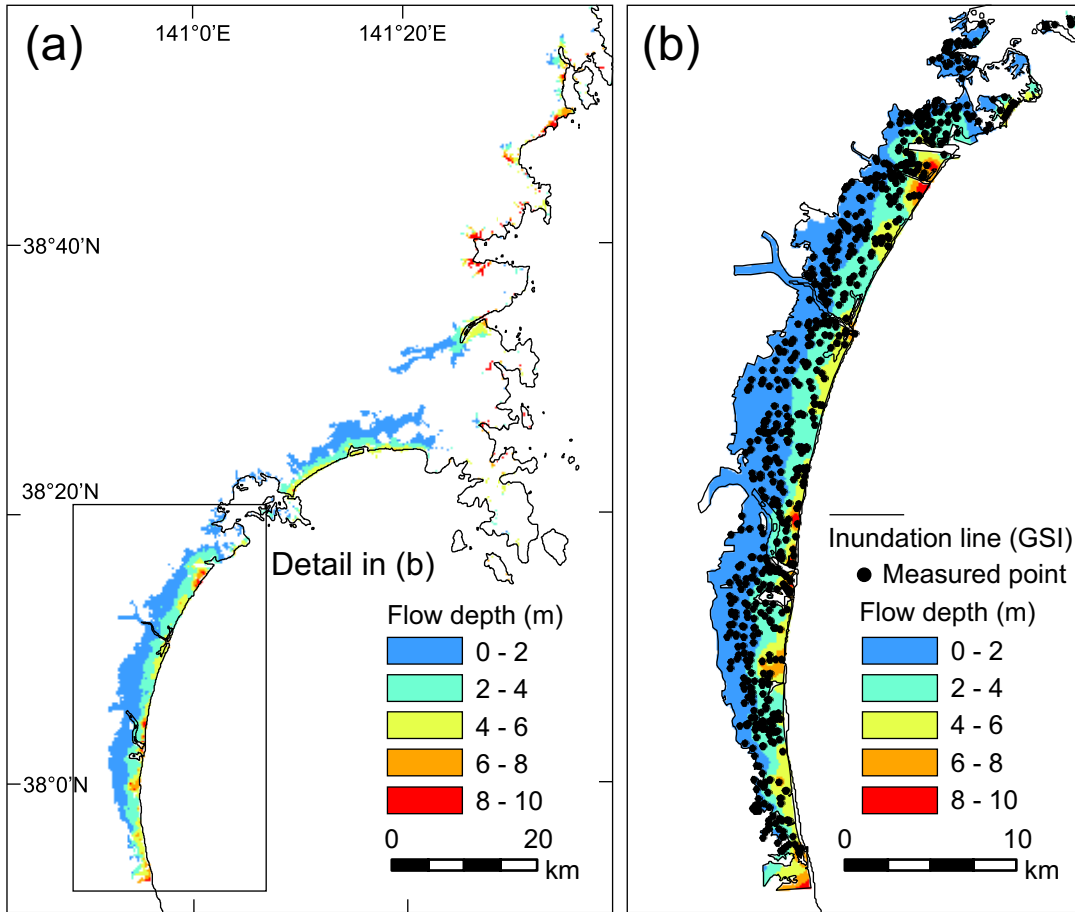


Figure 15 Mapping the tsunami flow depth measured by Miyagi Prefecture and the post-tsunami survey team. Black dots are the points of measurement.

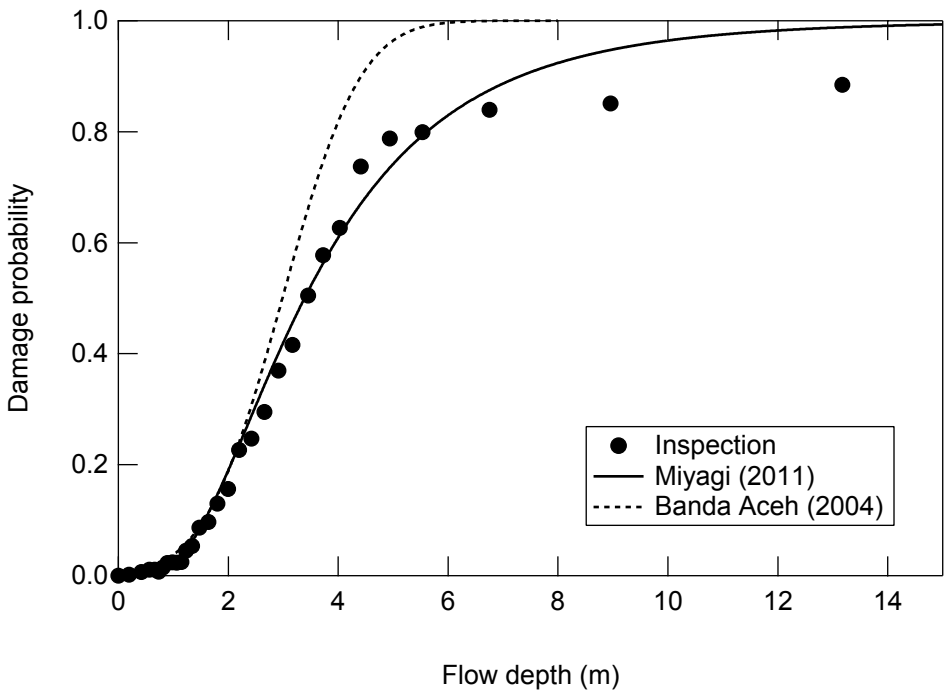


Figure 16 Tsunami fragility curve for structural destruction (washed-away structures).

The solid line is obtained from Miyagi Prefecture (from the 2011 event) and the dashed one is from Banda Aceh, Indonesia (the 2004 Indian Ocean tsunami).

The Tsunami's Impact on Schools – Tragedy in Okawa Elementary School

Many pupils and teachers were affected by the 2011 Tohoku earthquake and tsunami. On 6 October 2011, Japan's Ministry of Education, Culture, Sports, Science & Technology published a report of student fatalities and injuries: in total, 635 children, students and teachers were killed by the tsunami, and 221 were injured.

Especially hard hit was Okawa elementary school in Ishinomaki city, located 5 km inland along the Kitakami river: the school lost 74 pupils (70 killed and 4 still missing) out of a total of 108 and 10 teachers (9 killed and 1 still missing) in the 2011 tsunami (see Figure 17 on page 21). At least 50 minutes elapsed after the earthquake, before the tsunami attacked the school. After the strong ground shaking had stopped and the tsunami warning had been issued, the teachers and pupils gathered on school grounds to discuss where to go.

They had two options. One was a hill with a steep slope behind the school, which looked difficult for small children to climb. The other was a small overlook at the river bridge, 200 m away from the school. Consequently, teachers decided to head for the bridge, walking along the river. Shortly thereafter, the tsunami penetrated along the river and overtopped the riverbank, sweeping away pupils and teachers.

The causes of their deaths are still under investigation by the Ishinomaki city educational council. But we must learn the lessons of this sad incident. What is the requirement that should be put into place for safer school buildings that can withstand both strong ground shaking and a devastating tsunami—how much building height must be required, so that the inhabitants can survive? (The Okawa elementary school building withstood the devastating tsunami inundation flow but was totally submerged.) How we can educate children to be prepared? How should teachers be trained to provide appropriate guidance to save children's lives and their own?

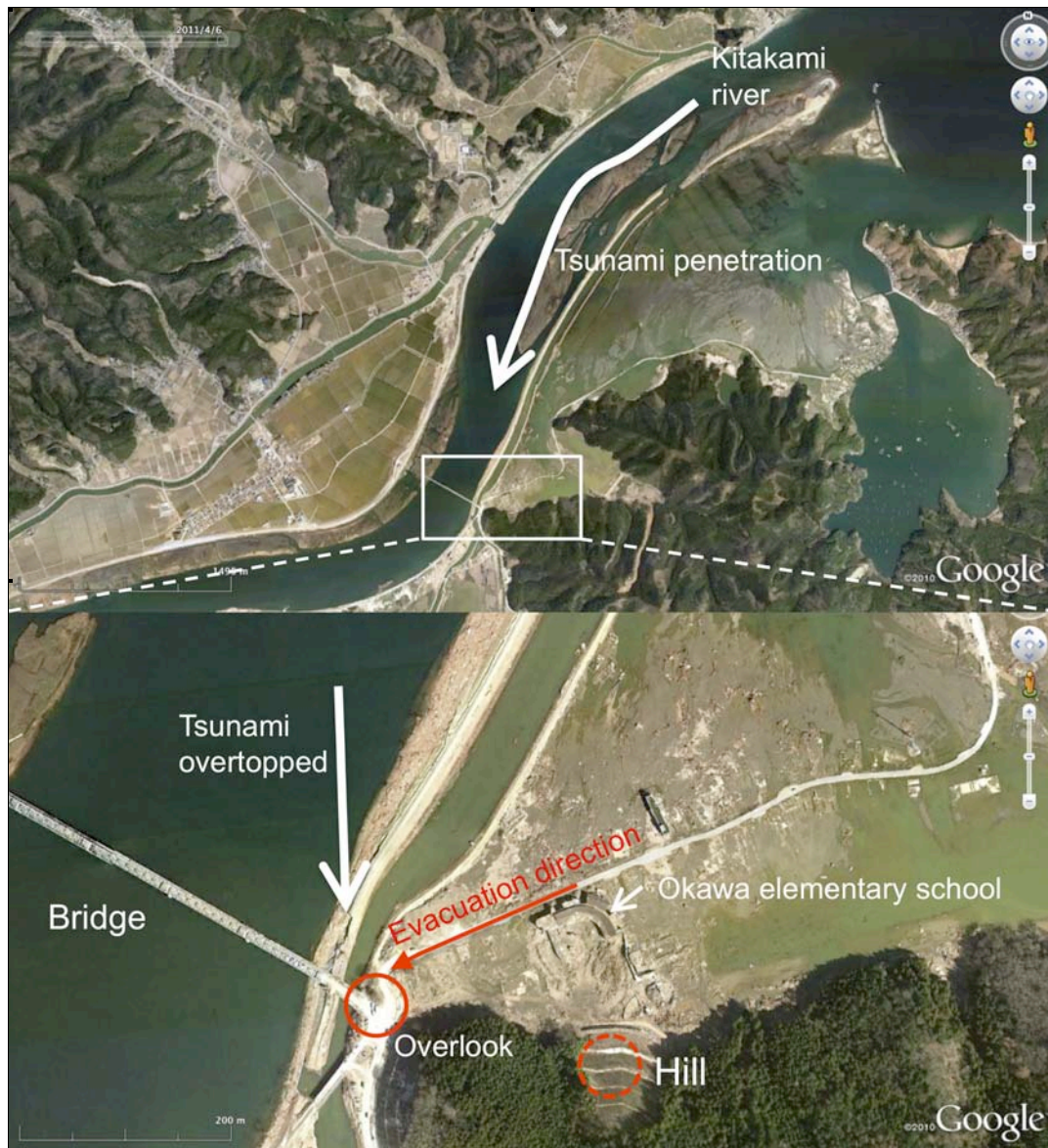


Figure 17 Okawa elementary school devastated by the 2011 Tohoku tsunami. The tsunami killed 74 Okawa pupils and 10 teachers, who were on their way to an elevated bridge.

Summary

The 2011 Tohoku earthquake and tsunami offer valuable lessons that should be applied, in order to build safer and more resilient coastal communities:

- Know which areas are at risk. This is critical, but one must also recognize the predictive limits of science and technology.
- Governments can reduce risk, but communities must not become complacent. Computer simulations cannot predict everything that will happen in a disaster. Hazard maps cannot always accurately predict areas at risk.
- Coastal infrastructure such as breakwaters and seawalls cannot always protect life and property: even great seawalls can fail. Seawalls should be designed with the assumption of overtopping and destruction, and communities should not rely on coastal infrastructures alone for

protection.

- Never go to the coast to watch a tsunami! If you do, then you must run faster than motorcycles to survive it.
- To survive a tsunami, evacuate to a higher place as soon as possible. The place for evacuation should be discussed in advance among family members. Find a safe place that you can reach within several minutes. If you can walk or run, then do not use a car.
- As observed in devastated areas in Japan, tsunami flow depth over 2 m has potential to severely damage houses.
- Highrise reinforced concrete buildings with robust columns and walls can withstand tsunami flow depth over 2 m and can be used for vertical evacuation.
- School buildings should have similar construction requirements, in order to ensure children's safety.
- Teachers, parents and children should have more opportunities to learn about their risk and how to survive in emergency situations.
- Citizens should find out how what disaster information resources are available, but they should not rely exclusively on official information in an emergency. Strong ground shaking will be a first alert to take action, in order to survive a tsunami.

Acknowledgements

The post-tsunami field survey was conducted by a group of 20 scientists and engineers. All the data of the team's measurements can be found online at <http://www.tohoku-tsunami.jp/>

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