The 2011 Great East Japan Earthquake

Sendai Plain Field Guidebook

災害科学国際研究所

IRIDeS

Cover photograph: View of the Sendai Plain from Sendai Airport, looking seaward (taken March 2013).

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Field guidebook working group: International Research Institute of Disaster Science, Tohoku University

Published Japanese version (1st March 2014), translated in English (6th August 2014)

1. Preface

A Mw 9.0 earthquake on March 11, 2011, triggered a large-scale tsunami that struck the Pacific coast of eastern Japan. The tsunami inflicted widespread and severe damage to coastal areas of the Tohoku district. The disaster ensuing from the 2011 earthquake and tsunami, one of the severest disasters in Japanese history, is called "The Great East Japan Earthquake" (hazard name is "the 2011 off the Pacific Coast of Tohoku Earthquake" defined by the Japan Meteorological Agency). The recovery process in tsunami devastated areas is ongoing. Many scientific data have been collected since the 2011 event. Many issues remain to be resolved, such as mental and financial care for the victims, reconstruction of devastated residential areas, and long-term monitoring.

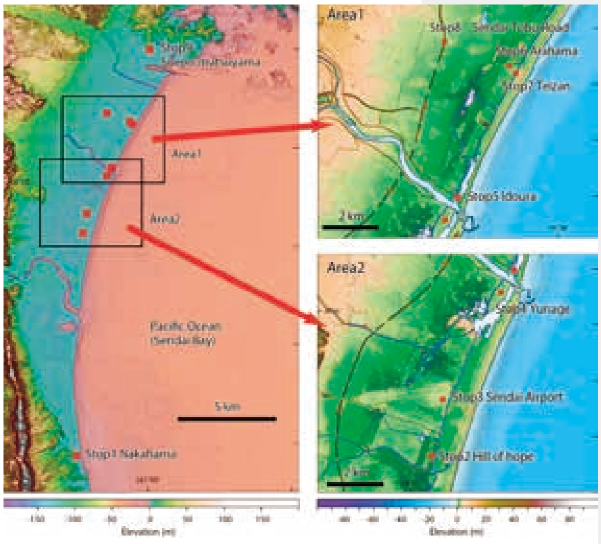


Figure 1: Stops in this field guidebook.

Since the 2011 disaster, many people have visited the tsunami-devastated area to understand what happened on March 11, 2011 and to ascertain how the recovery work has been progressing. We believe that persistent visits by people from other areas to the tsunami-devastated areas might encourage the people in those areas who were strongly affected by the disaster. It is expected to be worthwhile for people living in those areas and for those who must confront future tsunami risks.

In this context, we have noticed that there is no appropriate guidebook for the 2011 disaster in terms of its academic aspects. It is apparently difficult for people who want to know where to look. The International Research Institute of Disaster Science (IRIDeS), Tohoku University, was founded in April 2012 to develop action-oriented scientific studies for natural disasters. The faculties of IRIDeS have been conducting field trips to the tsunami-devastated areas continually. This guidebook was edited based on leaflets and reports that were prepared and used for earlier field trips. We selected nine sites of tsunami-related locations from the Sendai Plain. A person might be able to visit these sites by car within a single day (Fig. 1). Moreover, this guidebook explains earlier and ongoing plans for disaster prevention in this area, and presents descriptions of historic and prehistoric records of past large-scale tsunamis.

We hope this guidebook will be useful for you to understand the characteristics of large-scale earthquakes and tsunamis better, and to act for future natural disasters. We note especially that this guidebook was first published in Japanese on March 2014 and was then translated into English on August 2014. Situations in tsunami-devastated areas have been changing continuously day by day. We expect that some of the guides might not fit what might be observed in the field at the time of your visit. In addition, most sites introduced in this guidebook are within residential areas or near them. We sincerely appreciate that you might take appropriate care of that fact when in the field.

Chapters 2, 4, 5, and 7 of this guidebook were reprinted (or modified) from a guidebook published for field excursions of the 2013 annual meeting of the Geological Society of Japan.

March 2014 (translated in English on August 2014)

Yuichi Ono, Yoshi Abe, Suppasri Anawat, Mas Erick, Miwa Kuri, Kazuhisa Goto, Daisuke Sugawara

Stops

Stop 1 Nakahama Elementary School, Yamamoto Town (37°54'60.0"N 140°55'03.6"E)

Stop 2 Hill of Millennium Hope, Iwanuma City (38°07'35.8"N 140°56'02.7"E)

Stop 3 Sendai Airport (38°08'15.3"N 140°55'47.0"E)

Stop 4 Yuriage, Natori City (38°10'20.4"N 140°57'14.3"E)

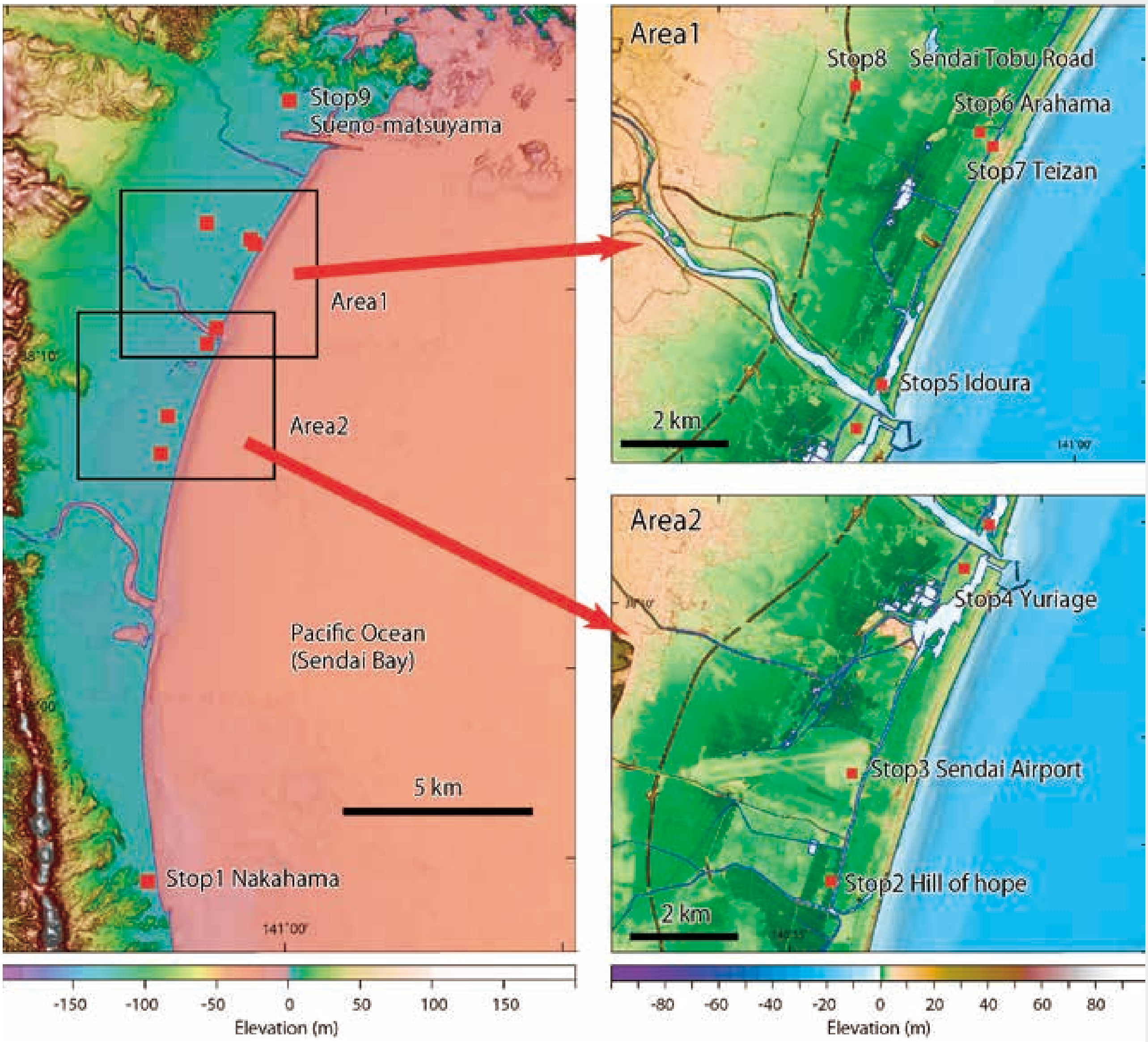
Stop 5 Idoura, Sendai City (38°11'02.0"N 140°57'33.6"E)

Stop 6 Arahama, Sendai City (38°13'06.7"N 140°59'05.5"E)

Stop 7 Teizan Canal (38°13'10.6"N 140°58'57.5"E)

Stop 8 Sendai Tobu Highway (38°13'53.1"N 140°57'14.4"E)

Stop 9 Sueno Matsuyama, Tagajo City (38°17'15.6"N 141°00'12.1"E)



2. Geological setting of Sendai Plain

Sendai Plain has been developed from sediments supplied from rivers (Abukuma, Natori, and Nanakita rivers) and coastal sand drifts. The plain is characterized by topographic features such as beach ridges (sand dunes), natural levees, and back marshes. The plain elevation is 10 m at most. The coastal area within a few kilometers from the present coastline has particularly lower elevations (0–3 m; Fig. 2). A 40-km-long, continuous sandy beach has developed on the Sendai Bay coast, stretching from Gamou, Sendai City at the northernmost area to Isohama, Yamamoto Town at its southernmost extent. The sand dune has a typical elevation of 3–4 m and comprises medium-grained sand (0.25–0.50 mm). Since the early Edo period (ca. 400 years ago), many Japanese black and red pine trees have been planted on the coastal sand dunes to protect farmlands that had been developed in the marshlands. The sand dune nearest to the present coastline had been regarded as higher than natural conditions because of the trapping of wind-blown sands by the coastal forests (Ito, 2006). Engineered coastal dikes had been built on top of the sand dune. The dikes installed before the 2011 tsunami had been designed as countermeasures against storm surges. The elevation of the topmost part of the dike was 5–6 m. The implementation of the coastal dikes remained ongoing at the time of the 2011 Tohoku earthquake. Vertical or oblique walls were employed for the dikes, depending on the location and year of construction.

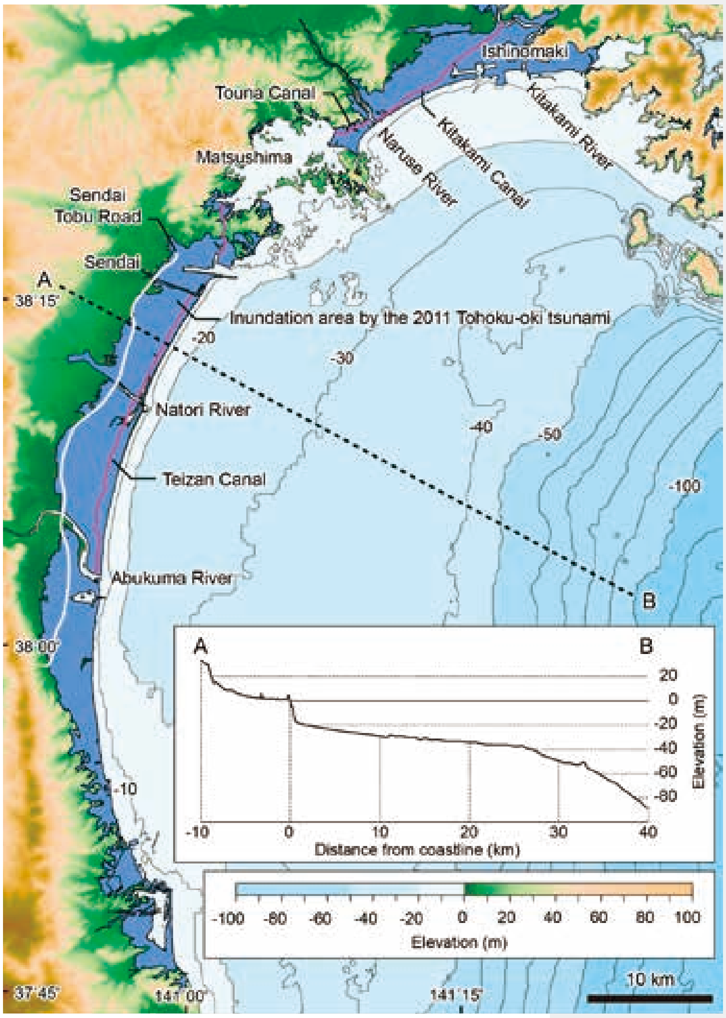


Figure 2: Bathymetry and topography of the Sendai Bay area. The tsunami inundation area is based on Haraguchi and Iwamatsu (2011) (modified after Sugawara and Minoura, 2013).

In the present Sendai Plain, three to four rows of the beach ridges are identified. In general, they are the traces of the coastal sand dunes in the past time. Small coastal lakes are found in the marshlands located between the older beach ridges (Matsumoto, 1981). The paleo-coastline of the Sendai Plain about 6,000 years ago (Jomon period) was situated 5–8 km inland of the present shoreline because of the sea-level rise during the warm period after the Last Glaciation. Since then, the sea level dropped continually, causing a gradual seaward migration of the shoreline, and formation of the sandy beach ridges. In Sendai City, three beach ridges (I, II, and III, which are located respectively 3, 2, and 1 km from the present shoreline) can be recognized. The formation ages of the beach ridges were dated at 5,000–4,500 yrBP for the ridge I, 2,800–1,600 yrBP and 1,000–700 yrBP for the ridges II and III, respectively (Matsumoto, 1984). The beach ridge III is divisible into three sub ridges (IIIa, IIIb, and IIIc). The formation ages of the sub ridges IIIa, IIIb and IIIc were estimated at ca. 1,300 yrBP, 1,100 yrBP, and 350 yrBP, respectively

(Ito, 2006). The area of the Sendai Plain had been expanding during the last 5,000 years. The rate of shoreline migration is calculated as 0.4–1.1 m/yr (Matsumoto, 1994).

Natural levees are found near the rivers and old (buried) channels. The levees comprise medium-grained sands, which were deposited by major floods. Lowlands near the levees are covered by fine sediments such as silt and clay. Human activities in the past are evident in many archeological sites found from the older beach ridges and natural levees. Extensive development of rice paddies and dry fields in the Sendai Plain started after the establishment of the old Sendai Castle by the feudal lord, Masamune Date, about 400 years ago. Until that time, land use of the plain might have been limited in small areas near communities founded on the older beach ridges and natural levees.

(Modified from Sugawara and Minoura, 2013)

3. Countermeasures implemented for disasters before the 2011 earthquake

Possible coastal disasters that might occur around the coastal areas of the Sendai Bay were summarized in a plan document of coastal management provided by Miyagi Prefecture (Fig. 3; Miyagi Prefecture, 2004a). Designs for hardware-oriented countermeasures such as implementation of engineered coastal dikes were specified in the plan document to protect coastal areas from damage and beach erosion caused by storm surges and tsunamis. The long-term risk evaluation of the Miyagi-oki earthquake tsunamis, which was announced by the Japan Headquarters of Earthquake Research Promotion, had been considered in the countermeasures. The plan was aimed to protect the coastal lowlands from the hazards of high tides caused by typhoons and storms from low pressure fronts. As a result, coastal dikes with elevations of 5.2–7.2 m have been implemented along the southern Sendai Bay coast, from Gamou in Miyagino ward in Sendai City to Yamamoto Town. Details of the coastal dike design are described in the plan document of coastal management of Sendai Bay (Miyagi Prefecture, 2004a).

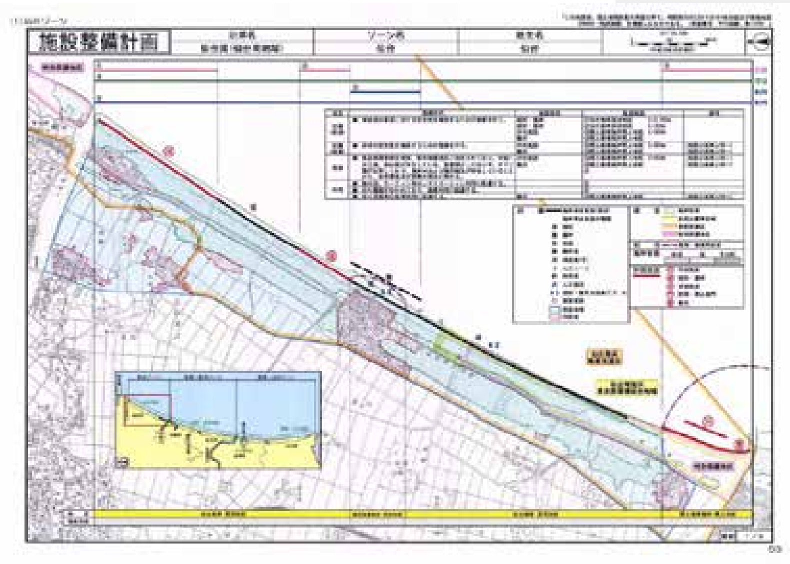


Figure 3: Planning map of shore protection facilities along the southern part of Sendai Bay (based on Miyagi Prefecture, 2004a).

Projected tsunami scenarios in this area were announced in January 2006 by the Investigation Committee of the Earthquakes in Japan and Kuril Trenches, which was organized as a part of the Central Disaster Management Council (CDMC). The scenarios included eight different earthquake scenarios, such as the multi-segment Miyagi-oki earthquake (M8.2) and the Meiji-Sanriku type earthquake (M8.6). Possible damage to humans and property, as well as economic losses, were assessed in each tsunami scenario (CDMC, 2006). In 2004, Miyagi Prefecture announced “the third survey report of projected earthquake scenarios”, which included prefecture-wide hazard maps that identified the arrival time, maximum water level and inundation area of the projected tsunamis (Miyagi Prefecture, 2004b). Most local communities have developed their own detailed tsunami hazard maps, which account for the inundation areas of previous tsunami disasters. The maps were distributed to local residences. However, the inundation areas and tsunami heights that were caused by the 2011 Tohoku earthquake were far beyond these projected tsunami scenarios (e.g., Specific Investigation Committee of Countermeasures for Earthquake and Tsunamis Related to the 2011 Tohoku Earthquake in CDMC, 2011).

Practical countermeasures for tsunami disasters, including software-oriented measures, had been determined in the plan documents announced by the local governments and tsunami guidelines published by Miyagi Prefecture (Miyagi Prefecture, 2003). In the software-oriented countermeasures, a framework for tsunami information and evacuation had been implemented considering the announcement of tsunami warnings from the Japan Meteorological Agency (JMA) and local Meteorological Offices. Tide gauges to detect tsunamis have been implemented by JMA and other governmental organizations, including the Ministry of Land, Infrastructure and Transportation (MLIT) and Geospatial Information Authority (GSI). Some local communities in Miyagi Prefecture installed their own acoustic sensors and pressure gauges to detect tsunamis. For example, an acoustic tide gauge had been installed in Yuriage area in Natori City, just south of Sendai City. Five wave gauges using the Global Navigation Satellite System (GNSS) are installed offshore of the Tohoku district. The GNSS wave gauges detected the tsunami waves before the tsunami struck the coasts. The warnings for the 2011 Tohoku earthquake tsunami were upgraded using data from the GNSS wave gauges, although the timing of the announcement seems to have been too late for evacuation at some locations.

4. Traces of past tsunamis

In the coastal plains of Sendai Bay, little was known about past large-scale tsunamis before the 2011 Tohoku earthquake, which caused extensive inundation and widespread damage. For example, the 1896 Meiji and the 1933 Showa Sanriku tsunamis, which have been well known as the severest historical tsunamis that struck the coastal areas in Tohoku region, did not markedly affect the coastal areas in Sendai Bay. The height of the 1896 Meiji Sanriku tsunami was only 0.6 m on the coast of Ishinomaki City in the north of Sendai Bay. Some damage by the 1933 Showa Sanriku tsunami was documented from Yamamoto Town in the southernmost part of Sendai Bay. However, very little or no damage was reported from other locations in the bay. The 1960 Chilean earthquake tsunami gave significant effects to the Pacific coast of Japan. The Sanriku Coast was again severely damaged by the tsunami. Nevertheless, the tsunami heights ranged 2–3 m in Sendai Bay, and did not cause notable damage (Watanabe, 1998). The 1978 Miyagi-oki earthquake caused severe damage to humans and urban infrastructure because of severe seismic vibration, but the observed tsunami height at Sendai New Port was around 0.5 m; the effects of the tsunami were quite minor (Watanabe,

Table 1. Historical tsunamis that affected the Sendai Bay coast

Year	Month	Day	Latitude (°)	Longitude (°)	Magnitude	Tsunami height and location (m)	
869	7	13	37.5-39.5	143-145	8.6		
1611	12	2	39	144.4	8.1	6-8	Iwanuma
1616	9	9	38.1	142	7		
1717	5	13	38.5	142.5	7.4-7.5		
1793	2	17	38.5	144.5	8.2	2.5-3	Ogatsu
1835	7	20	38.5	142.5	7.0-7.3	5-6	Nobiru
1861	10	21	38.55	141.15	7.4	2-3	Nobiru
1896	6	15	39.5	144	8.2	0.6	Ishinomaki
1897	2	20	38.1	141.9	7.4	1	Ogatsu
1897	8	5	38.3	143.3	7.7	1.5	Ofunato
1898	4	23	38.6	142	7.2	0.2	Ayukawa
1915	11	1	38.3	142.9	7.5	0.6-0.9	Arahama (Watari)
1933	3	3	39.14	144.31	8.1	2.4	Yuriage
1933	6	19	38.05	142.3	7.1	0.18	Hachinohe
1936	11	3	36.26	142.065	7.4	0.9	Onagawa
1960	5	22	72.6W	38.2S	9.5	2.4	Yuriage
1978	6	12	38.15	142.167	7.4	0.49	Sendai Port

1998). The Miyagi-oki earthquake has been regarded as a characteristic earthquake with a 37-year recurrence interval. Up to five preceding Miyagi-oki earthquakes during 1793–1936 have been identified from historical documents. The oldest, the 1793 Miyagi-oki event, is regarded as a multiple-segment earthquake. It generated a 2–5-m-high tsunami along the Iwate and Miyagi coasts. Nevertheless, no considerable damage was reported from the coastal areas of Sendai Bay.

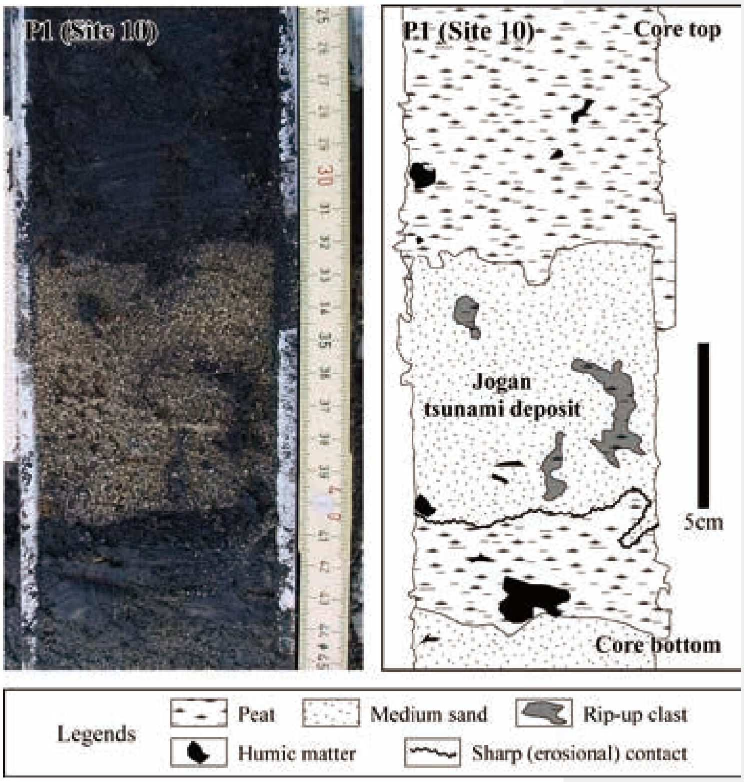


Figure 4: AD869 Jogan tsunami deposit derived from the Sendai Plain (modified after Sugawara et al., 2012).

Widespread and severe damage caused by the 1611 Keicho earthquake tsunami was reported from the Sanriku coast and Sendai Bay (Watanabe, 1998). Historical records are few. Most reliable records are obtainable from the Sanriku area. The tsunami heights and damage in Sendai Bay have not yet been clarified. According to local traditions, masterless samurais (*ronin* people) had settled in Sendai Plain, including the Arahama area, to cultivate lands devastated by the 1611 tsunami. An anecdote was reported from Iwanuma City: a small fishing boat was washed upstream along the Abukuma River, where it drifted onto a branch of a pine tree (legend of Sengan-matsu). Recent historical and geological studies indicate the possibility that the magnitude of the 1611 earthquake and the size of the ensuing tsunami was equivalent to the 2011 event. However, surficial sediments of the coastal plains have been under the influence of land development since the 1611 tsunami. Geological research might work in coastal lakes and ponds, where surficial sediments are likely to be preserved under natural conditions. A sand layer corresponding to the 1611 Keicho event, together with a sand layer by the 869 Jogan tsunami, was identified from a coastal pond (Suijin-numa) in Yamamoto Town (Sawai et al., 2008).

The only historical account of the 869 Jogan earthquake tsunami is found in *Sandai-jitsuroku*, which was written and compiled as a national history of ancient Japan. The collapse of buildings and ground fissures caused by the seismic shocks were described in the document, along with extensive inundation of the coastal plain. The Jogan tsunami deposit was first reported from the Sendai Plain by Minoura and Nakaya (1991). Results of subsequent studies have implied that the tsunami reached 3–4 km from the past coastline. Minoura and Nakaya (1991) also found other two sand layers, which might have been deposited by the predecessors of the Jogan event. The earlier one was dated at 50±100 AD; another one was dated at 740±100 BC. Subsequent studies also found sand layers corresponding to the Jogan event's predecessors (Sawai et al., 2007, 2008, 2012). A sand layer by the predecessor of the Jogan tsunami at ca. 2,000 yrBP was found from the ancient rice paddies in archeological sites in Sendai Plain. Recent archeological studies have analyzed the distribution of the archeological sites and artifacts, revealing that coastal villages were abandoned for a long time after the large-scale tsunami, and that inland areas free from the tsunami disasters were developed as new settlements (Saino, 2012).

According to the geological studies, the 2011 Tohoku earthquake tsunami is apparently a recurrence of the Jogan tsunami, which leads the 2011 Great East Japan Earthquake as a so-called “disaster with 1,000-year periodicity.” However, we cannot distinguish tsunami layers deposited within few to a few tens of years because of the limitations of sampling and dating of sediments. In case an aftershock or induced earthquake of the Jogan event had created a large-scale tsunami and deposited sandy sediments, it is difficult to discriminate it from the original Jogan sand layer. It is not necessary to add that the next large-scale tsunami is expected to take place some time during the next 1,000 years.

(Modified from Sugawara and Minoura, 2013)

5. Damage by the Great East Japan Disaster in Sendai Plain

The seismic intensities (in Japanese scale) of the 2011 off the Pacific Coast of Tohoku Earthquake at each city were 6+ at Sendai City, Natori City, and Yamamoto Town and 6- at Iwanuma City and Watari Town. A major aftershock occurred on April 7, 2011 with intensity of 6+ at Sendai City and 6- at Natori and Iwanuma Cities. Damage to buildings and infrastructure because of the aftershock was severe. During the main and after shocks, liquefaction in coastal areas, landslides in hilly areas, and collapse of developed land were not unusual.

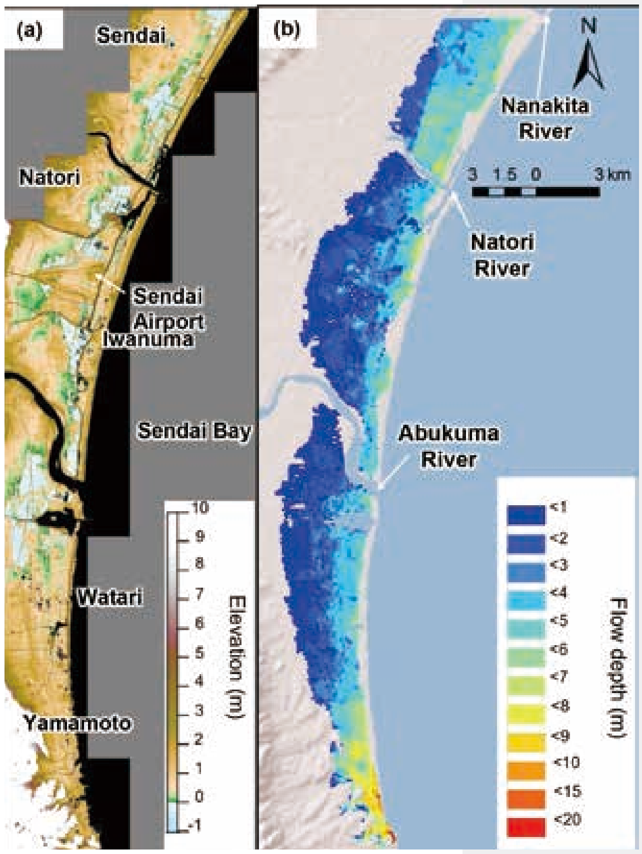


Figure 5: Elevation (left) and maximum flow depth (right: tsunami height from the ground) based on Goto et al. (in press).

The tsunami arrival time at the Sendai Plain was 60–70 min after the earthquake. According to an eyewitness account by a helicopter crew of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), tsunami inundation started from the north near the Sendai New Port. The initiation of the tsunami inundation in the area between the Abukuma and Natori Rivers might have been the latest in the Pacific coast of Tohoku. The tsunami height on the Sendai Plain was ca. 8 to 9 m along the shoreline. At some places, tsunami heights were recorded as more than 10 m (Fig. 5, Mori et al., 2012). Tsunami heights on the Ishinomaki Plain, located north of Sendai Bay, were generally lower than those at the Sendai Plain. According to numerical modeling (Fig. 6), the tsunami near Sendai Airport reached ca. 4 km inland from the coastline within 22 min after its arrival time (Sugawara and Goto, 2012). Tsunami inundation in the Sendai and Ishinomaki plains ultimately reached 4–5 km inland from the coastline (Fig. 7).

Seawater flooding continued for approximately 2 months after the tsunami in some places. Damage to drainage systems and region-wide coseismic subsidence were also reasons why seawater flooding had persisted for a long time. Areas with zero-meter elevation were expanded

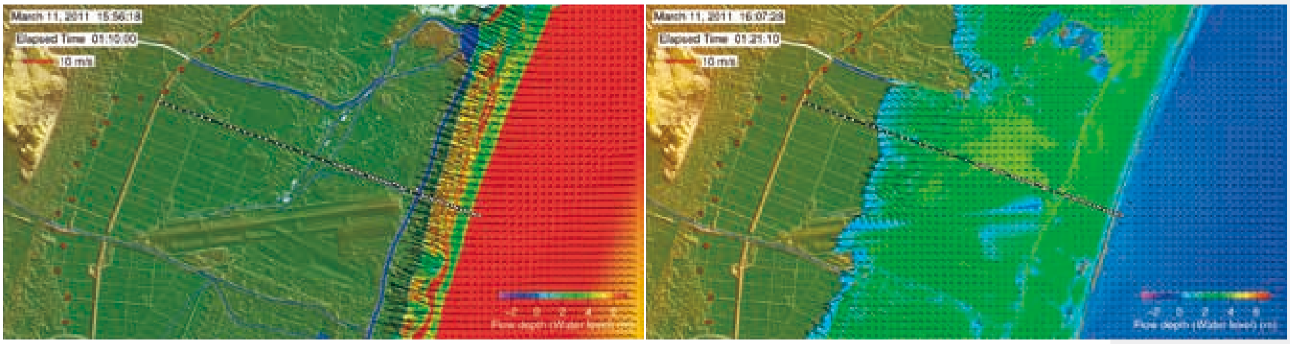


Figure 6: Numerical results of tsunami inundation of the Sendai Plain (near the Sendai Airport): 15:56JST (left) and 16:07JST (right).

because of the coseismic subsidence. Before the event, about 3 km^2 areas from Sendai City to Yamamoto Town had sub-zero elevation. However, that area with sub-zero elevation expanded to 16 km^2 after the event. Natural drainage of the tsunami seawater was not expected at that time. Consequently, the flooded water was drained from many places using mechanical pumps. It took more than a few weeks to complete the seawater drainage.

Death tolls in the Sendai Plain (Tagajo, Sendai, Natori, Iwanuma Cities, and Watari and Yamamoto Towns) eventually mounted to 3,244 people. In addition, 98 people remain missing. Regarding damage to humans and property, 39,923 and 118,309 buildings were completely or partially destroyed, respectively (Miyagi Prefecture, 2014).

(Modified from Sugawara and Minoura, 2013)

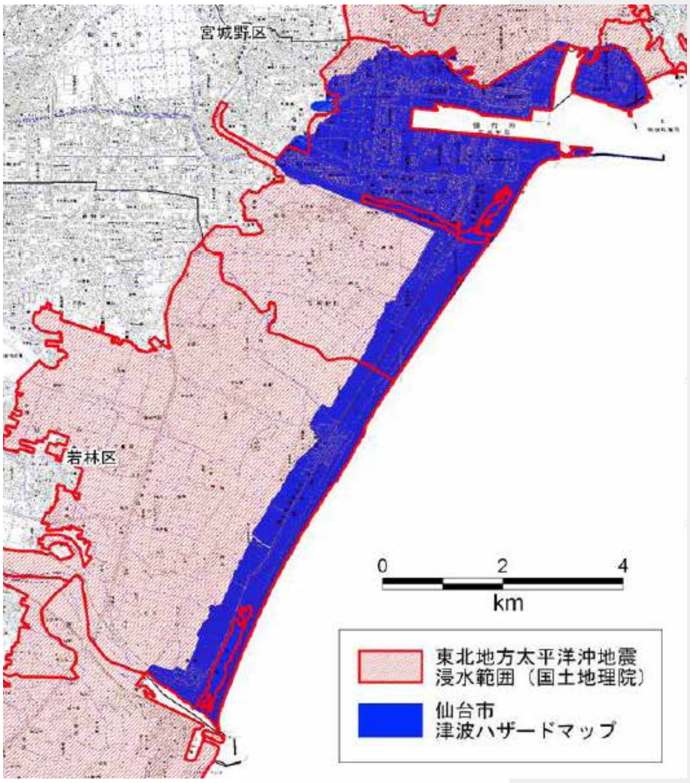


Figure 7: Comparison of the inundation area by the 2011 tsunami (red) and pre-tsunami hazard map (blue). Central Disaster Management Council (2011).

6. Tsunami countermeasures implemented after the 2011 event

The 2011 Tohoku earthquake and tsunami caused severe damage to humans. Infrastructure was also severely damaged, including the airport, sewer treatment facilities, and agricultural fields. The 2011 Tohoku disaster underscores the fact that engineered coastal facilities such as control forests and coastal dikes are not always effective to protect people and property from a large-scale tsunami. After the 2011 disaster, both national and local governments came to advise multiple layers of protection, including elevation of roadways and railways, and building canals parallel to the shoreline to reduce the tsunami energy and consequent damage (Fig. 8).

For the restoration of the tsunami-devastated coastal dikes, an important issue is to determine the design height of dikes intended as countermeasures against future tsunamis. The height of an extreme, but infrequent, tsunami, such as the 2011 event (so-called level-2 tsunamis), was not adopted for design. Instead, the height of more frequent, but less intensive tsunamis, which have a recurrence interval of a few tens of years to hundreds of years of (so-called level 1 tsunamis), was used as the basis of designing the coastal dikes. The design height of the reconstructed coastal dikes accounts for storm surges (Fig. 9). In the southern Sendai Bay, the design height of the dikes was determined to be as high as 7.2 m above Tokyo Peil (T.P.) (Miyagi Prefecture, 2011a, b).

Figure 8: Image showing multiple defenses for tsunami countermeasures (Miyagi Prefecture, 2011a).

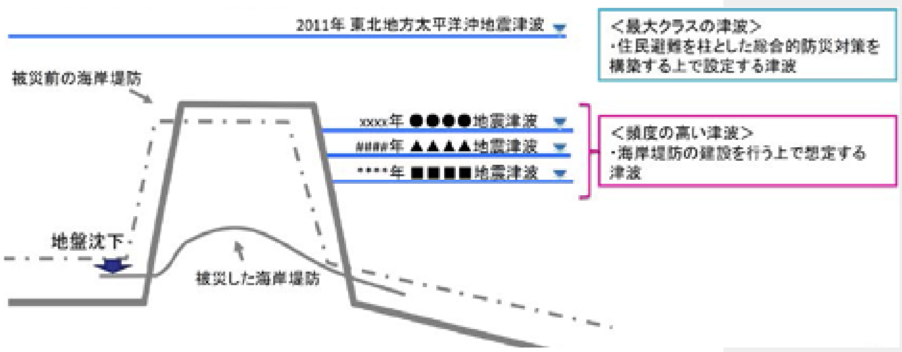


Figure 9: Images showing how to infer the height of a sea structure against a Level 1 tsunami and the estimated tsunami wave height at the southern part of Sendai Bay (Miyagi Prefecture, 2011b).

Except for some locations in the southern Sendai Bay, coastal dike reconstruction has been conducted by the central government. The reconstruction was started near important infrastructure, such as the Sendai Airport and sewerage disposals. By December 2013, approximately 60% (18 km) of the coastal dikes had already been reconstructed. Considering the analysis of processes and patterns of the damage caused by the 2011 tsunami, the new coastal dikes were designed to be more resistant against the tsunami overwash and scouring (Committee of the Tsunami Countermeasures along the Coast, MLIT, 2011). The tsunami deposits were used to construct the embankments for the coastal dikes. In some areas, the lee side of the coastal dikes was covered by soil. Then trees were planted there to produce a “green coastal dike”, to maintain harmony with the natural environment and scenery.

In tsunami-devastated areas, most local governments designated restrictions for residency near the coastal zones. Public housing for the victims will be constructed on high ground and inland, to facilitate the movement of people from vulnerable areas.

As for software-oriented countermeasures, communication systems such as wireless networks were reconstructed to send tsunami information or evacuation advisories swiftly to the public. Redundancy is important for disaster communication. Local governments chose to incorporate communication tools of various kinds, such as FM broadcasts, mobile phones, as well as Twitter and Facebook.

Because most areas of the Sendai Plain are lower than 3 m, it was also regarded as important to set up high evacuation areas. Local governments are planning the construction of tsunami-evacuation towers in coastal areas. Evacuation stairs with banisters were attached on the embankment of the Sendai Tobu Road. Although the road was not designed initially for tsunami evacuation, many people climbed up the embankment and survived the tsunami in 2011. Since implementation of the stairs, safety exercises have been conducted periodically.

7. Stops

Stop 1 Near the Nakahama Elementary School in Yamamoto town

You might find the remnants of Nakahama Elementary School building and “Tsunami Bay” at this stop (Fig. 10). The tsunami rushed into the two-story elementary school building, which was made of reinforced concrete, through the windows in the east side. The waters reached up to the roof of the second floor. Nevertheless, not one of the 90 people in the building, including children, teachers and some local people, died. They all succeeded in evacuating to the roof terrace. The tsunami did not ultimately flood the terrace. Tsunami-damaged buildings have been disappearing as clearing and reconstruction work progresses. Few remain in southern Miyagi Prefecture. People have begun to devote attention to such buildings as tsunami memorials. Local governments are now considering the use of the damaged buildings as monuments.

"Tsunami Bay" is located 200–300 m east of the elementary school building. It is visible from the building terrace, from which one can reach the bay with a five-minute walk. The 2011 tsunami induced substantial sediment transport and created many erosional features all around the sandy beaches of southern Sendai Bay. Mechanisms and factors involved in the creation of tsunami bay are the retreat of the sandy beach because of long-term coastal erosion, the collapse of engineered dikes caused by the tsunami overwash and scouring, and formation of deep ditches in the lee side of the dike. The Tsunami Bay is a rare landscape showing interaction between the tsunami and anthropogenic coastal protection.

Figure 10: Overview of old Nakahama Elementary School of Yamamoto town (building with orange roof in left center side) and “Tsunami Bay (eroded arc-shaped coast in right center side).”

Stop 2 Hill of millennium hope

"Hill of millennium hope" is a reconstruction project planned for Iwanuma City. The coastal area of Iwanuma City was damaged by the tsunami, as were Sendai and Natori Cities. The tsunami debris will be used for construction of the hill (Fig. 11). The planned height of the hills is 8 m. The hill is designed to mitigate the effects of infrequent large-scale tsunamis such as the 2011 event, and to be tsunami-evacuation areas. The construction of a part of the hill was completed in June 2013. Work is expected to continue in the future.

Figure 11: Schematic of "Hope Hill for a thousand year perspective" as a reconstruction plan in Iwanuma city.
http://www.city.iwanuma.miyagi.jp/kakuka/040700/documents/image_illustration.pdf

Stop 3　Around Sendai Airport

Sendai Airport is located across Natori and Iwanuma Cities. The airport area was originally used for agriculture. During World War II, the Japanese army set up an air base in 1940 for pilot training. After the war, the US army occupied the base. After occupation by the US army had ceased, the land was again used for agriculture for several years. The present Sendai airport was opened for domestic flights in 1957. International flights to the airport began in 1990.

Figure 12: Damage conditions of sand embankments and preserved forests: (A) photograph taken on November 11, 2010 by Dr. Kentaro Imai, Tohoku University), and (B) photograph taken on May 5, 2011 (Sugawara and Minoura, 2013).

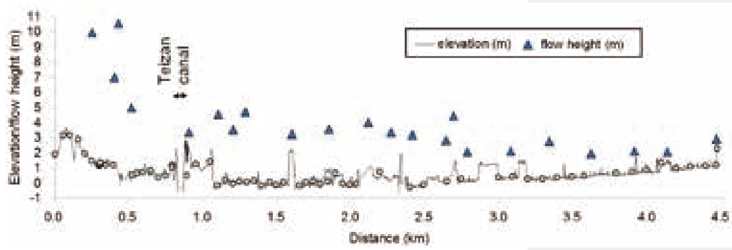


Figure 13: Cross section of topography and tsunami inundation height near the Sendai airport (Goto et al., 2011).

Elevation of this low-flat area used to be around 0–1 m. The land became much lower than sea level because of coseismic subsidence resulting from the 2011 earthquake. No damage occurred to commercial airplanes from the tsunami, but many small airplanes and helicopters were completely washed away. The tsunami flow height measured at the airport terminal building was 5.6 m above mean sea level (Mori et al. 2012). Although the tsunami completely inundated the first floor, 1,422 people including travelers, staff members, and local residents had evacuated to and survived on the second and the third floors of the building. Recovery of the airport was done by the Japanese Self-Defense Forces and aid from the US Air Force and Marines under a campaign designated as "Project *Tomodachi*." The airport was soon recovered and used for emergency helicopter operations four days after the tsunami. The runway was cleared five days later. Commercial flight operations were resumed one month thereafter.

Along the Sanriku Coast, in particular in the northern part of Kamaishi City, seawalls with 10 m high were implemented in consideration of the 1896 Meiji and 1933 Showa tsunamis. However, the coastal dikes in Sendai Bay and along the Joban Coast, which have a typical height of 5–6 m, were designed to protect the coast from storm surges because the effects from the 1896 and 1933 tsunamis were minor in Sendai Bay, and because pre-2011 coastal protection was intended mainly as a countermeasure against high tides and storm surges. The coastline from Kitagama, east of the airport, to Yuriage, south of Natori River, was not protected by engineered dikes. Sand embankments covered by plants and trees were built in this area (Fig. 12A).

The 2011 tsunami height was 10.6 m T.P. (inundation depth = 9.6 m) behind the sand dunes and around 3–4 m (inundation depth = 2–3 m) at distances of 0.5–2.5 km from the coast (Goto et al., 2011; Fig. 13A). The tsunami reached 2.7 m elevation near the Sendai Tobu Road at about 4.8 km from the coastline. The flow depth there was about 0.2 m. The tsunami flooding near the Sendai airport can be seen in a video taken by the Japan Coast Guard. The video is crucially important for estimating the speed of the tsunami flow on land. Based on analysis of the video, the wave front velocity was estimated at about 4 m/s at distances of 1.1–2.1 km from the coast (Goto et al., 2011). The high flow speed was one cause of the large-scale erosion of the sand dunes (Fig. 12B).

(Modified from Sugawara and Minoura, 2013)

Stop 4 Yuriage area

Figure 14: (A) Hiyoriyama Hill in the Yuriage area. (B) Damage to the Yuriage area in a photograph taken from the top of Hiyoriyama Hill (June 24, 2011).

Yuriage area in Natori City is a fishing village located near the mouth of the Natori River. Even at the time of the transgression during the Jomon period, the coastline of this area is thought not to have been much different from that of the present coastline because of substantial sediment supplied from the river (Matsumoto, 1981). Elevated areas are found on natural levees near the river (Matsumoto, 1981). The levees have been used for residential areas for a long time. Inhabitation and formation of communities started during ancient times and continued to the middle ages in Japan (Heian period). Markedly rapid development of the Yuriage community took place during and after the Edo period (Kahoku Shimpo News, 2012). After excavation of the Kobiki-bori Canal, which is a part of Teizan Canal and which connects the mouths of the Abukuma and Natori Rivers, Yuriage was a lodgment of products such as timber and rice. The village was changed to a fishing port after the commercial development of Shiogama and Ishinomaki cities in the northern part of Sendai Bay.

Hiyoriyama is a small hill located about 800 m from the sea. The top of the hill offers a panoramic view of the area (Fig. 14). The 6.3-m-high hill was built using sediments dredged from the Teizan Canal. Wooden houses in the residential area within 1 km from the coastline were washed away completely by the tsunami. The Hiyoriyama hill is the only high ground in this area, but the tsunami overtopped the hill and washed out some stone monuments including a memorial of the 1933 Showa-Sanriku tsunami. The tsunami height measured on this hill was 7.9 m (Mori et al., 2012). The 911 casualties in Natori City include 40 missing, most of whom were reported from Yuriage (750 deaths out of 5,612 pre-disaster population in this area). At present, many people, including relatives of victims, volunteers

Figure 15: Stopped clock at Yuriage Elementary School.

and tourists, frequently come to the hill and offer prayers for the tsunami victims.

Yuriage Junior High School and Yuriage Elementary School are located, respectively, at 1.8 km and 2.1 km from the coastline. The measured tsunami height was about 4.4 m at these locations (Mori et al., 2012). Hundreds of people had evacuated to the buildings and survived the tsunami. A high water mark is still visible at the Yuriage Elementary School building together with a clock, which was stopped by the 2011 event (Fig. 15). A pedestrian bridge can be found at the crossing point of the Prefectural Road 10 and the City Road (Fig. 16). At the time the tsunami struck, some people climbed the stairs and survived on the top of the bridge. A sign on the bridge's pillar shows the tsunami height. In October 2011, Natori City's government proposed a reconstruction plan for the Yuriage area, which includes leveling the ground to 3 m higher than it is currently and calling the local people to return to the area. The government produced a mock-up of the elevated land, together with a planned layout of new coastal dikes, to let people know how high the area will be and how safe the residents will be against large-scale tsunamis in the future. However, many people want to move away from Yuriage, or have already left and made new homes in other areas. Because three years have passed since 2011, the expected population of the new Yuriage community has been decreasing. The reconstruction plan has been revised many times.

Figure 16: Pedestrian bridge at the cross junction of the prefectural road no. 10 and the city road.

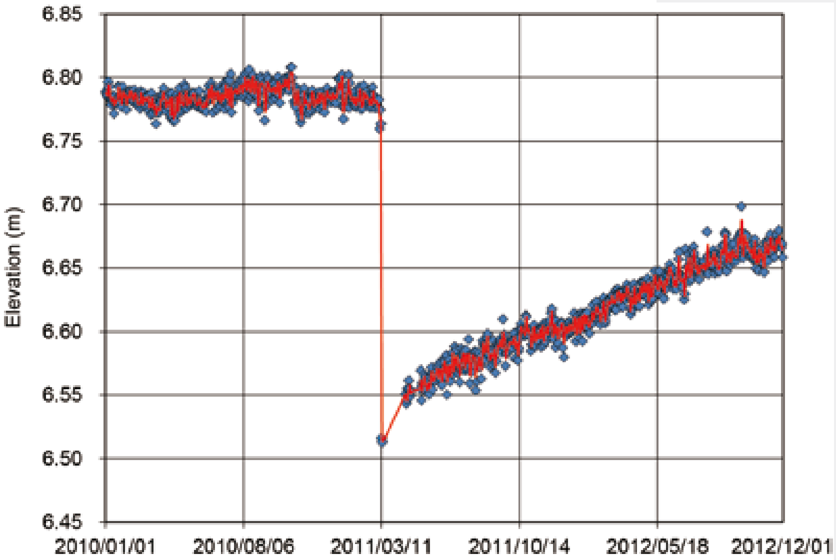


Figure 17: Land elevation change before and after the 2011 earthquake at the GSI standard point in Natori (Sugawara and Minoura, 2013).

An automatic observation station of geodetics, operated by the Geospatial Information Authority of Japan, is installed in the Yuriage Junior High School grounds. At the time of the 2011 earthquake, a coseismic subsidence of 28 cm took place at this point (Ozawa et al., 2011). Since then, the elevation has recovered because of the postseismic crustal deformation. Half of the coseismic subsidence was cancelled out by the beginning of December, 2012 (Fig. 17). According to detailed analysis of the geodetic data, the postseismic uplift is occurring in areas from the Oshika Peninsula to the Sendai Plain, whereas postseismic subsidence is occurring in the northern and middle Sanriku Coast (Iinuma et al., 2012).

(Modified from Sugawara and Minoura, 2013)

Stop 5 Idoura Lagoon

Idoura Lagoon is located north of the mouth of Natori River. A notable change in topography occurred in this lagoon because of the 2011 tsunami. The sand bar that borders the lagoon was eroded severely and flattened by the tsunami. Most of the bar became submerged.

The lagoon was selected as an important wetland area of Japan, considering the preservation of biodiversity in many environments, including wetlands, rivers, lakes and lagoons. Another lagoon, Hiroura, is located further to the south. The mouth of Natori River changed its position because of major river flooding. It had been wandering for a long time around the two lagoons. For example, an old topographic map shows that the river flowed out from the Hiroura Lagoon (Fig. 18). Guide walls were built recently to stabilize the river mouth. The average water depth of the lagoon is 0.5–1.0 m. The maximum water depth is 2.0 m. Waterway traffic is not convenient even for small boats because of the shallow bathymetry.

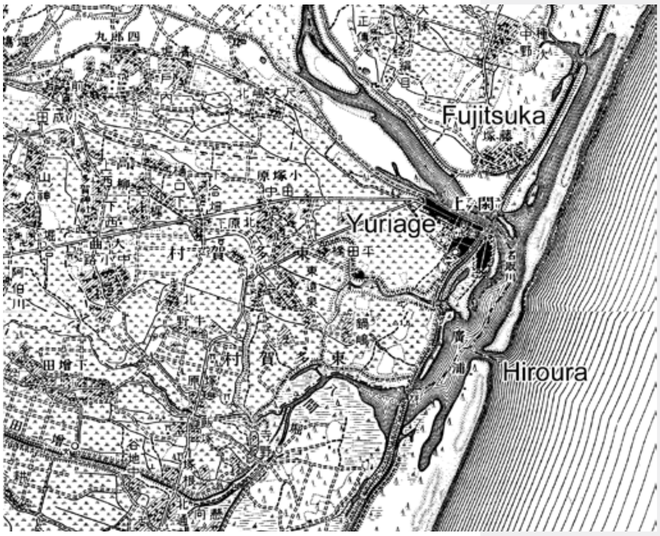


Figure 18: Topographic map at the Natori River mouth (1:50,000) (based on Sugawara and Minoura, 2013).

Figure 19 presents a view of the remaining part of the sand bar. The black sand includes plenty of iron minerals (magnetite grains). Sediments supplied from the river are placed under the influence of segregation by coastal currents. Because of the difference in density, heavier grains tend to remain near the sediment source. Lighter grains are washed away from the source by the northward alongshore currents in Sendai Bay. Using iron-rich sand, iron manufacturing was conducted around 70 years ago for military purposes (Editorial Board of Rokugou wo saguru kai, 2005)

Figure 19: (A) Deposition of iron sand at Idoura; (B) view from the southern end of the sand bar remnant (based on Sugawara and Minoura, 2013).

Figure 20 shows LIDAR topography near the Idoura Lagoon, as surveyed respectively in the winter of 2005, March 2011, and May 2011. In March 2011, the lagoon was connected

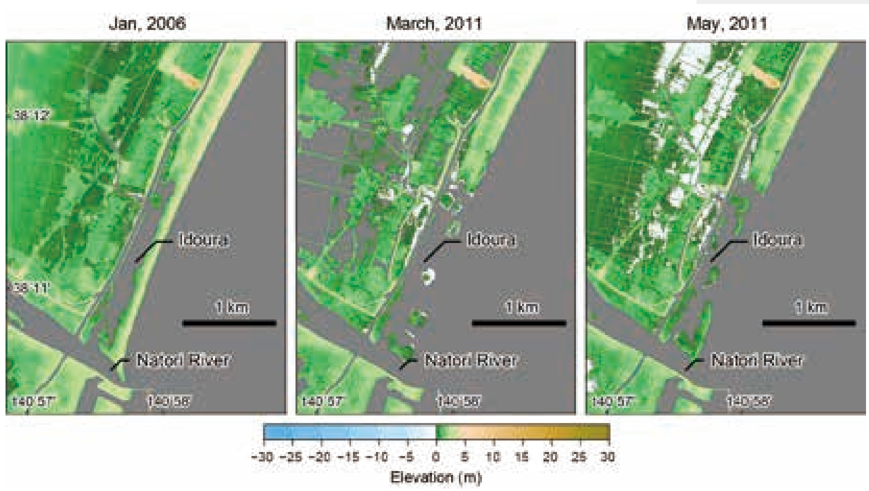


Figure 20: Digital Elevation Model (5 m grid) before and after the tsunami, based on Geospatial Information Authority of Japan (based on Sugawara and Minoura, 2013).

Figure 21: Google Earth images before and after the 2011 earthquake and tsunami at the Natori River mouth.

to the open ocean because of the sand bar erosion. In May 2011, sediment accumulation had already begun, and a new sand bar had begun to be formed west of its earlier position (See GoogleEarth satellite imageries). Results show that the lagoon area was reduced considerably. Similar extensive erosion of the sand bar was observed in Gamou Lagoon, located north of the Arahama area. However, the post-tsunami recovery process of coastal geomorphology in the Gamou Lagoon differs somewhat from that of the Idoura Lagoon. Satellite images show that the sand bar of the Gamou Lagoon almost entirely recovered its original shape soon after the tsunami.

The tsunami height was measured at 9.3 m near the Natori River embankment, which is located south of the residential area (Mori et al., 2012). The community near the Idoura Lagoon (called Fujitsuka) had around 90 houses. The 2011 tsunami washed away most of the houses and caused 24 fatalities (Kahoku Shimpo, November 28, 2012). Live video taken by an NHK helicopter clearly captured tsunami flooding in this area. According to analysis of the video, the tsunami front speed and the flow speed were estimated respectively at 6 m/s and 8 m/s (Hayashi and Koshimura, 2012). The intense seismic shocks created a yawning gap across the beams of the Yuriage Bridge near the river mouth. Road traffic was stopped completely. Although the tsunami nearly washed over the bridge, a policeman left behind on the bridge survived.

(Modified from Sugawara and Minoura, 2013)

Step 6 Arahama area

Figure 22: (A) Arahama area before the 2011 tsunami; (B) Tsunami hazard map located near the coastal forest (photograph taken on May 6, 2009) (Extracted from Sugawara and Minoura, 2013).

Arahama means "a wild beach" in Japanese. Two areas along the Sendai Bay coast are called Arahama: one in Wakabayashi ward, Sendai City, and another one near the Abukuma River in Watari Town. Arahama in Sendai City has another name, Fukanuma, which means "deep pond." In fact, most of Sendai Plain, including the Arahama area, is marshland, as noted in Section 2. Swimming has been prohibited in general at most the beaches on the Sendai Bay coast because of rough waves from the open ocean. Arahama is an exceptional swimming beach because of the implementation of detached breakwaters.

Some historical records reveal that the Arahama area was developed after the 1611 Keicho Sanriku earthquake tsunami. At that time, people from other places settled in the tsunami-devastated area and cultivated the land. The Arahama area consisted of an old community in the north and a new town in the south. The northern area was a fishing village. It has maintained its historic housing (Fig. 22A). The southern area was developed during and after rapid economic growth in the 1960s. There were about 750 houses in the Arahama area before the 2011 tsunami (Kahoku Shimpo, 2012). As in other areas, almost all the wooden houses were washed away; 186 people lost their lives. Arahama area, a famous location of the 2011 tsunami disaster, has been covered frequently in mass-media news reports. A tsunami memorial and a statue of the Buddhist Goddess of Mercy were donated and placed next to the seawall.

The tsunami height near the coastline was about 9–12 m (Mori et al., 2012). Figure 22B shows the tsunami hazard map published before the 2011 tsunami. As described earlier, the projected earthquake scenario in this area before the 2011 tsunami was the Miyagi-oki earthquake, which had 37.1 years of recurrence and typical magnitude of 7.3–7.5. The largest known Miyagi-oki earthquake occurred in 1793 (5th year of the Ansei period) with magnitude of 8.2. Considering the fault rupture in multiple segments, tsunami heights of 2–5 m were predicted along the Iwate and Miyagi coasts. Considering the migration of tsunami effects by the seawalls and coastal forests, the tsunami inundation area had been assumed to terminate within the coastal forest or the Teizan Canal, or at most around the building of Arahama Elementary School (Fig. 7).

Although the 2011 tsunami arrived at Sendai and Natori coasts about 70 min after the time of origin, no natural high ground can be found throughout the Sendai Plain. The high embankment of the Sendai Tobu Road was a possible evacuation place, but it was 3 km distant from the coast. Therefore, it is expected to be difficult for people to evacuate from the tsunami inundation area by walking if they had decided to escape immediately before the tsunami arrival. Many people used their own vehicles for the tsunami evacuation, causing severe traffic jams. This was confirmed by NHK air live broadcasts and much other video footage. Many private cars had concentrated on the roads and were forced to stop because of the traffic jams. The tsunami flooding inundated the entire area.

The Arahama Elementary School building was the only possible tsunami evacuation shelter. It was sufficiently high and robust against tsunami inundation. The tsunami reached the second floor of the building (tsunami height = 7.8 m). Nevertheless, 233 local residents, with 87 students and teachers, evacuated to upstairs areas and survived on the rooftop (Kahoku Shimpo, 2012). Those who were in bad physical condition were rescued earlier by helicopters. Others were rescued by boat. At present, the school building is no longer used for its original purpose, but it is expected to be used again as an emergency evacuation shelter for future tsunamis and evacuation drills.

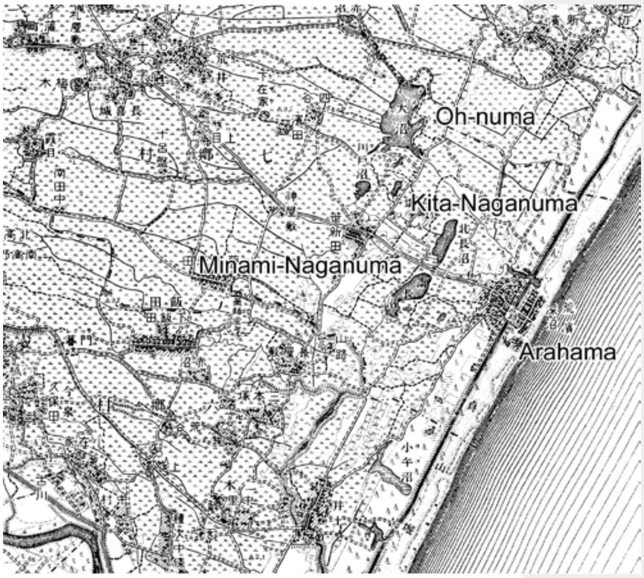


Figure 23: 1:50,000 land elevation map of Arahama (in 1912) (Extracted from Sugawara and Minoura, 2013).

Figure 24: Management office of the coastal adventure park.

Because of large-scale erosion by the tsunami, many topographic undulations were formed on the beach ridges, which include residential areas. The erosion was as deep as 3 m at the back side of the coastal dike. Seaward of the dike, the tsunami erosion formed many waterways that cut across the sandy beach. Tanaka et al. (2011) pointed out that old river channels played an important role for the creation of these waterways during the tsunami backwash. A topographic map published during the Meiji period shows a small water body north of the Arahama area. It was connected to ponds located northwest of the area: Kitanaganuma and Onuma (Fig. 23). In an older map, the water body was shown as a river. Consequently, the location of the breaching of the sandy beach corresponds to the old channels (Tanaka et al., 2011). Formation of the waterways on the sandy beach can be confirmed by Google Earth images taken on March 18, 2011. However, the waterways were filled up by sand, as shown in the image taken six days later on March 24, 2011. Parts of the coastal dikes on the beach ridge were completely collapsed. Some of the fragments, which consisted of large concrete masses, were moved inland as far as 100 m. Nevertheless, the detached breakwaters, which comprise piles of blocks, were not moved at all.

Figure 24 shows the coastal adventure park located 400 m from the coast. This place was once a pond, as presented in Fig. 23. The pond became filled by soil and an artificial hill had been constructed. Then the park was opened on it. The hill elevation was greater than 15 m, and the 2011 tsunami did not reach on the top. The tsunami near the coast, about 10 m high, inundated the first floor of the office located in the west side of the hill. Reportedly, five people survived on the hill.

Stop 7 Teizan canal

Figure 25: (A) Landscape of Teizan canal before the Tohoku Great Earthquake and Tsunami on January 29, 2010. (B) The disaster landscape of Teizan canal after the Tohoku Great Earthquake and Tsunami post-disaster, shot with same position and direction on March 17, 2011. (Reprinted from Sugawara and Minoura, 2013).

A remarkable feature in the coastal zones of Sendai Bay is a system of shore-parallel waterways, consisting of Teizan, Tona, and Kitakami canals (Fig. 2). These canals are situated approximately 500 m from the coastline. The Teizan canal connects the mouth of Abukuma River and Shiogama Port in Matsushima Bay with length of about 27 km. It consists of three portions, named the Kobiki-bori, Shin-bori, and Ofunairi-bori canals. The Tona canal, about 4 km long, extends from Matsushima Bay to the mouth of Naruse River via Nobiru area in Higasimatsushima City. The Kitakami canal extends from the left bank of Naruse River to Old Kitakami River in the center of Ishinomaki City, via the Jo River in Ishinomaki Industrial Port with length of about 14 km. The canal system, with total length of 44 km around Sendai Bay, is the largest in Japan.

The Kobiki-bori canal is the oldest among the Teizan canal system. It was excavated by Sir Kawamura Magobe Shigekichi (1575–1648) in the early Edo Period. Although the age of the construction has not yet been determined, it is likely that the canal was constructed before 1633 (the tenth year of Kan'ei Period), based on a drawing made during that period (Goto, 2010). Some historical documents suggest that the construction was conducted during 1597–1601 (Civil Engineering Section, Miyagi Prefecture, 2008). However, considering the historical background (the civil war lasting from the middle age of Japan until the Edo Period), it might have been difficult to carry out a project to excavate the big canal during this period. Because the castle town of Sendai had developed, the Ofunairi canal was excavated during 1661–1658, to enhance transportation. The construction of Shin-bori canal was conducted during 1870–1872 (3rd – 5th year of Meiji Period), to provide jobs to Samurai people who lost their salaries because of the Meiji Restoration. "Teizan" was named in the Meiji Period after the honorific name of the feudal lord of Sendai: Masamune Date. The Teizan canal is located in the marshlands in the beach ridge III. Based on the understanding of the nature of Sendai Plain, it is likely that ancient people might have used the area. The Teizan canal was once very shallow and largely carved. The canal was repaired and expanded extensively during and after the Meiji Period. The canals were linearized and dredged. Now they have a typical width of about 50 m and depth of about 3 m. Since the Meiji Period, the importance of the canals for the transportation of products has been reduced because of the development of terrestrial traffic. The main use of the canal is for leisure, such as fishing and boating.

Because of the impact of the 2011 tsunami, the canal embankments collapsed. Most of the canal gates and bridges were washed away (Fig. 25). Nevertheless, a post-tsunami survey revealed that the tsunami height was reduced by about 3 m across the Tona canal in Higashi-matsushima City, suggesting that the canal can reduce the impact of the tsunami waves (Goto, 2012).

(Modified from Sugawara and Minoura, 2013)

Stop 8　Sendai Tobu Highway

Figure 26: Landscape of contrasting disaster situation in Sendai eastern highway on March 12, 2011. (Reprinted from Sugawara and Minoura, 2013): (A) west side of the highway (land side); (B) east side of highway (sea side).

Sendai Tobu Highway runs parallel with the coastline at a distance of about 2–3 km from Sendai city to Watari town (Fig. 2). Since opening in 1994, this highway had been connected with the Joban highway in the southern part and with the Sanriku highway in the northern part. This highway has a high embankment formed at the height of 7–10 m above sea level. In the Sendai Plain there are few areas with higher ground where one might evacuate from a tsunami. Therefore, the government and residents had held conferences with the highway company during a few years before the 2011 earthquake, negotiating for the use of highways for evacuations. At the time of the 2011 earthquake and tsunami, they had not yet reached an agreement and preparation for usage of the highway. Nevertheless, about 350 people evacuated by climbing to the highway embankment (Kahoku Shimpo, December 22, 2012). Now evacuation stairs have been provided in five places along the highway. Drills to use them have been held.

The tsunami entered the inland side through the underpass and the part of the elevated way. The tsunami force was reduced considerably across the road, and the appearance of the damage differed greatly east and west of the highway (Fig. 26). Particularly, the effect of preventing the debris inflow was very large. The plan of relocation and raising of the road was adopted near the coast road (Shiogama-Watari line of country road No. 10) because of the good example of its unexpected effect as a breakwater (Fig. 8; Disaster Recovery Office, Sendai city, 2011).

(Modified from Sugawara and Minoura, 2013)

Stop 9 Around *Sue-no-Matsuyama*

Figure 27: March 31, 2011: (A) landscape of Sue-no-Matsuyama; (B) landscape of damaged area immediately after the Great Tsunami near Sue-no-Matsuyama (tsunami depth about 2 m).

Sue-no-Matsuyama (Fig. 27A) with big pine trees is located on a small hill behind the *Houkokuji* temple beside Sunaoshi River south of Tagajo Station. This area became famous because of the legend of the Jogan tsunami in *Kokin-Waka-shu*, the Japanese ancient anthology of poems, (e.g. Shimizu et al., 2000). That poem is the following.

Kimi wo Okite Adashi Kooro wo Waga Motaba Sue-no-Matsuyama Nami mo Koenamu
(Anonymous, *Kokin Waka –shu*)

It means that "If I forgot you to love another, waves have broken over *Sue-no-Matsuyama* (The end of a hill with pine trees, by a literal translation). I will never forget you as the waves have never broken over *Sue-no-Matsuyama*."

First, Yoshida Togo, the famous historical geographer, had interpreted this poem in an academic view. He interpreted that the phrase of *Sue-no-Matsuyama* has been used as "*Uta-makura*", a symbolic decorative expression, and indicated that no wave had broken over this place (Watanabe, 2012). However, there is another interpretation that the tsunami had broken over the *Sue-no-Matsuyama*.

The maximum altitude of *Sue-no-Matsuyama* on a hill is about 13 m. Eastern and southern parts of *Sue-no-Matsuyama* are parts of the old beach ridge I. The lagoon extended along the inner side of this beach ridge during the Jomon to early Heian periods (Board of Education in Sendai City, 2010). Some remnants, including *Numamukai*, are still present around this coastal lagoon. Sandy deposits formed by the Jogan tsunami have been found in these remains. During a few hundred years after the tsunami at the Yayoi period, as described above, the base of production moved inland in the Sendai coastal plain. However, such a change was not observed after the Jogan tsunami. Consequently, it has been interpreted that effects of the Jogan tsunami were smaller than those of the Yayoi tsunami. It is likely that tsunami sizes are related to these differences but there are expected to be cultural backgrounds of each age. The development of agricultural production became important for the usage of coastal areas as the preferred location for agricultural work (Saino, 2012). It is likely that villages in the Sendai plain were restored rapidly by the victims of Jogan earthquake and tsunami. Actually, tsunami deposits formed by the Jogan tsunami were scattered throughout a wide area on the Sendai plain and are not continuous. This is true probably because not only was the distribution of tsunami deposits affected by the local topography, but also the deposits were removed by human activities after the Jogan tsunami.

Although geography (e.g., topography and shoreline position) at the time of the Jogan tsunami differed from the present one and although direct comparison of the tsunami size is difficult, the 2011 tsunami did not break over the *Sue-no-Matsuyama*. The flow depth at *Sue-no-Matsuyama* was 2–3 m during the 2011 tsunami. In Sendai Plain, many houses were washed away when the flow depth became greater than 2 m. However, around the *Sue-no-Matsuyama*, fewer houses were washed away even though the flow depth became greater than 2 m, probably because the flow velocity was slow, despite the flow depth. However, human and material damage was extensive because of the impact of automobiles because this area is located near the Sendai Port, where many cars had been parked for export by freight ferry.

(Modified from Sugawara and Minoura, 2013)

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