## DAMAGE ALONG COASTS IN SENDAI BAY CAUSED BY THE 2011 GREAT TSUNAMI

Kazuya Sakai[1], Takaaki Uda[1], Toshiro San-nami[2] and Tatsuya Shimizu[3]

A great earthquake with a magnitude of 9.0 occurred on March 11, 2011, with an epicenter 130 km offshore of the Oshika Peninsula in Miyagi Prefecture. After the earthquake, a giant tsunami inundated a large area along Japan's eastern coastline. We carried out field observations to investigate the damage to Arahama Town and the formation of a trench as a result of local scouring by the jet flow over the coastal dike. Here, the results of the field observations on the inundation of the tsunami into a wide residential area on Shobuta Beach and in Arahama Town were reported. Then, the destruction of the coastal dike, as well as the formation of a large trench immediately behind the coastal dike due to the tsunami overflow on the Yamamoto coast, was investigated, where the tsunami height reached up to 19.2 m above mean sea level (MSL), estimated from the run-up height on the slope of a hill.

*Keywords: 2011 Great Tsunami; tsunami damage; trench formation; coastal dike; coastal forest*

### INTRODUCTION

A massive earthquake with a magnitude of 9.0 occurred at 14:46 on March 11, 2011, with an epicenter 130 km offshore of the Oshika Peninsula in Miyagi Prefecture (Fig. 1). Such a massive earthquake had never been experienced in Japan's recorded history of earthquakes. After the earthquake, a large tsunami, which was generated by the abrupt crustal subsidence and uplift, inundated a large area along Japan's eastern coastline. The damage was particularly severe along the coasts of Iwate and Miyagi Prefectures, and damage also occurred on the coasts of Fukushima, Ibaraki and Chiba Prefectures (Fig. 1). To record tsunami trace heights along the coastal zone, the Tohoku Earthquake Tsunami Joint Survey Group was organized by Japanese coastal engineers and tsunami researchers (Shibayama, 2011; Shibayama et al., 2011), and the tsunami height along east Japan's coast was reported in detail (Joint Research Group of 2011 Great Tsunami of JSCE, 2011).

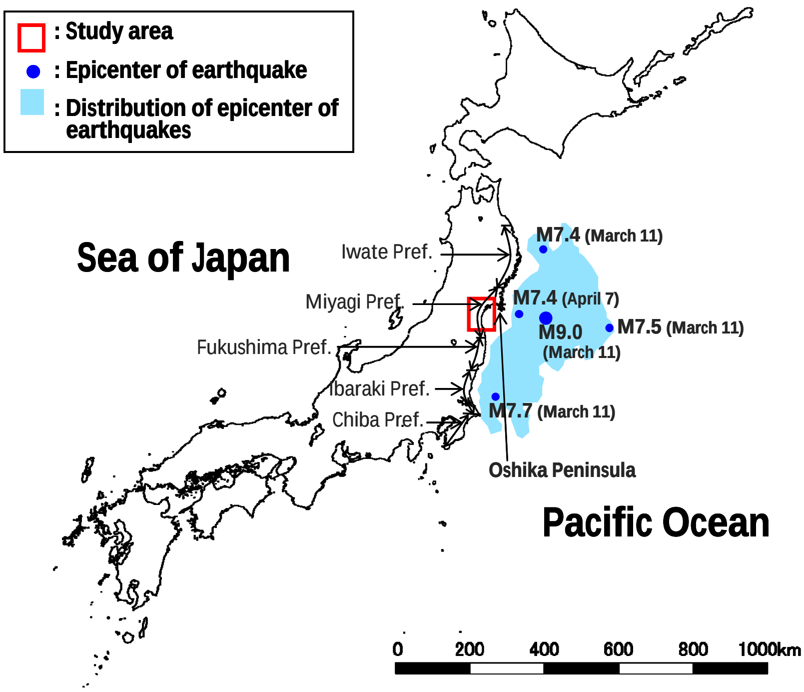



**Figure 1. Epicenter of the 2011 Great Earthquake.**

[1] Public Works Research Center, 1-6-4 Taito, Taito, Tokyo 110-0016, Japan
[2] Coastal Engineering Laboratory Co., Ltd., 1-22-301 Wakaba, Shinjuku, Tokyo 160-0011, Japan
[3] ICOMNET, Ltd., Elevage Kanda-Nishikicho Bldg., 3-16-11, Kanda-Nishikicho, Chiyoda, Tokyo 101-0054 Japan

Shibayama et al. (2011) pointed out that Arahama Town, located 7 km east of Sendai City, was severely damaged because the coastal forest was narrower than in other areas, as already described by Harada et al. (2000). Tanaka et al. (2011) investigated beach changes in the same area on the basis of aerial photographs taken before and after the tsunami and field observations. Regarding the formation mechanism of a large-scale channel across the sandy beach, they pointed out the following three causes: (1) return flow that was concentrated at the previous river mouth was generated, (2) the joint of the coastal dike with different structures or with different crown heights alongshore produced a structural weak point, resulting in the concentration of the tsunami return flow, and (3) the seawall had not been built continuously without gaps; thus, the seawall was destroyed by the return flow, which was concentrated at the gaps. They argued that the case of Arahama corresponded to Case 1, and also argued that a trench was formed owing to the scouring behind the coastal dike, but they did not give details.

On April 20 and August 12, 2011, we carried out field observations to evaluate the effect of the tsunami along the coasts of Sendai Bay. During these field observations, the following specific features of tsunami damage were observed in Arahama Town and on Shobuta Beach and the Yamamoto coast, as shown by rectangular regions in Fig. 2: tsunami inundation into a town located in the hinterland of Shobuta Beach, in contrast to the absence of damage at Gosha Shrine on a top of a hill, and the inundation of the tsunami into a wide residential area in Arahama Town and the destruction of the coastal dike as well as the formation of a large trench behind the coastal dike by tsunami overflow on the Yamamoto coast, where the tsunami height reached up to 19.2 m above mean sea level (MSL), estimated from the run-up height on the slope of a hill. Although we have already reported some of the study results (Uda et al., 2012), in this paper, the overall results of field observations at three locations are reported in detail.

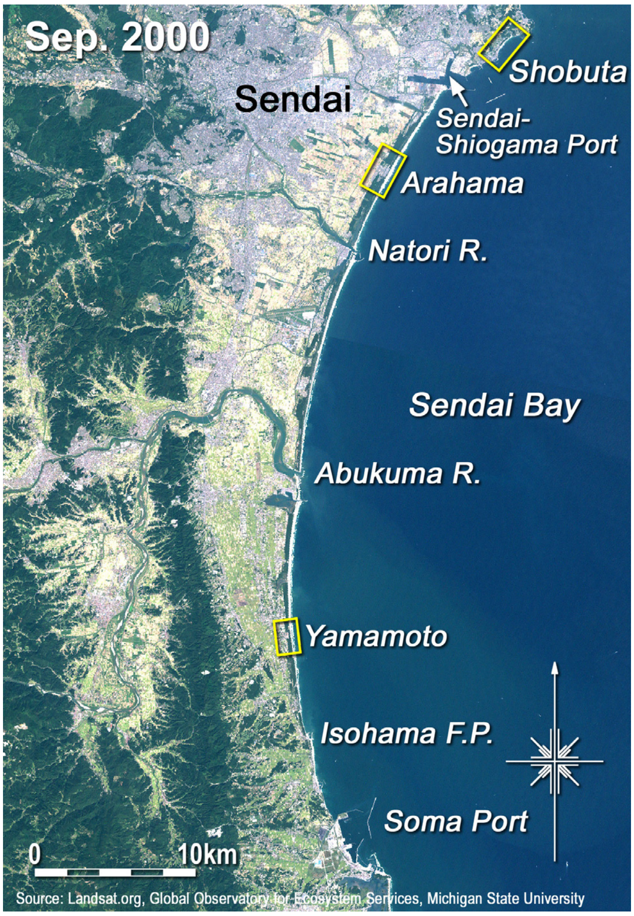



**Figure 2. Locations of Arahama Town, and Shobuta Beach and Yamamoto coast along Sendai Bay.**

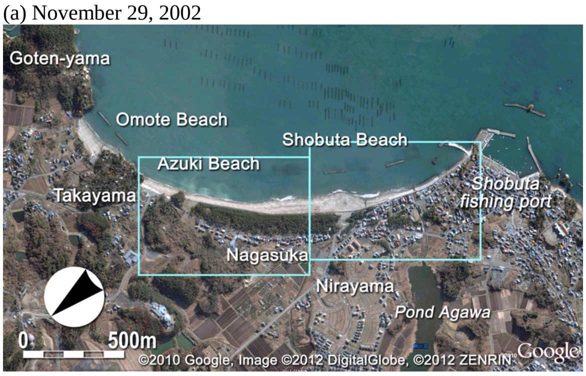
## DAMAGE ON SHOBUTA BEACH

### Overview of Tsunami Damages

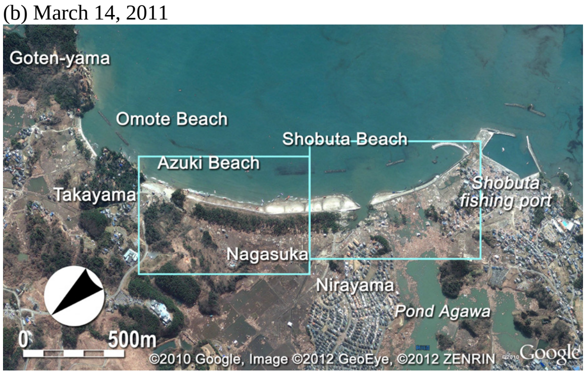
Shobuta Beach is located immediately north of Sendai-Shiogama Port at the north end of the coastline facing Sendai Bay, as shown in Fig. 2. Figure 3 shows enlarged satellite images of the rectangular area of Shobuta Beach shown in Fig. 2 that were obtained before and after the tsunami, respectively. The study area is a pocket beach of 1.7 km length bounded by Shobuta fishing port and Point Takayama, as shown in Fig. 3.

In Fig. 3(a), the locations of Omote and Azuki Beaches, which are separated by short headlands, are also shown along with the location of Shobuta Beach. In the northern half of Shobuta Beach, a dense coastal forest of 100 m width consisting of pine trees extended over a distance of 700 m as one of the protective measures against tsunamis, and two detached breakwaters of 100 m length and an artificial reef of 200 m length had been constructed offshore of the coast, resulting in the formation of cuspate forelands owing to the wave-sheltering effect of these coastal structures.

(a) November 29, 2002




(b) March 14, 2011




(c) April 6, 2011

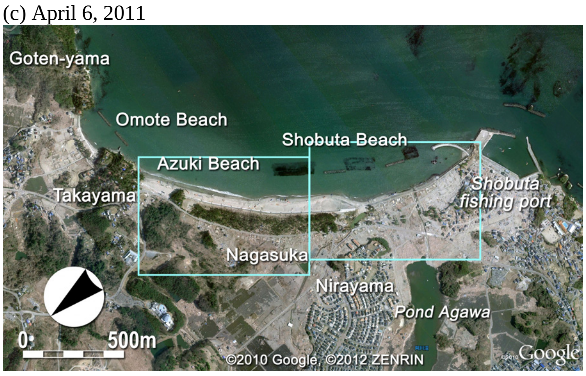
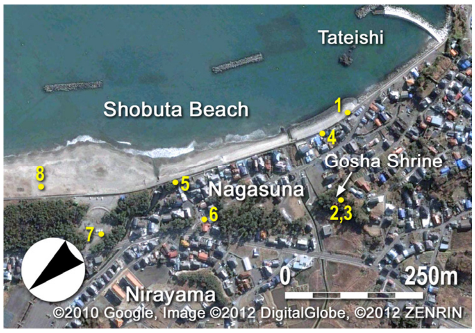
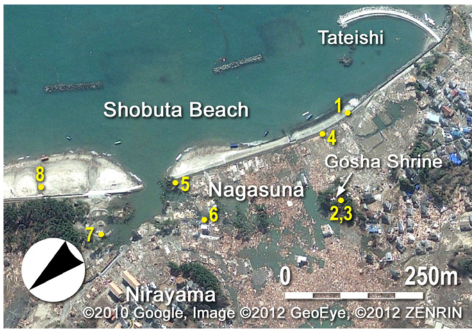



**Figure. 3. Satellite images of Shobuta Beach taken on November 29, 2002, March 14, 2011, immediately after the tsunami, and on April 6, 2011.**

(a) November 29, 2002




(b) March 14, 2011




(c) April 6, 2011

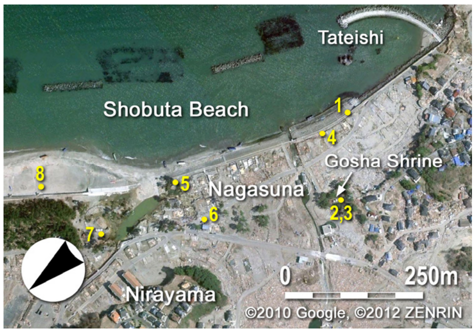



**Figure. 4. Enlarged satellite images of southern Shobuta Beach.**

Comparing the satellite images in Figs. 3(a) and 3(b) taken in 2002 and on March 14, 2011, respectively, it is observed that a curved groin next to Shobuta fishing port had already been constructed with a total length of 200 m, and many houses had been built in the hinterland of Shobuta Beach before the tsunami. A massive tsunami hit these areas, resulting in major damage to the coastal area and destroying many houses built along the coastline. The largest change was the breakdown of the coastal dike in front of Nirayama Town owing to the tsunami return currents, leaving a deep wedge-shaped scouring hole in the hinterland. The breakdown of the coastal dike occurred at the opening of the detached breakwaters, implying that the tsunami currents concentrated there.

In contrast to the breakdown of the coastal dike at the center of the coast, beach changes around the cuspate forelands behind the detached breakwater located at the north end and the artificial reef were minimal. Although the shoreline changes at Azuki Beach north of Shobuta Beach were also small, the shoreline markedly retreated at Omote Beach located at the north end, resulting in the disappearance of the beach of 50 m width. In the southern part of this coast, Agawa pond, which was surrounded by reclaimed land in the coastal lowland, was markedly enlarged owing to tsunami inundation.

In Fig. 3(c) taken on April 6, 2011, the opening of the coastal dike formed by tsunami currents was buried by the sand transported from both sides to the opening. The beach width increased in the area between the north end of Shobuta Beach and Azuki Beach. Because this area is a pocket beach with a closed system with no sand supply by longshore sand transport, shoreward sand transport was assumed to occur under calm wave conditions after the tsunami, resulting in sand deposition near the shoreline. Since the image in Fig. 3(c) was taken in a period when the sea water was transparent, artificial reefs placed between the detached breakwaters on the shallow seabed can be clearly identified.

The location of the breakdown of the coastal dike corresponded not only to the mouth of a small river but also to the landward location of the artificial reef constructed in the opening of the detached breakwaters, implying that such a location with these characteristics is difficult to protect from a tsunami in accordance with the results of Tanaka et al. (2011).

## Site Observation in Southern Part of Coast

On April 20, 2011, site observation was carried out on Shobuta Beach to investigate tsunami damage from the south end to the north end of the beach. Figure 4 shows enlarged images of the rectangular area shown in Fig. 3 with the location of the observation points. The number in each image corresponds to the number of the site photograph.

Photo 1, taken on top of the coastal dike facing north, shows the coastal condition. The tsunami flowed over the crown of the coastal dike and strong currents flowed down the back slope of the dike, and all the houses built along the coastal dike were completely destroyed leaving only their foundations. An isolated hill surrounded by pine trees could be seen 150 m inland of the coastal dike, which seemed to be unaffected by the tsunami. On top of the hill exists Gosha Shrine, which survived the tsunami, as did many shrines in other areas subjected to the large tsunami.

Photo 2 shows the front of the shrine. Tsunami debris was scattered around the shrine, implying that the ground level was approximately equal to the tsunami inundation height. Photo 3 shows the side wall of the shrine, where a large amount of tsunami debris was also scattered. From these observations,


**Photo. 1. Devastated houses with only their foundations left and Gosha Shrine located on top of isolated hill.**

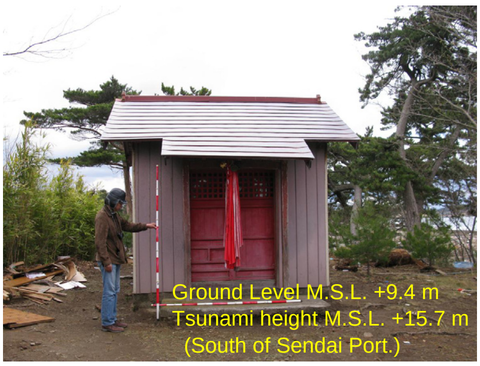



**Photo. 2. Front of Gosha Shrine.**

**Photo. 3. Sidewall of Gosha Shrine and tsunami debris.**

**Photo. 4. Tsunami damage immediately inland of coastal dike.**


**Photo. 5. Breakdown of coastal dike.**

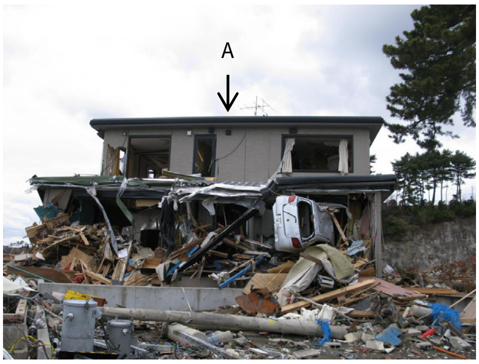



**Photo. 6. Destroyed house and debris inside it.**

the tsunami inundation height was measured to be +9.7 m above MSL at this location, taking the debris scattered around the shrine into account.

Photo 4 shows the scouring hole formed by the overflow of the tsunami over the top of the coastal dike, where houses had been built, as shown in Fig. 4(a) before the tsunami. All the houses were destroyed by tsunami currents. Photo 5 shows the site of the complete breakdown of the coastal dike, as shown in Fig. 4(b). A large hole was formed by the tsunami currents that broke down the concrete coastal dike.

Photo 6 shows the two-story house (indicated by an arrow A in Photo 5) severely damaged by the tsunami. A car and debris from houses were carried into the room. Photo 7 shows a large body of water left behind the coastal dike after the breakdown of the coastal dike, as shown in Fig. 4(b), owing to the tsunami currents. A deep channel was formed inland of the coastal dike. North of the breakdown of the coastal dike, the sandy beach in front of the coastal dike was severely eroded with a backshore elevation decrease of 2.4 m, as shown in Photo 8, although the dike itself was left intact.

### Site Observation in Northern Part of Coast

Figure 5 shows the northern half of Shobuta Beach with the numbers of observation points. All the houses in Nagasuka Town built behind the coastal forest of 100 m width were entirely destroyed. Because this town had been protected by the coastal dike and a densely planted coastal forest, people believed that this area would be safe against tsunamis, but in reality, all the houses were destroyed by the tsunami along with the destruction of the coastal pine trees, suggesting the limited effectiveness using pine trees as a defence against tsunamis.

Photo 9 shows the destroyed pine trees in the coastal forest zone behind the coastal dike. Before the tsunami, pine trees densely grew close to the coastal dike, but almost all the trees fell in the landward direction. At a location where the direction of the coastal dike slightly changes, the asphalt pavement on the crown of the coastal dike was torn off and carried away, forming the scouring hole shown in Photo 10. Photo 11 shows the rocky headland located at the north end of the beach, where a steel signboard fell down in the direction normal to the coastline, showing the propagation direction of the tsunami.

**Photo. 7. Large body of water left behind coastal dike after its breakdown.**

**Photo. 8. Erosion of sandy beach by 2.4 m depth due to tsunami.**


**Figure. 5. Enlarged satellite images of northern Shobuta Beach.**

**Photo. 9. Damaged coastal forest due to tsunami overflow.**

**Photo. 10 Damaged coastal forest and scouring behind coastal dike.**


**Photo. 11. Steel signboard that fell normal to coastline.**

## TSUNAMI DISASTER IN ARAHAMA TOWN

### Landform Changes Caused by Tsunami in Arahama Town

Figure 6 shows enlarged images of the rectangular areas of Arahama shown in Fig. 2. Figures 6(a) and 6(b) show the same areas before and immediately after the tsunami, respectively. Points A-D in Fig. 6 show the locations of site observation. Arahama Town had been separated into two parts by the Teizan canal, and the residential area extended over 200 m seaward of this canal. The coastal forest extended over 70 m seaward of the residential area, which protruded into the coastal forest zone, and the sandy beach further extended over 140 m. In addition, six detached breakwaters had been constructed offshore to protect the residential area against waves. Although it is difficult to recognize its location in Fig. 6, a straight coastal dike with a crown height of +6.2 m above MSL extended between the coastal forest composed mainly of pine trees and the sandy beach. The tsunami inundation height in this area reported by the research group of JSCE was approximately 9.5 m. This part of the Teizan canal, which separates the residential area into two parts, was excavated during the early Meiji era in the late 19th century.

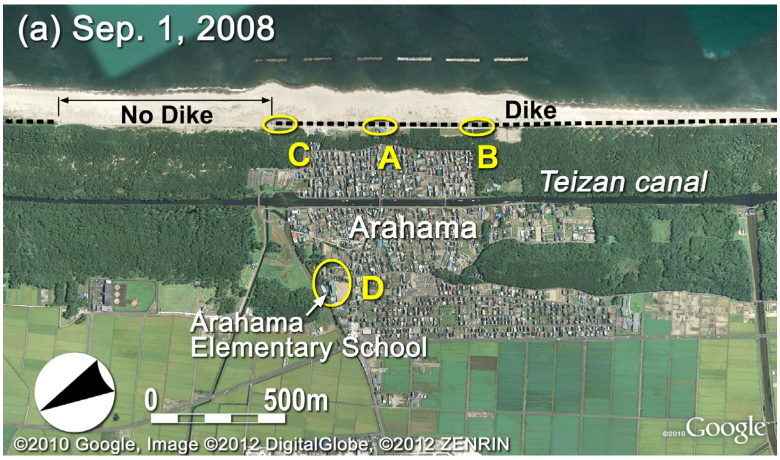
The residential area in Arahama Town was completely destroyed; in particular, the houses were destroyed to their foundations in the seaward area of the canal, and sand was deposited over the debris of houses, which was transported by landward tsunami currents. Although the coastlines north and south of the detached breakwaters continuously extended before the tsunami, as shown in Fig. 6(a), the sandy beach in the lee of the north detached breakwater disappeared, and a channel of 80 m width was formed by the tsunami (Fig. 6(b)). This channel expanded a long distance landward as a wedge along the north end of the residential area in Arahama Town. The location of the newly formed channel is superimposed on the junction between two small rivers, at which the two rivers obliquely joined each other before the tsunami (Fig. 6(a)), suggesting that its elevation was relatively low. The return flow of tsunami that deeply inundated inland areas was partly blocked by the coastal dike, causing longshore return flow along the coastal dike. The concentration of this flow is assumed to be one of the reasons for the formation of the channel. Once the channel had formed, the return flow of the tsunami is expected to have become further concentrated in this channel. A similar channel perpendicular to the shoreline was formed 800 m north of this channel, as shown by a black arrow in Fig. 6(b).

The condition of the area approximately 100 years ago was indicated in an old map produced in 1905. Figure 7 shows that the residential area seaward of the canal had not been developed recently; it already existed in 1905 in the Meiji era. This old map was produced nine years after the great Sanriku Earthquake in 1896.

### Results of Field Observation

(1) Damage to hinterland near point A

Photo 12 shows a large scouring hole formed at the south corner of a public restroom located at the entrance to the beach seaward of point A in Fig. 6. At the corner of the building, a large scouring hole of 3 m depth, directed slightly northward, was formed; the depth was greatest at the corner of the building and gradually decreased landward. Sand was not deposited in the vicinity of this hole, implying that sand was transported further landward by tsunami currents.



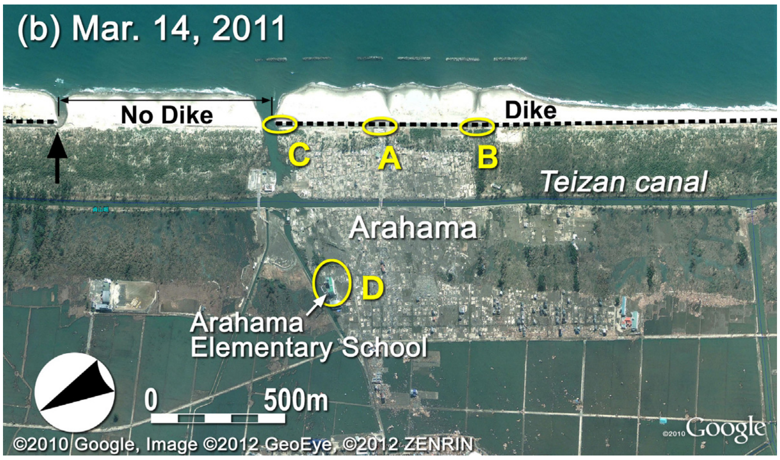




**Figure. 6. Satellite images of Arahama Town obtained on September 1, 2008 and on March 14, 2011.**

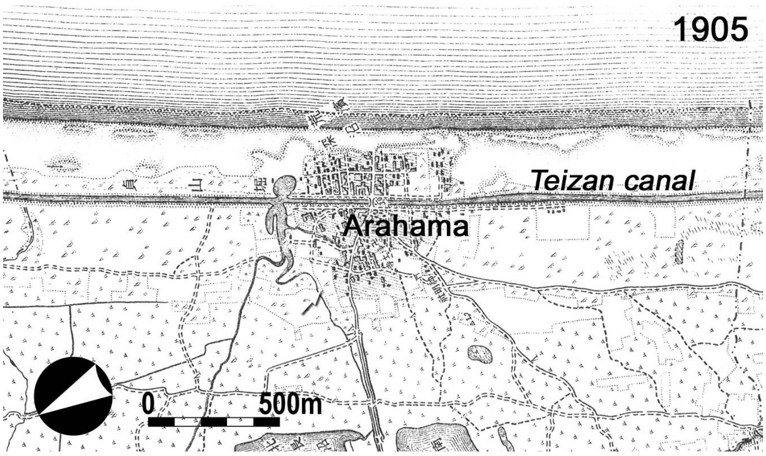



**Figure. 7. Old map of Arahama Town produced in 1905.**

Photo 13 shows the crown of the coastal dike facing south with an elevation of +6.2 m above MSL. The steel fence on the crown fell landward, suggesting the generation of strong tsunami currents. Although tsunami currents flooded over the dike, the coastal dike did not completely break down and the back slope of the dike retained its original shape. Photo 14 shows the damage to houses facing south. The houses were completely destroyed except for their foundations.

(2) South end (point B in Fig. 6) of coastal dike protecting Arahama Town

The seaward side of Arahama Town was protected by the concrete coastal dike with a crown height of +6.2 m, as shown in Photo 13. However, the crown height of this coastal dike decreased to +5.4 m above MSL at the south end of the residential area, and this coastal dike changed from a structure with a trapezoidal cross section to a vertical seawall, as shown in Photo 15. This allowed the tsunami to easily flow over the seawall.

**Photo. 12. Large scouring hole formed at south corner of public restroom.**


**Photo. 13. Concrete coastal dike with crown height of +6.2 m protecting seaward side of residential area.**

**Photo. 14. Damage to houses.**


**Photo. 15. Vertical seawall with smaller crown height.**


**Photo. 16. Deep channel formed at toe of back slope of coastal dike.**

**Photo. 17. North end of coastal dike and wide body of water.**

(3) North end (point C) of coastal dike

In the northern part of the study area, a deep trench was found at the toe of the back slope of the coastal dike, as shown in Photo 16, and the depth of this trench increased northward. The fact that the pine trees immediately inland of this trench obliquely fell inland demonstrates that this trench was mainly formed by the tsunami flow over the coastal dike. Furthermore, the longshore return flow of the tsunami along the coastal dike toward the opening, as shown in Photo 16, is considered to have deepened the trench owing to the blockage of the tsunami return flow by the coastal dike. The deepening of the trench toward the north end is evidence of the development of the longshore return flow of the tsunami along the coastal dike.

Further north of this area, there was no dike and a wide body of water was observed, as shown in Photo 17. Before the tsunami, this area was covered with a coastal forest (Fig. 6(a)); however, after the tsunami, it was severely eroded, leaving a wide channel (Fig. 6(b)). Considering that there was a sandy beach before the tsunami, as shown in Fig. 6(a), this channel is considered to have been formed by the concentration of the tsunami return flow. Further north of this channel perpendicular to the shoreline, there were no coastal protection facilities except for a wooden fence preventing wind-blown sand from entering the area, enabling the tsunami to easily inundate the hinterland.

(4) Arahama elementary school (point D)

Arahama elementary school was a four-story building made of reinforced concrete located 600 m inland of the coastal dike. The first floor was severely flooded and the second floor was also inundated, as shown in Photo 18. Photo 19 shows the condition of the south side of the school building. A large amount of driftwood was deposited on the south side of the second floor of the building. The elevation of the upper limit of the driftwood was +5.5 m above the ground level. Because the ground elevation around the school was +1.5 m above MSL, the tsunami inundated the building up to a level that was +7 m above MSL. Photo 20 shows the debris accumulated in a corridor of the school building. At the end of the corridor of the first floor, the deposited debris reached the ceiling, and a long pine tree and a car were transported into the corridor.

**Photo. 18. Damage to Arahama elementary school.**


**Photo. 19 Condition of south side of school building.**

**Photo. 20 Debris accumulated in corridor of school building.**

### Coastal Topography and Land Use

From the geomorphological viewpoint, part of the Teizan canal in Arahama Town was excavated during the early Meiji era and the canal has been stably maintained since then without a large amount of sand deposition, even though small-scale maintenance dredging has been regularly carried out. This fact shows that this area is lowland without a sand source that would induce the development of a high sand dune, making it vulnerable to tsunami disaster. In addition, the location where a wide channel perpendicular to the shoreline was formed coincided with that of small rivers, implying that the channel formation is closely related to the concentration of the return flow of the tsunami.

Both large and small tsunamis have hit east Japan's Pacific coast in the past, including the Jogan Tsunami in 869, the Keicho Tsunami in 1611, the Ansei Tsunami in 1856, the Meiji Sanriku Tsunami in 1896, the Showa Sanriku Tsunami in 1933 and the Chilean Tsunami in 1960. Because the reduction of tsunami damage by the coastal forest was observed to be significant after the Showa Sanriku Tsunami in 1933, by which a major disaster was triggered, the necessity of establishing a coastal forest as a measure against tsunamis was recognized; thus, coastal forests have been widely established in many areas, including Arahama Town (Murai et al., 1992) and Shobuta Beach. The original plan after the Showa Sanriku Tsunami in 1933 was to establish a coastal forest of 600 m width. However, because residents did not agree with the plan proposed by the local government and the residential area had already been established before pine trees were planted, the residential area was left as it was, close to the coastline (Figs. 6(a) and 7), resulting in high vulnerability to tsunamis. In addition, this area is coastal lowland. Once a tsunami hits this area, there are no evacuation areas.

## TRENCH FORMATION BEHIND COASTAL DIKE

### Landform Changes Caused by Tsunami on Yamamoto Coast

On the Yamamoto coast, during the giant tsunami with a height of 19.2 m, a large trench of approximately 50 m width was formed immediately inland of the coastal dike, and the back slope of the dike was destroyed. Figures 8(a) - 8(c) show satellite images of the Yamamoto coast obtained in August 2010, on March 12, 2011, immediately after the tsunami, and in April 2011, respectively. The numbers in Fig. 8(c) correspond to the locations where site photographs (Photos 21-28) were obtained.

The Yamamoto coast had been protected by a straight coastal dike with a crown height of 6.5 m above MSL along with a coastal forest of 200 m width, as shown in Fig. 8(a). During the tsunami, the coastal dike was destroyed, all the trees were uprooted and transported landward, and a continuous trench was formed along the coastal dike, as shown in Fig. 8(b). Moreover, many indentations with irregular shapes were formed in the inland part of this continuous trench by the return flow of the tsunami. The tsunami run-up height was 19.2 m above MSL at a location 6.5 km south of this area (Public Works Research Center, 2011), which was three times larger than the crown height of the coastal dike, 6.5 m above MSL.

Although the trench was formed behind the undestroyed coastal dike, the irregular coastline with many indentations formed by the return flow had been reduced to a smooth shoreline of pocket beaches by April 6, 2011 owing to the action of waves diffracted from the opening, as shown in Fig. 8(c).

### Damage to the Crown of Coastal Dike

On August 12, 2011, field observation was carried out along the coastal dike between points A and B indicated in Fig. 8. Although the coastal dike extended between points A and C, 100 m south of point A, before the tsunami, the coastal dike was severely destroyed, as shown in Fig. 8(b). Sand bars extended landward from the south and north ends of the coastal dike (A and B, respectively), and a trench continuously extended behind the undestroyed section of the coastal dike.

Photo 21 shows part of the destroyed coastal dike, facing south from point A shown in Fig. 8(b). At a location 100 m south of point A, the remains of the coastal dike were observed and the sandy beach extended between points A and C. Sand deposition was not observed near point C in April 2011, as shown in Fig. 8(c), although a cuspate foreland had formed near point A. This implies that a large amount of sand was transported and deposited by wave action during the period between April 2011 and August 12, 2011.

Photo 22 shows the coastal dike and a trench north of point A. There was no deformation of the asphalt pavement of the crown, although the pine trees planted on the seaward slope of the dike were uprooted. In contrast, the back slope of the concrete dike was destroyed, and a trench of 50 m width was formed inland of the destroyed back slope. The destruction of the back slope was considered to be due to the local scouring at the toe of the back slope and the suction of the sediment that filled the dike when the tsunami flooded over the dike. Photo 23 shows the damage to the crown in an area further north. The back slope, as well as the asphalt pavement, was much more severely damaged than that in the southern part. Approaching the north end of the coastal dike (point B in Fig. 8(b)), the coastal dike was destroyed and almost the entire crown of the dike collapsed (Photo 24).

Photo 25 shows the cuspate foreland behind the coastal dike, which was formed near point B, as shown in Fig. 8(b). Because the partly destroyed coastal dike functioned as an impermeable detached breakwater, a large-scale cuspate foreland was formed behind the partly destroyed dike. In contrast to the severe damage to the back slope, no major changes were observed on the seaward slope, as shown in Photo 26.

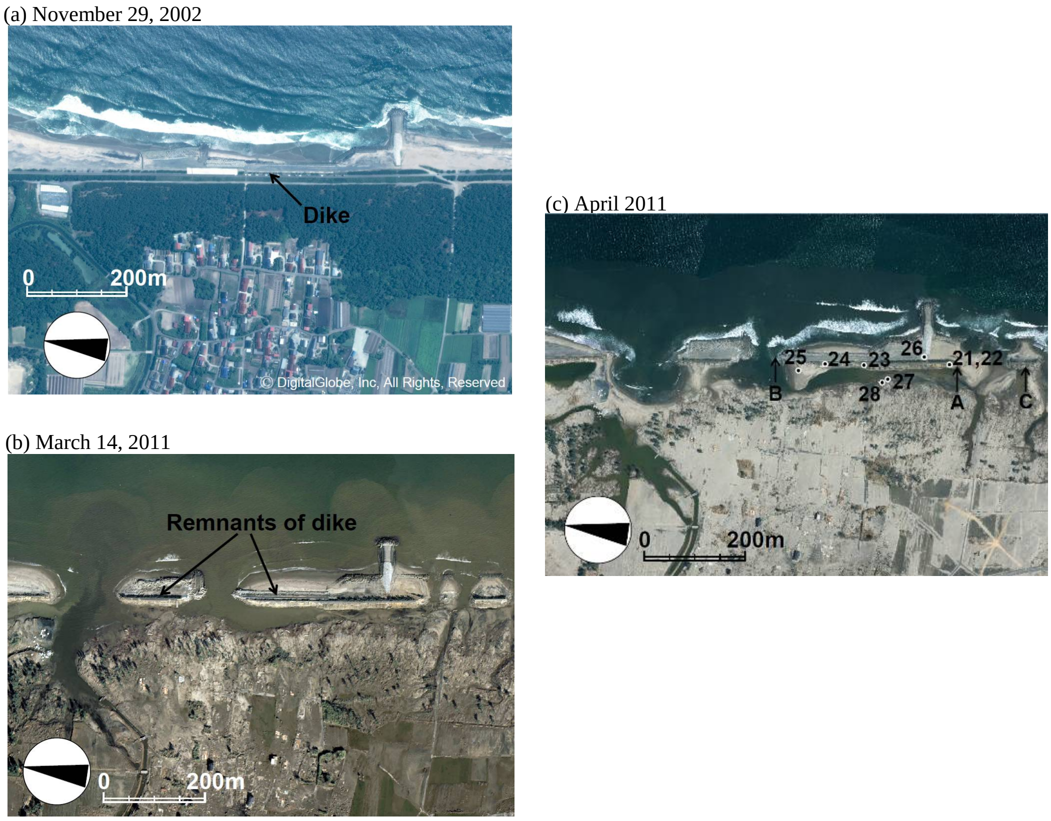



**Figure. 8. Satellite images of Yamamoto coast and locations where photographs were taken.**


**Photo. 21. Part of destroyed coastal dike.**

**Photo. 22. Crown of coastal dike north of point A.**

**Photo. 23. Damage to crown in area further north.**

**Photo. 24. Severely damaged coastal dike.**

**Photo. 25. Cuspate foreland behind partly destroyed coastal dike.**

**Photo. 26. Seaward slope without major changes.**


**Photo. 27. Photograph of uniform trench formed alongshore behind coastal dike (south).**

### Trench Formation

The Yamamoto coast was severely eroded even before the tsunami, there were no sandy beaches, and the coastline was protected by a concrete coastal dike and concrete armor units. In this area, the coastal dike was severely destroyed. Photo 27 shows a uniform trench formed alongshore behind the dike facing south. Most of the back slope was destroyed by the tsunami and subsided. In addition, subsidence of the back slope also occurred owing to the discharge of earth that filled the dike. It is considered that because the trench was continuously formed alongshore, the scouring occurred two-dimensionally.

Across the trench formed inland of the damaged dike, where sand deposition did not occur, the cross-shore profile (Fig. 9) was measured across the trench. The width and depth of this channel at the ground level were 50 m and 2 m, respectively.

Regarding the back slope of the coastal dike, the sediment that filled the dike was discharged and the concrete slab was broken. Such conditions can be clearly observed in Photo 28, in which concrete frames were broken and left in the air owing to the scouring. Taking the development of the trench behind the partly destroyed dike into account, it is concluded that the ground level rapidly decreased near the toe of the back slope, forming openings beneath the toe. The sediment was discharged through these openings, and finally the back slope was destroyed.

**Structure of Coastal Dike**

The general cross section of a coastal dike in the design manual of shore protection facilities in Japan is shown in Fig. 10. On the toe of the seaward slope of the dike, a curtain wall must be built because the seaward slope is expected to be subject to strong wave action, and there is only a small amount of foot protection and a small drainage channel at the tip of the back slope. Considering wave overtopping, the top of the dike and the back slope must be protected using concrete, as indicated in the Japanese design manual. However, regarding the back slope, there is no suggestion that large scouring may occur at the toe of the back slope. Thus, the back slope is considered a weak point of the structure against local scouring behind the dike during a tsunami with a height exceeding the crown height.

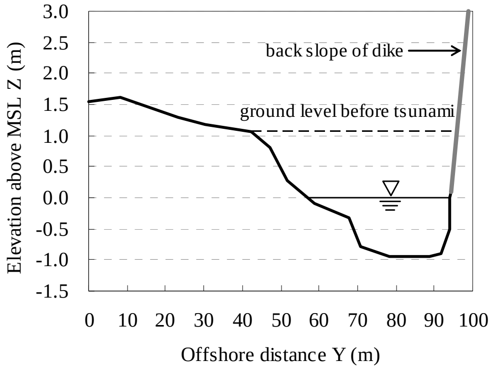



**Figure. 9. Measured cross section of trench behind the coastal dike.**

**Photo. 28. Trench formation and back slope of damaged seawall.**

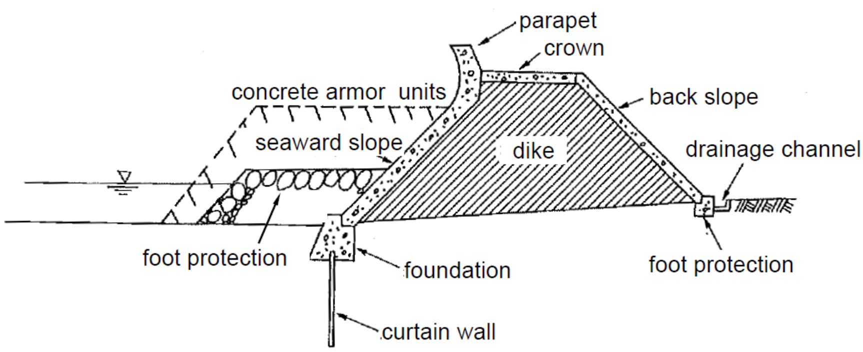



**Figure. 10. Typical cross section of coastal dike based on Japanese shore protection manual.**

## CONCLUSION

Specific features of tsunami damage observed in Arahama Town and on Shobuta Beach and the Yamamoto coast were briefly reported. On Shobuta Beach, located at the north end of the study area, the coastal dike was broken down and a large hollow was formed inland of the coastal dike by the tsunami returning currents immediately after the tsunami. After the tsunami, however, sand was transported to the eroded location by the action of wind waves to fill the concave shoreline, and finally a continuous shoreline was formed again. In addition, it should be noted that a shrine in the area built on top of a hill was not damaged by the tsunami, similarly to many other shrines in the tsunami-affected area, even though the tsunami height reached +9.7 m above MSL, because the ground elevation of the shrine was slightly higher than the tsunami height.

In Arahama Town, the inundation of the tsunami into a wide residential area was observed. Then, the necessity of reestablishing land use with both a sufficient buffer zone and protection facilities was pointed out. Under the present legal system, the coastal land is subject to the Coastal Act, and the coastal forest is subject to the Forest Law. The residential area is private land under the rights permitted in the Constitution of Japan. To enhance the security of the coastal zone area, setting back of the shore protection zone and the resultant landward movement of the residential area are required. For this purpose, the adjustment of rights for private and public land is considered to be necessary.

On the Yamamoto coast, the formation of a large trench behind the coastal dike and the resultant destruction of the back slope of the coastal dike by tsunami overflow were observed. It was found that the back slope is a weak point of this structure against local scouring behind the dike during a tsunami with a height exceeding the crown height.

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