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# Two Distinguished Effects of the 2011 Great Tsunami to the Coasts along Sendai Bay: Damage to Arahama and Trench Formation behind the Dike on Yamamoto Coast

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**Abstract**

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 great tsunami inundated east Japan's coastline extensively. We carried out field observations to investigate the damage to Arahama and the formation of a trench as a result of local scouring by jet flow over the coastal dike. Here, the results of the field observations on the inundation of the tsunami into a wide residential area in Arahama 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.

**Key words:** *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, 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 owing to the abrupt crustal subsidence and uplift, inundated east Japan's coastline extensively. The damage was particularly severe along the coasts of Iwate and Miyagi Prefectures and also occurred on the coasts of Fukushima, Ibaraki and Chiba Prefectures (Fig. 1). To record tsunami trace heights along the coastal zone comprehensively, 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

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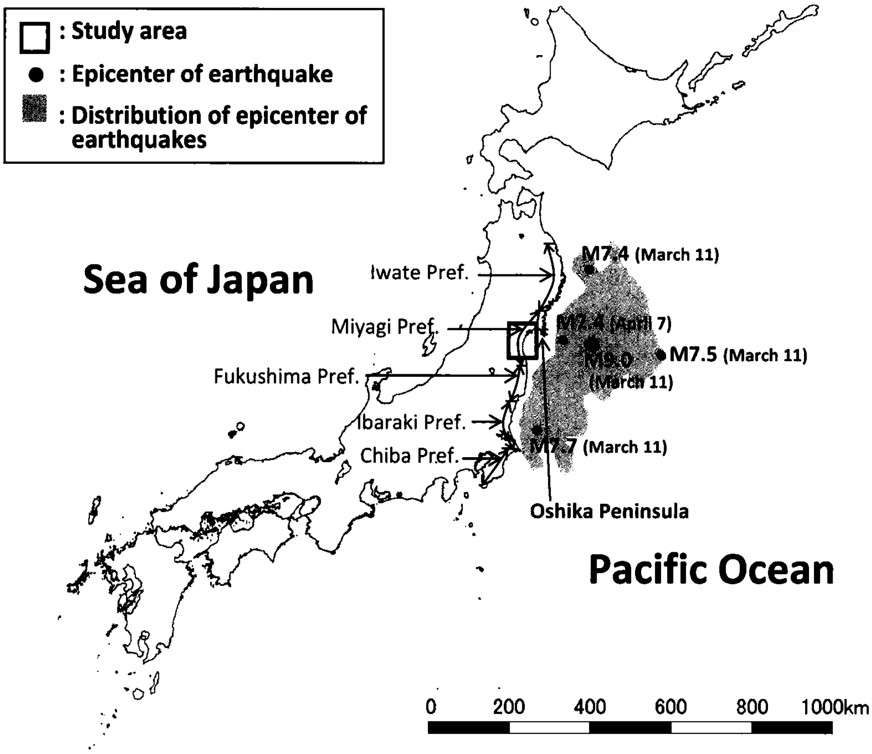


**Fig. 1.** Epicenter of the 2011 Great Earthquake.

height along east Japan's coast was reported in detail (Joint Research Group of 2011 Great Tsunami of JSCE, 2011).

Shibayama et al. (2011) pointed out that Arahama located 7 km east of Sendai City was severely damaged because the width of the coastal forest was narrow compared with the other areas, which had already been described by Harada et al. (2000). Tanaka et al. (2011) investigated beach changes in the same area on the basis of the aerial photographs which were taken before and after the tsunami and field observations. On the formation mechanism of a large-scale channel across the sandy beach, they pointed out the following three causes: (1) return flow concentrating on the previous river mouth was generated, (2) the joint of the coastal dike with different structures or with different crown height alongshore produced a structural weak point, to have resulted in the concentration of the tsunami return flow, and (3) the seawall had not been built continuously without gaps, so that the seawall was destroyed by the return flow concentrated on this gap. They argued that the case of Arahama corresponded to Case 1, and also argued that a trench was formed due to the scouring behind the coastal dike, but they did not show the detail.

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 and on the Yamamoto coast, as shown by rectangular regions in Fig. 2: the inundation of the tsunami into a wide residential area in Arahama and the destruction of the coastal dike

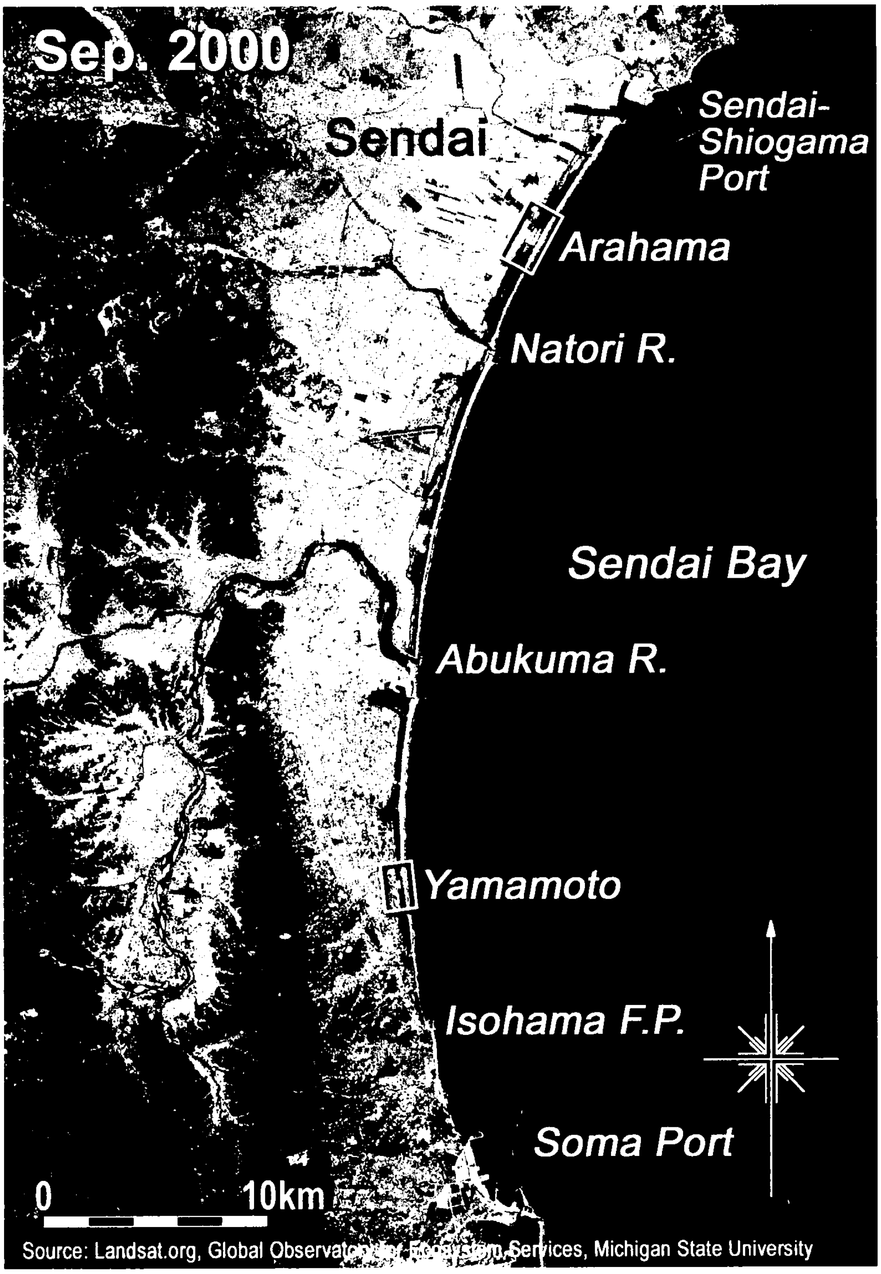


**Fig. 2.** Locations of Arahama and Yamamoto coast along Sendai Bay.

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. In this study, the results of the field observations are reported.

## Tsunami disaster in Arahama

*Landform changes by tsunami in Arahama*

Figure 3 shows an expanded image of the rectangular areas of Arahama shown in

Fig. 2. Figures 3 (a) and 3 (b) show the same areas before and immediately after the tsunami, respectively. Points A-D in Fig. 3 show the locations of site observation. Arahama had been separated into two parts by the Teizan canal, and the residential area extended seaward of this canal over 200 m. 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. 3, a straight coastal dike with a crown height of +6.2 m above MSL extended between the coastal forest composed of mainly 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

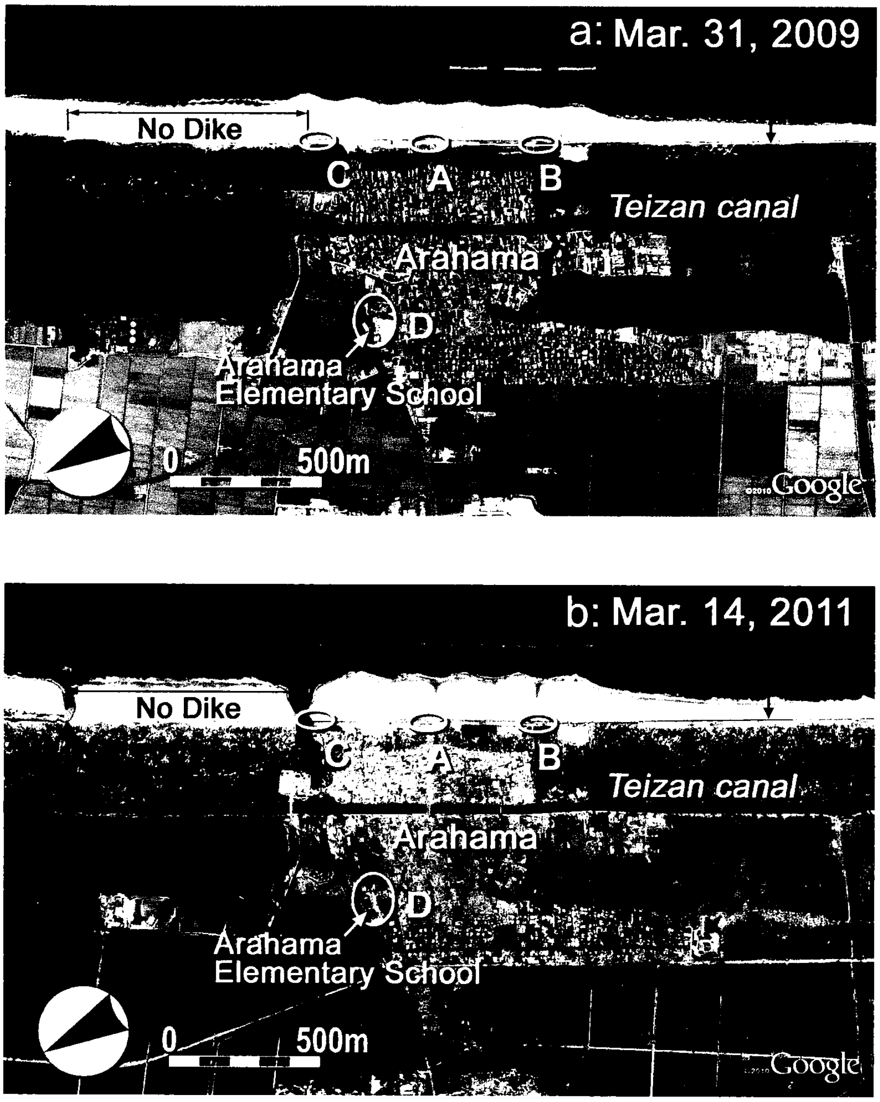


**Fig. 3.** Satellite image of Arahama obtained on March 31, 2009, and on March 14, 2011.

late 19th century.

The residential area in Arahama 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. 3 (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. 3 (b)). This channel expanded a long distance landward as a wedge along the north end of the residential area in Arahama. The location of the newly formed channel is superimposed to the junction between two small rivers, at which two rivers obliquely joined each other before the tsunami (Fig. 3 (a)), suggesting that its elevation was relatively low. The return flow of tsunami inundated deep inland was partly blocked by the coastal dike, causing longshore return flow along the coastal dike. The concentration of such flow is assumed to one of the reasons for the formation of such a channel. Once a channel was formed, the return flow of tsunami was expected to concentrate further in this channel. A similar channel perpendicular to the shoreline was formed 800 m north of this channel, as shown by a thick black arrow in Fig. 3 (b).

The condition of the area before approximately 100 years ago was indicated in an old map produced in 1905. Figure 4 shows that the residential area seaward of the canal was not developed recently, but already it 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

Figure 5 shows a large scouring hole formed at the south corner of a restroom for public use located at the entrance to the beach seaward of point A in Fig. 3. At the corner of the building, a large scouring hole of 3 m depth, directed slightly northward, was formed, and the depth showed its maximum at the corner of the building and gradually decreased landward. In the vicinity of this hole, sand was not deposited,

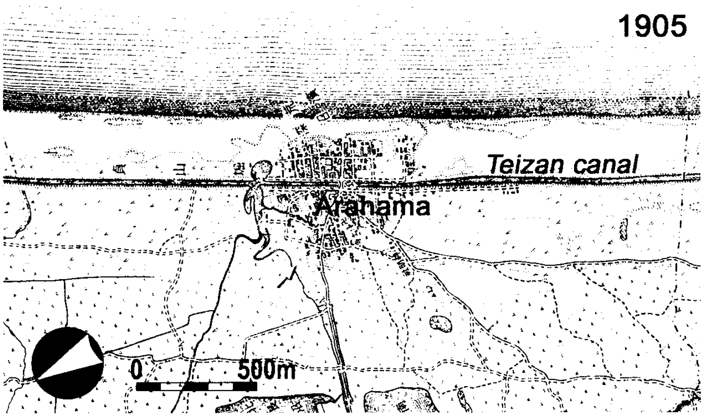


**Fig. 4.** Old map of Arahama produced in 1905.

implying that sand was transported further landward by tsunami currents.

Figure 6 shows the crown of the coastal dike with an elevation of +6.2 m above MSL, facing south. The steel fence on the crown fell down landward, suggesting the generation of strong tsunami currents. Although tsunami currents flooded over the dike, the entire breakdown of the coastal dike did not occur and the back slope of the dike retained its original shape. Even though the residential area near point A was protected by the coastal dike, the houses were entirely destroyed by the tsunami. Figure 7 shows the damage to houses, facing south. The houses were completely destroyed except for their foundations.

(2) South end (point B in Fig. 3) of the coastal dike protecting Arahama

The seaward side of Arahama was protected by the concrete coastal dike with a

**Fig. 5.** A large scouring hole formed at the south corner of a restroom for public use.


**Fig. 6.** Concrete coastal dike with crown height of +6.2 m protecting seaward side of residential area.

crown height of +6.2 m, as shown in Fig. 6. However, the crown height of this coastal dike decreased to +5.4 m above MSL, 0.8 m lower than that of the coastal dike in the north part, at the south end of the residential area, and its structure also altered from a coastal dike with a trapezoidal cross-section to a vertical seawall, as shown in Fig. 8. This allowed easy overflow of the tsunami. There was a gap between the vertical seawall in the south part and the coastal dike in the north part, and the tsunami was concentrated at this gap. A large scouring hole was formed around this gap, where the original ground was eroded at the corner, as shown in Fig. 9, implying the generation of strong tsunami currents. The arrow in Fig. 9 shows the direction of expected tsunami currents around the corner.

**Fig. 7.** Damage to houses.

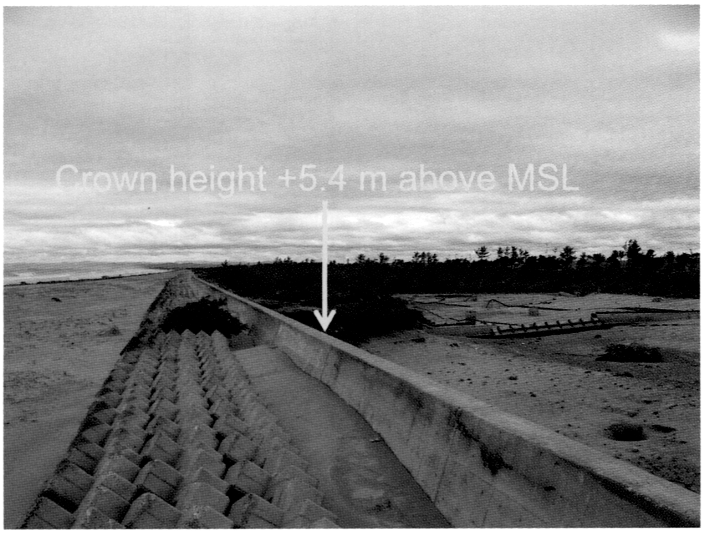


**Fig. 8.** Vertical seawall with lower crown height.

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

In the north part of the study area, a deep trench was found at the toe of the back slope of the coastal dike, as shown in Fig. 10, and the depth of this trench increased northward. The fact that the pine trees immediately inland of this trench obliquely fell down directing inland demonstrates that this trench was mainly formed by the tsunami flow over the coastal dike. Furthermore, longshore return flow of tsunami along the coastal dike toward the opening, as shown in Fig. 10, is considered to deepen the trench due to the blockage of tsunami return flow by the coastal dike. The deepening of the trench toward the north end is the evidence for the development of the longshore return flow of tsunami along the coastal dike.

Further north of this location, there was no dike and a wide water body was

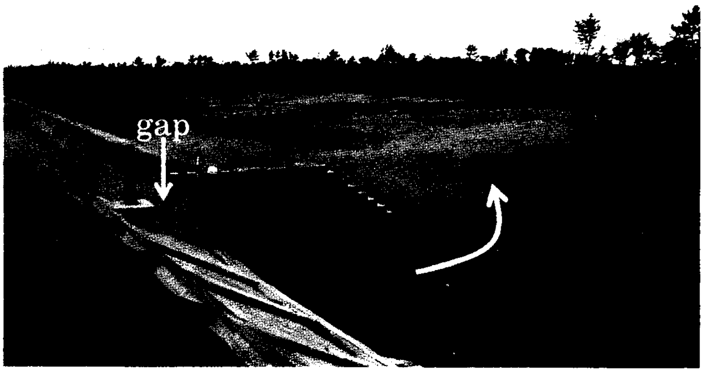


**Fig. 9.** A large scouring hole formed around the gap between vertical seawall and coastal dike.

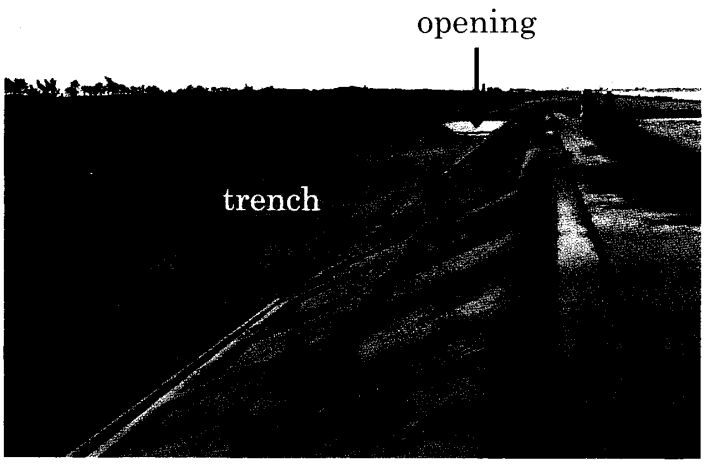


**Fig. 10.** Deep channel formed at the toe of back slope of coastal dike.

observed, as shown in Fig. 11. Before the tsunami, this area was covered with a coastal forest (Fig. 3 (a)); however, after the tsunami, it was severely eroded, leaving a wide channel (Fig. 3 (b)). Considering that there was a sandy beach before the tsunami, as shown in Fig. 3 (a), this channel was considered to be formed by the concentrating return flow of tsunami. Further north of this channel perpendicular to the shoreline, there were no coastal protection facilities, with only a wooden fence preventing wind-blown sand from entering the area (Fig. 12), enabling the tsunami to inundate the hinterland easily.

(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

**Fig. 11.** North end of coastal dike and wide water body.

**Fig. 12.** Destroyed wooden fence preventing wind-blown sand at the north of channel.

second floor was also inundated, as shown in Fig. 13. Figure 14 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. Figure 15 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.

*Coastal Topography and Land Use*

From the geomorphological view point, the fact that the part of the Teizan canal in

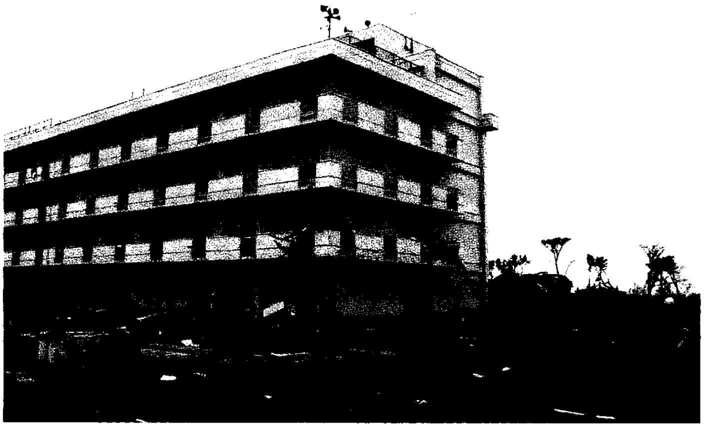

**Fig. 13.** Damaged Arahama elementary school.


**Fig. 14.** Condition of the south side of school building.

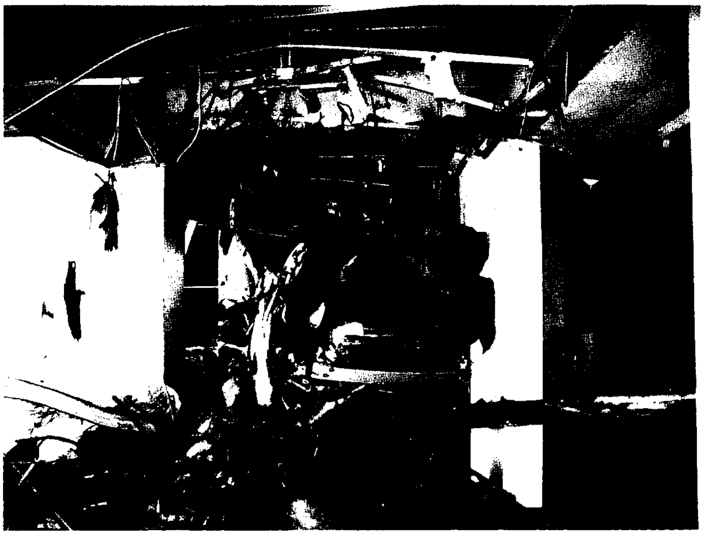

**Fig. 15.** Debris accumulated in the corridor of school building.

Arahama was excavated during the early Meiji era and such a 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 tsunami.

Along the East Japan's Pacific coasts, large tsunamis have hit in the past: e.g., 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, as well as smaller-scale tsunamis. 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 great 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 (Murai et al., 1992). The original plan after the Showa Sanriku Tsunami in 1933 intended 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. 4 and 3 (a)), resulted 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 the coastal dike and destruction of the dike on the Yamamoto coast

*Landform changes by the tsunami on Yamamoto coast*

On the Yamamoto coast, during the great 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 16 – 18 show satellite image 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. 18 correspond to the locations where site photographs (Figs. 19 – 27 and 29) 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. 16, before the tsunami. 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. 17. Moreover, many indentations of 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 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 was 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. 18.

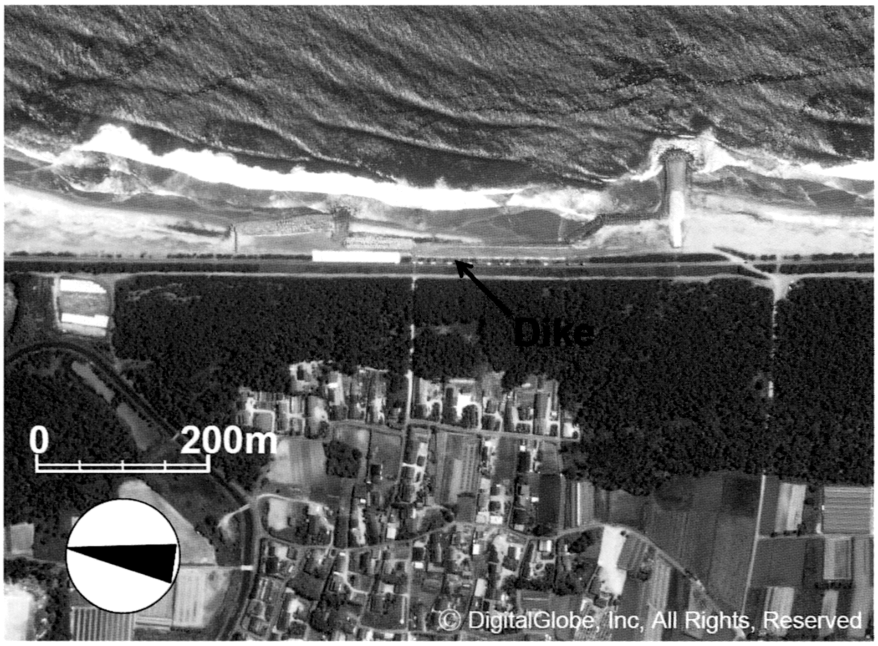


**Fig. 16.** Satellite image of Yamamoto coast (August 2010).

*Damage to the crown of coastal dike*

Field observation was carried out along the coastal dike between points A and B indicated in Fig. 18. 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. 18. Sand bars extended landward from the south and north ends (A and B) of the coastal dike, respectively, and a trench continuously extended behind the

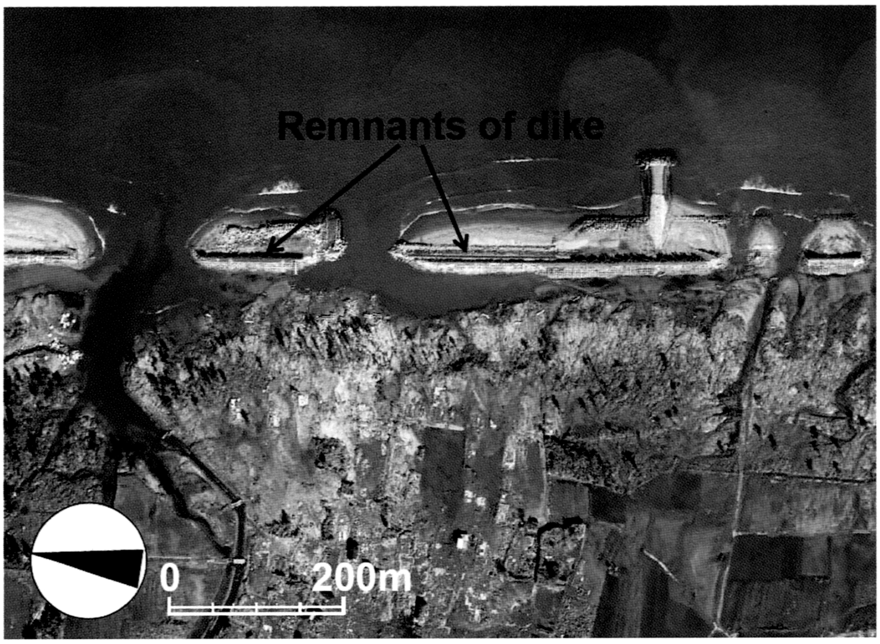


**Fig. 17.** Satellite image of Yamamoto coast (March 12, 2011).

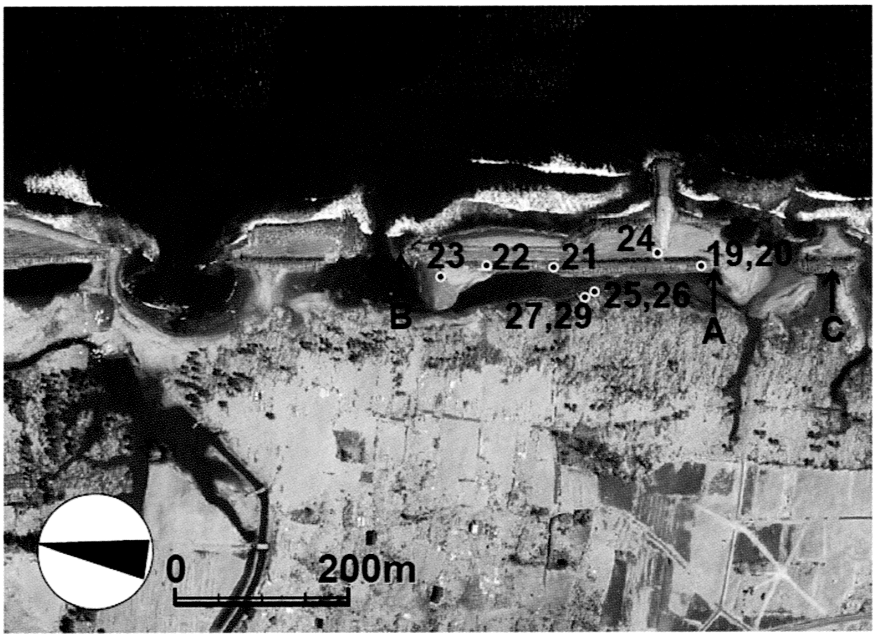


**Fig. 18.** Satellite image of Yamamoto coast and locations where photographs were obtained (April, 2011).

undestroyed section of the coastal dike.

Figure 19 shows a part of the destroyed coastal dike, facing south from point A shown in Fig. 18. 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. 18, although a cuspate foreland was 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.

Figure 20 shows the coastal dike and a trench north of point A. There was no deformation in the asphalt pavement of the crown, although pine trees planted on the seaward slope of the dike were uprooted. In contrast, the back slope of the concrete dike was severely destroyed, and a trench of approximately 50 m width was formed inland of the destroyed back slope. The failure 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. Figure 21 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 south part. Approaching the north end of the coastal dike (point B in Fig. 18), the coastal dike was severely destroyed and almost the entire crown of the dike fell down (Fig. 22).

Figure 23 shows a photograph of the cuspate foreland behind the coastal dike, which was formed near point B as shown in Fig. 18. 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 Fig. 24.

*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. Figures 25 and 26 show photographs of the trench uniformly formed alongshore behind the dike, which were obtained looking south and north, respectively. Most of the back slope was destroyed by the tsunami and slid down. In addition, the subsidence of the back slope also occurred due to the discharge of earth materials 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, as shown in Fig. 27, where sand deposition did not occur, the cross-shore profile (Fig. 28) 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 shown in Fig. 27, sediment that filled the dike was discharged and the concrete slab was broken. Such condition can be clearly realized in Fig. 29, in which the concrete frames were broken and left in the air due to the


**Fig. 19.** Part of destroyed coastal dike.

**Fig. 20.** Crown of coastal dike north of point A.

**Fig. 21.** Damage to crown in the area further north.

**Fig. 22.** Severely damaged coastal dike.

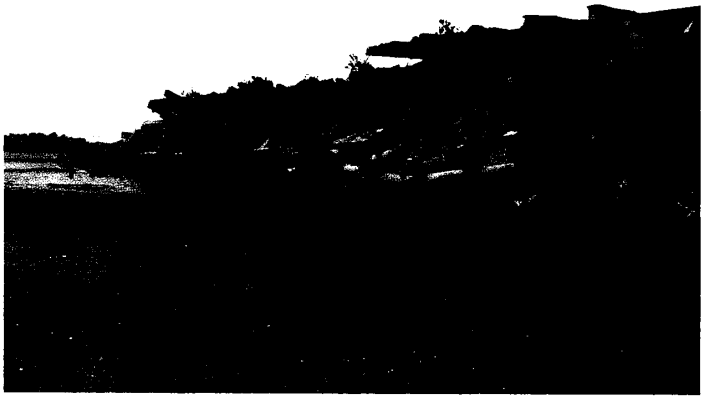

**Fig. 23.** Cuspate foreland behind partly destroyed coastal dike.

**Fig. 24.** Seaward slope without major changes.

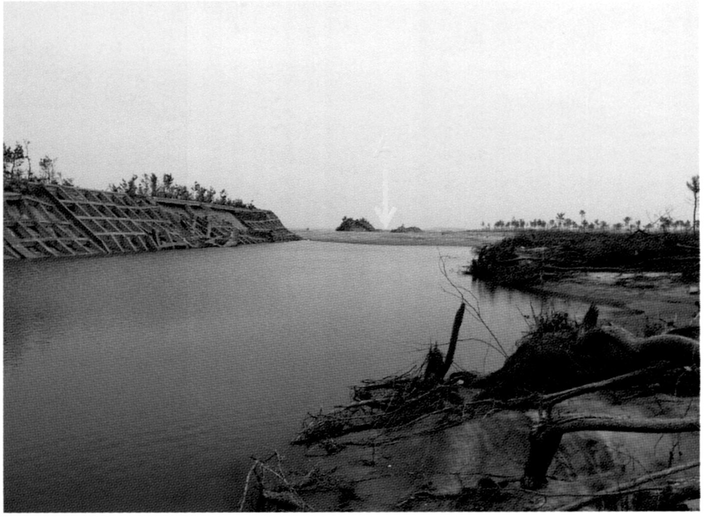

**Fig. 25.** Photograph of trench uniformly formed alongshore behind coastal dike (south).

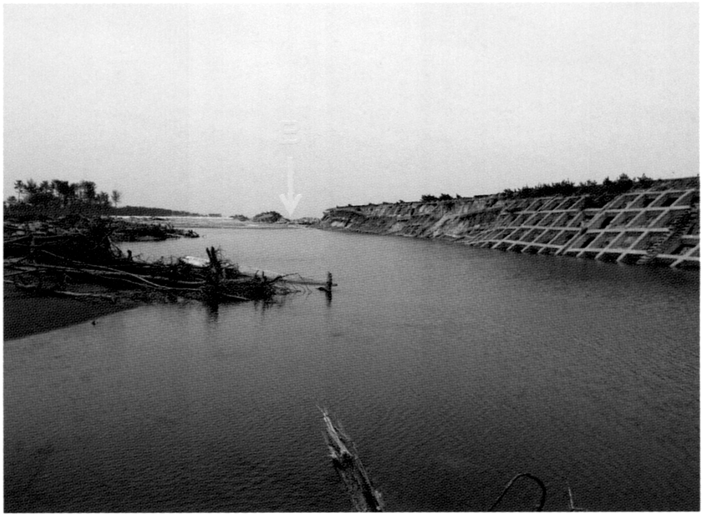

**Fig. 26.** Photograph of trench uniformly formed alongshore behind coastal dike (north).

**Fig. 27.** Trench formation and back slope of damaged seawall.

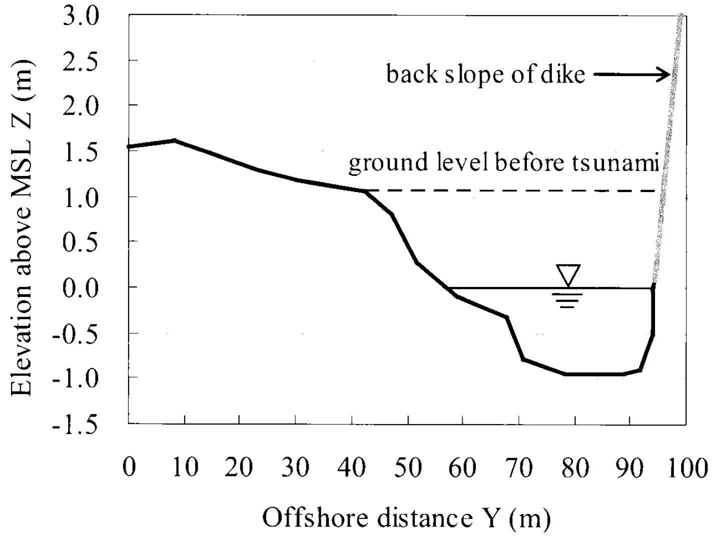


**Fig. 28.** Cross-shore profile measured across trench.

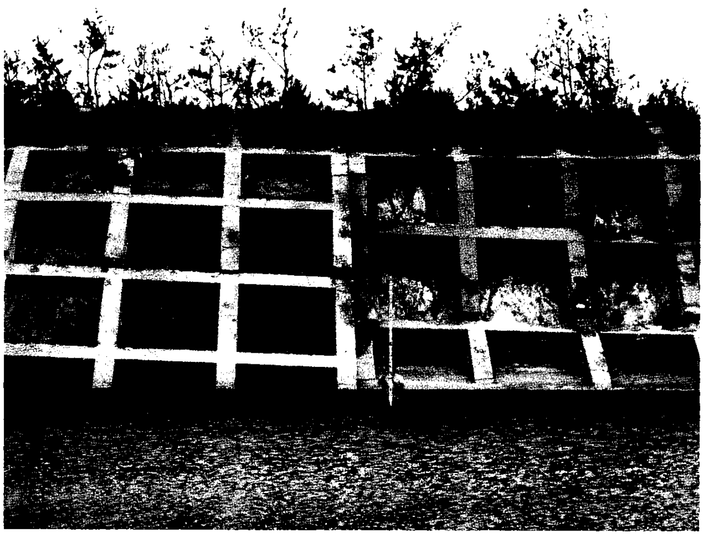

**Fig. 29.** Back slope of damaged coastal dike.

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 of the back slope. 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. 30. 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, whereas there are only a small amount of foot protection and a drainage channel at the tip of the back slope. Considering wave overtopping, the top of the dike

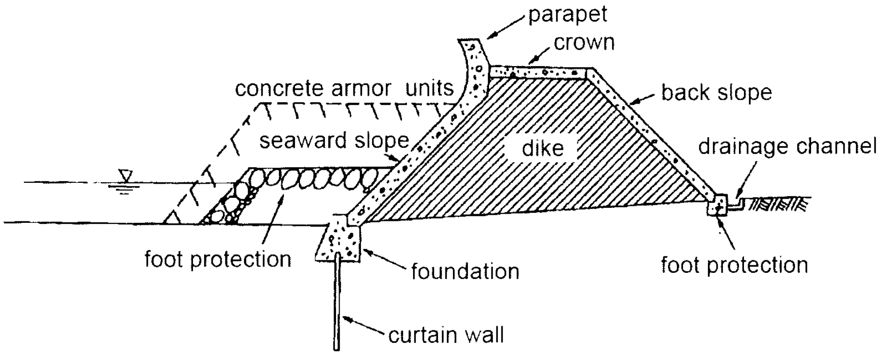


**Fig. 30.** Typical cross section of coastal dike based on Japanese shore protection manual.

and the back slope must be protected using concrete, as indicated in the Japanese design manual. However, regarding the back slope, there was no suggestion that large scouring would occur at the toe of the back slope. Thus, the back slope became a weak point of the structure against local scouring behind the dike during a tsunami having the height of which exceeded the crown height.

## Conclusions

Specific features of tsunami damage observed in Arahama and on the Yamamoto coast were briefly reported. In Arahama, 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 ruled under the Coastal Act, and the coastal forest under 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 resultant destruction of the back slope of the coastal dike by tsunami overflow were observed. It was found that the back slope became a weak point of this structure against local scouring behind the dike during a tsunami having the height which exceeded the crown height.

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