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Coastal Morphology Change Before and After 2011 Off the Pacific Coast of Tohoku Earthquake Tsunami at Rikuzen-Takata Coast

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This study investigates the changes in coastal topography of the Rikuzen-Takata Coast in Iwate Prefecture, Japan before and after the 2011 off the Pacific coast of Tohoku Earthquake Tsunami and the effects of coastal structures on these changes. The changes in coastal topography were analyzed using bathymetry data and aerial photographs before and after the tsunami in addition to aerial video during the tsunami. The bathymetry data were obtained from 1989 to 2002 during the construction of three submerged breakwaters and from after the 2011 tsunami until 2013. The aerial photographs were acquired from 1947 to 2015, and the aerial videos were acquired during the tsunami run-up and backwash. The results demonstrated that the coast was eroded mainly due to the tsunami backwash, and the submerged breakwaters trapped the seaward transport of sediment from the coast. Erosion was partly prevented in locations where the seawall was not washed away. The coastal structures had significant effects on the behavior of the coastal tsunami and on sediment transport. We also found that the coast did not recover naturally at the desired speed after the tsunami because the coast had been stable before the tsunami. Coastal restoration five years after the 2011 tsunami are also summarized in the Appendix to illustrate the future reconstruction plan for the study coast.

Keywords: Submerged breakwater; seawall; sediment transport; land loss; coastal forest.

1. Introduction

The 2011 Great East Japan Earthquake (GEJE) led to a worst-case-scenario tsunami disaster. Regarding coastal erosion, coseismic subsidence caused by the earthquake [Geospatial Information Authority of Japan, 2011] and sediment transport caused by the tsunami resulted in the serious loss of coastal land in a wide area from Iwate to Fukushima Prefecture. Udo *et al.* [2016] reported that the change in shoreline due to the transport of sediment by the tsunami was much greater than that caused by coseismic subsidence (see Fig. 1), and the main cause of land loss was erosion by the tsunami.

After the 2004 Indian Ocean Tsunami, several studies analyzed the changes in shoreline caused by the tsunami using field data and satellite images [Mascarenhas and Jayakumar, 2008; Pari *et al.*, 2008; Choowong *et al.*, 2009]; however, few studies have been reported on the changes in coastal topography due to a lack of topographical data, particularly data for before the tsunami. Paris *et al.* [2009] studied the spatial distribution of tsunami deposits at West Banda Aceh, Indonesia along 18 km of the coastline and reported a maximum coastal retreat of 123 m. Goto *et al.* [2011]

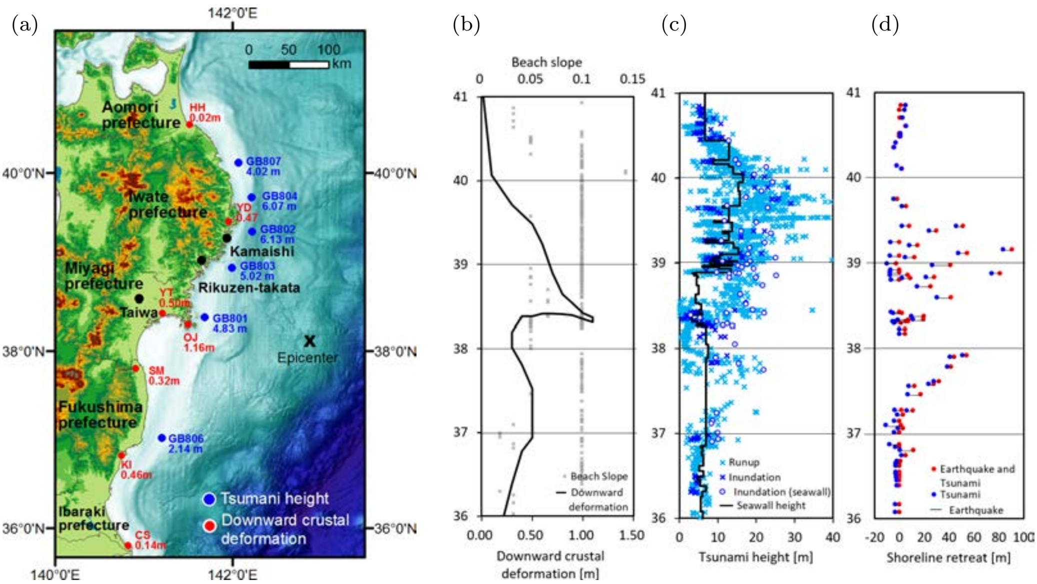


Fig. 1. (Color online) (a) Locations of the study area (i.e. Rikuzen-Takata Coast), the Kamaishi wave station, and the places from where nourishment sand was obtained (i.e. Taiwa Town, Miyagi Prefecture) with distributions of earthquake epicenters (black ×), permanent GPS stations where downward crustal deformation was measured (red circles) [Geospatial Information Authority of Japan, 2011], and GPS buoys where tsunami heights were observed (blue circles) [Kawai *et al.*, 2013]. Distributions of (b) downward crustal deformation observed by permanent GPS stations and beach slope [Biodiversity Center of Japan, 2012], (c) tsunami watermark height [TTJS, 2012] and seawall height before the earthquake and tsunami, and (d) shoreline retreat due to both the earthquake and tsunami (red circles) and only to the tsunami [blue circles; revised from Udo *et al.*, 2016].

investigated bathymetric changes due to the tsunami along 2 km of coastline including Kirinda Harbor, Sri Lanka. They demonstrated that sedimentation along the shoreline occurred due to the tsunami except in the harbor, where erosion occurred, and the bathymetry data were restored to pre-tsunami levels within a year after the tsunami.

Unlike for the 2004 Indian Ocean Tsunami, many data exist for both before and after the 2011 tsunami, including topographic data, land subsidence data, and satellite images. In addition, numerous images and videos with time stamps were taken before, during, and after the tsunami by individuals [Ushiyama and Yokomaku, 2012]. Thus, many studies have been conducted on shoreline change using field data and satellite images of both the plain and ria coasts, and several studies have been conducted on changes in topography [Tanaka *et al.*, 2012; Udo *et al.*, 2012; Tappin *et al.*, 2012; Adityawan *et al.*, 2014; Udo *et al.*, 2016]. The tsunami damage and mechanisms of damage obtained using the above data have provided suggestions for the mitigation of coastal disasters. Regarding coastal erosion, Tojo and Udo [2016] showed that massive erosion (land loss) is caused by cross-shore water paths such as those in the vicinity of seawall breaches or rivers where tsunami backwash concentrates. They also reported that the spatial distribution of the coastal recovery rate shows that the plain coasts tend to have recovered after the tsunami, whereas the ria coasts did not recover.

This paper focuses on the long-term coastal change at the Rikuzen-Takata Coast, a ria coast with submerged breakwaters, from 1947 until the present to reveal the effects of the 2011 tsunami. We discuss the effects of the breakwaters on sediment transport during the 2011 tsunami and its recovery after the tsunami. Furthermore, we review the restoration of the coast five years after the tsunami in the Appendix.

2. Study Area

Our study area is the Rikuzen-Takata Coast, which faces the Pacific Ocean in the northern part of Japan [Fig. 1(a)] and was significantly eroded by the 2011 tsunami. Several tsunami disasters struck the Rikuzen-Takata Coast in the last 150 years: the 1896 Meiji tsunami, the 1933 Showa tsunami, the 1960 Chilean tsunami, and the 2011 tsunami. The properties of these tsunamis, such as earthquake magnitude, representative tsunami height, and inundation area, are summarized in Liu *et al.* [2013]; the inundation area of the 2011 tsunami was the largest among the four tsunamis and roughly 2.5 times as large as that of the second largest (the 1960 tsunami). The change in shoreline during the study period (1947–2015) has been insignificant with the exceptions of during the periods affected by the 1960 and 2011 tsunamis (see Fig. 2).

Damages to the Rikuzen-Takata Coast caused by the 1960 Chilean tsunami and the corresponding restoration processes are reported in detail in Shuto [2011]. The tsunami, which had a height of 3–4 m, ascended the Kesengawa River and intruded

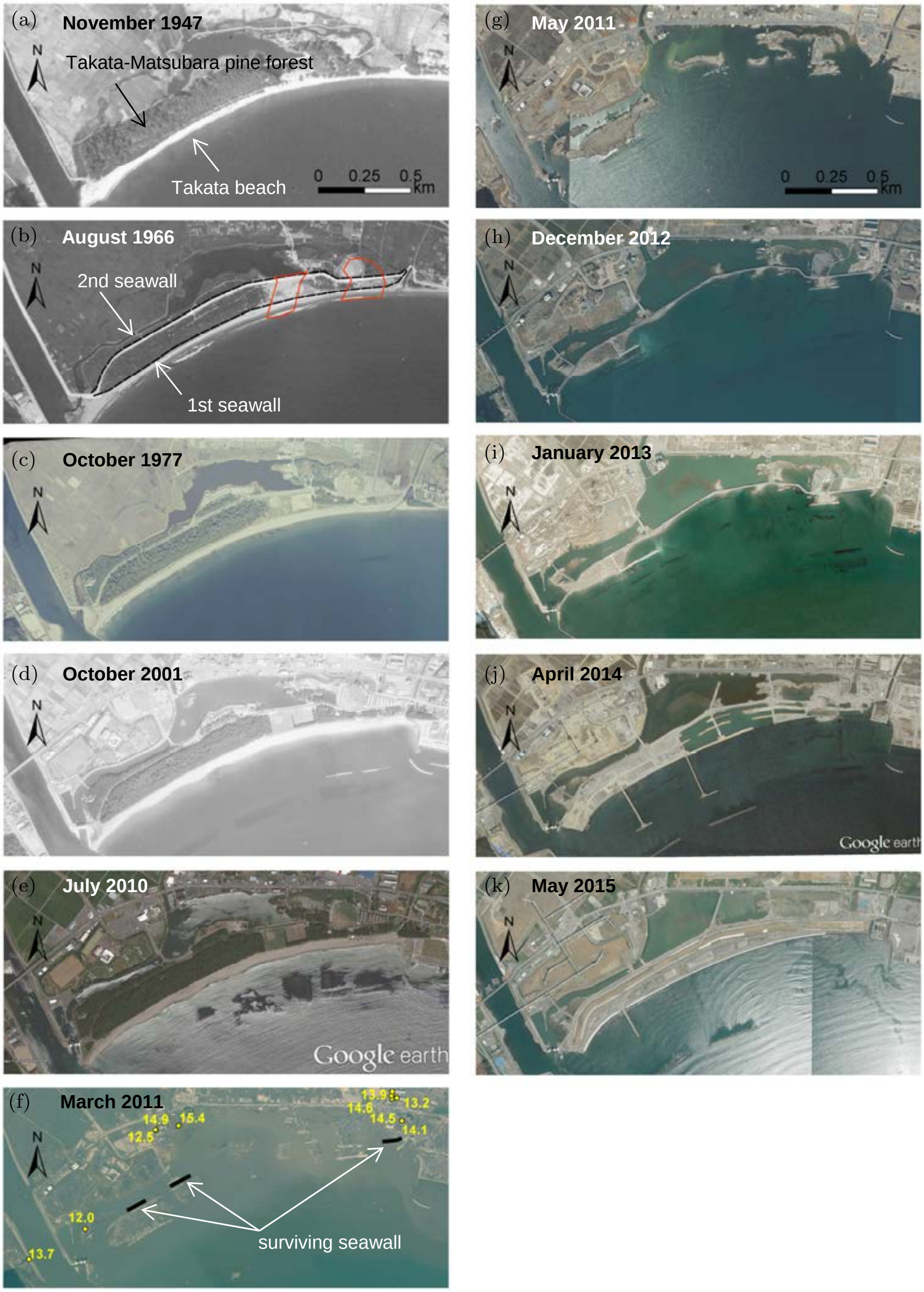


Fig. 2. (Color online) Aerial photographs taken in (a) November 1947, (b) August 1966, (c) October 1977, (d) October 2001, (e) July 2010, (f) March 2011, (g) May 2011, (h) December 2012, (i) January 2013, (j) April 2014, and (h) May 2015 by the Geospatial Information Authority of Japan, except for the images in (f) and (j) which were obtained from Google Earth. The red polygons in Fig. 2(b) show the areas eroded by the 1960 Chilean tsunami. Yellow numerals in Fig. 2(f) indicate the tsunami inundation heights.

inland through the relatively sparse area of the Takata-Matsubara coastal pine forest [see Fig. 2(a)]. Successive tsunami backwash separated the Takata-Matsubara forest, creating an erosion area with a width of 240 m and a maximum depth of 5 m [see the red polygons in Fig. 2(b)]. After the tsunami, the first seawall with a height of Tokyo Pail (T.P., Japanese vertical datum relative to the mean sea level of Tokyo Bay) +3.0 m was constructed between the beach and the forest to protect the foreshore and stabilize the shoreline; the Takata beach was then restored as a bathing beach [Fig. 2(b)]. In addition, a second seawall with a height of T.P. +5.5 m (1.0 m higher than the height of the Chilean tsunami) was also constructed between the forest and the Furukawa-numa marsh to prevent tsunamis from affecting inland areas.

Beginning in 1972, jetties and breakwaters were constructed at the Takata beach for foreshore protection and shoreline stabilization [see Fig. 2(d)]. In April 1988, the Takata beach was specified as a development area of coastal community zone (CCZ), and coastal projects had been carried out along with other projects such as park projects. In the period from 1990 to 2001, three submerged breakwaters were constructed in consideration of landscape preservation.

In March 2011, the Takata beach and the Takata-Matsubara forest were significantly eroded by the tsunami [Figs. 2(e) and 2(f)]. The maximum tsunami inundation height observed by the 2011 Tohoku Earthquake Tsunami Joint Survey Group [Mori *et al.*, 2012] based on water marks was 15.4 m. The tsunami almost completely washed away the first and second seawalls surrounding the Takata-Matsubara forest, although part of the second seawall remained.

Rikuzen-Takata City drafted the Basic Reconstruction Plan for restoration after the GEJE in December 2011 following the Basic Policy on Reconstruction, which was formulated in July 2011. In March 2015, the reconstruction plan was revised in consideration of restoration progress and changes in social and economic situations. The Basic Reconstruction Plan includes a strategy for the complete restorations of the Takata-Matsubara forest and the Takata beach to their conditions before the tsunami. Rikuzen-Takata City was selected as the location for the construction of Tsunami Reconstruction Memorial Park. The basic concept for the Takata-Matsubara Tsunami Memorial Park was released by the Tohoku Regional Bureau, Ministry of Land, Infrastructure, Transport, and Tourism, Iwate Prefecture, and Rikuzen-Takata City in June 2014; the park will include the forest and the beach.

3. Methods

The topographic changes in the study area from 1989 to 2013 were analyzed using bathymetry data obtained from the Department of Public Works, Ofunato Regional Development Bureau, Iwate Prefecture. The erosion of the Rikuzen-Takata Coast due to coseismic subsidence caused by the 2011 earthquake was not significant compared to that attributed to sediment transport caused by the tsunami [Fig. 1(d)]; therefore, the topographic change attributed to coseismic subsidence of 0.64 m [Kato *et al.*, 2012] was subtracted from the total change in the period from winter 2002 to autumn 2011 in order to determine the change in topography due to the tsunami. Aerial video taken by the Iwate Prefecture Police was used to understand the detailed behavior of the tsunami. The wave data at the nearest wave measurement station, Kamaishi, and the disaster records reported by the Japan Meteorological Agency (JMA; http://www.data.jma.go.jp/obd/stats/data/bosai/report/index.html) were also analyzed to determine the causes of topographic change.

To explain the changes in topography caused by wind waves, a beach profile parameter (C_s) proposed by Sunamura and Horikawa [1974] was calculated using

$$\frac{H_0}{L_0} = C_S(\tan\beta)^{-0.27}\left(\frac{d}{L_0}\right)^{0.67},$$

where H_0 and L_0 are the significant wave-height and length in deep water, respectively, d is the sediment grain size, and $\tan\beta$ is the beach slope. L_0 is calculated from the wave period T as $gT^2/2\pi$. The beach is classified as an advancing profile when C_s is smaller than around 18 and as a recessionary profile when C_s is larger than around 18. In this study, the values of H_0 and T were taken as those at Kamaishi (water depth is 49.5 m), where data have been collected since 1978 [see Fig. 5(a)] [Kawaguchi *et al.*, 2014]. Thus, we assumed that the wave climate in the study area is similar to that at Kamaishi.

4. Results and Discussion

The topography in 1989, 2002, and 2011 and its change from 1989 to 2002 and from 2002 to 2011 are shown in Fig. 3. The change in topography after the tsunami was reported to be insignificant [Udo *et al.*, 2015]; thus, the topographic data obtained in 2011 and 2013 were compiled to interpolate the data in 2011 using the 2013 data. The change in topography from 2002 to 2011 was mainly due to sediment transport caused by the tsunami. The changes in profile during the study period along lines A to E [see Fig. 3(d)] are shown in Fig. 4. Long-term wave data at Kamaishi are shown in Fig. 5 [see Fig. 1(a) for the location].

The bathymetry data for 1989–2002 (before the tsunami) indicate changes in the area shallower than 5 m and in the construction area of the three submerged breakwaters. The breakwaters No. 1 (west), 2 (middle), and 3 (east) were completed in 1996, 1993, and 2001, respectively, as shown by the changes in bathymetry data in Figs. 3(d) and 4 [Inoue *et al.*, 2002; Udo *et al.*, 2015]. The annual mean significant wave-height and period from 1978 to 2013 were 0.87 ± 0.06 m and 8.3 ± 0.3 s, respectively, and stormy events during which the maximum wave-height exceeded 5 m occurred once every few years. The beach slope and the grain size at the Rikuzen-Takata Coast were 0.075 and 0.26 mm, respectively. Therefore, for the annual mean wave climate, C_s at the coast is calculated to be around 5, which classifies it as

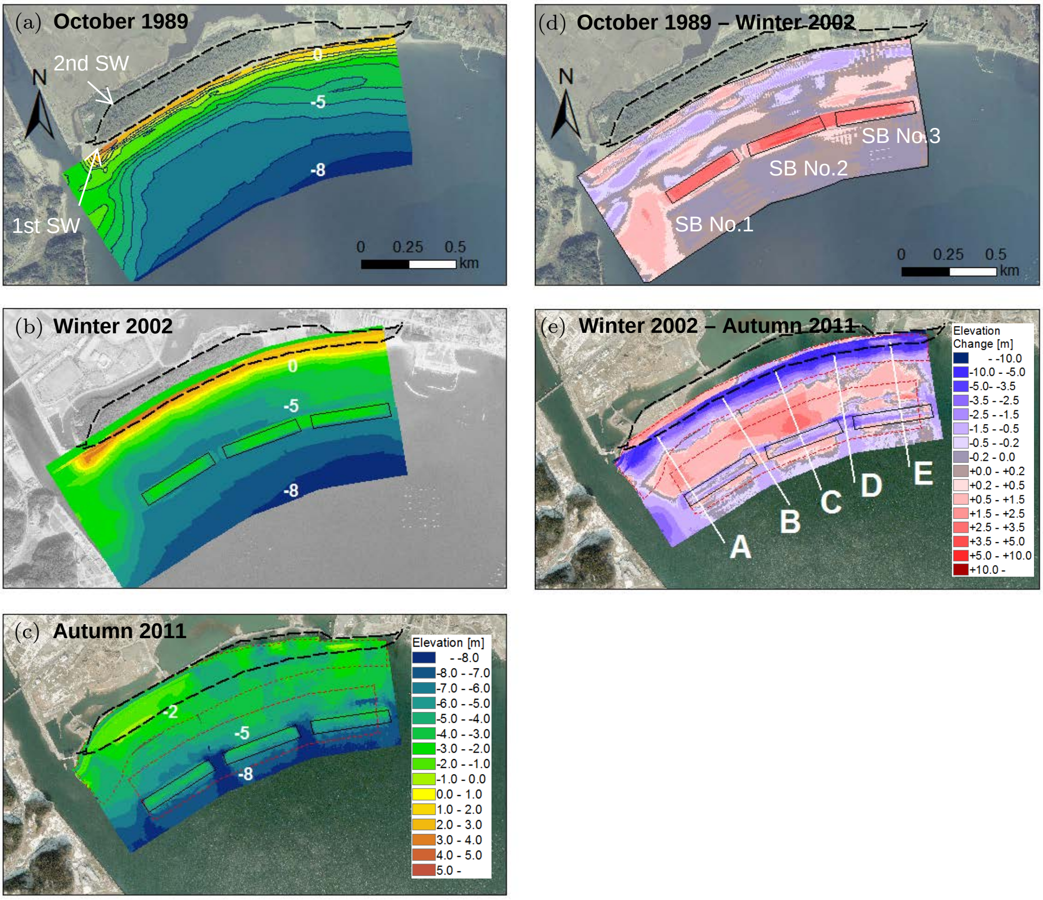


Fig. 3. (Color online) Coastal topographies in (a) October 1989, (b) winter 2002, and (c) autumn 2011 and topographic changes from (d) 1989 to 2002 and (e) 2002 to 2011 (partly 2013). The topographic change of 0.64 m due to earthquake-induced coseismic subsidence has been removed. The 2011 data outside of the red polygons were interpolated based on the 2013 data. The coastal profile transects A, B, C, D, and E in Fig. 4 are also shown in Fig. 3(e). These figures are modified from Udo *et al.* [2015].

an advancing profile. For the yearly maximum wave climate of 4–7 m in height and 10–13 s in period, C_s is in the range of 20–32, classifying it as a recessionary profile [Sunamura and Horikawa, 1974]. For such a wave climate, the long-term topography of the beach is thought to be stable, as supported by the topography data.

In addition, a river mouth terrace formed at the mouth of the Kesengawa river from 1989 to 2002 and was extended from 1997 to 2002 [Udo *et al.*, 2015]. This is attributed to the heavy rainfall caused by the typhoon No. 0206 in July 2002, just before the topography measurement, from the disaster records of JMA [see Fig. 5(b)]. Many studies have been reported on the formation of river mouth terraces due to floods [e.g. Tanaka and Huimin, 1993].

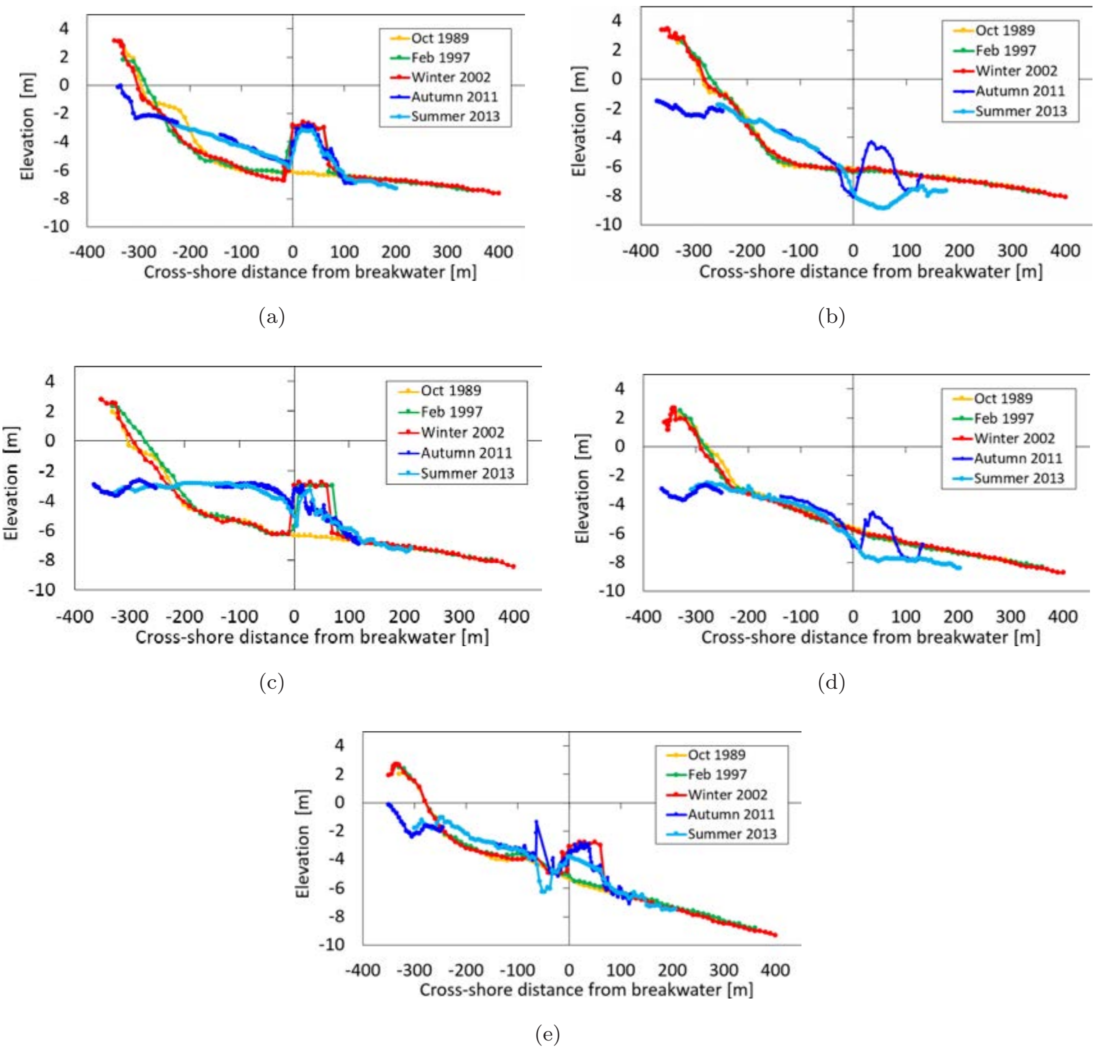
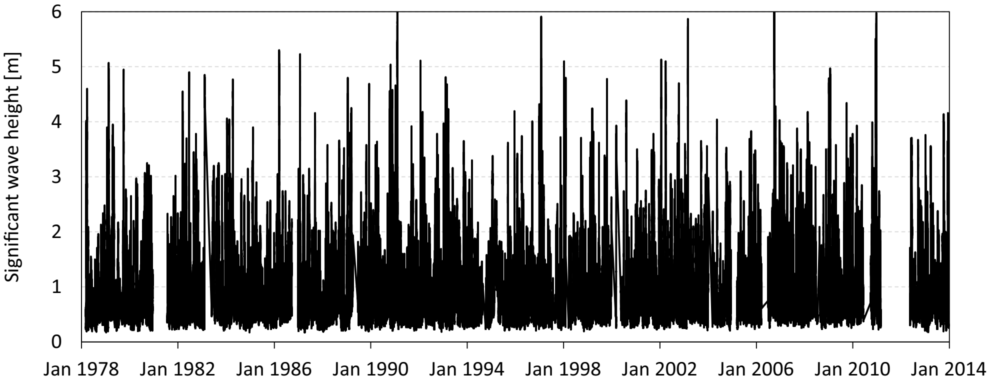
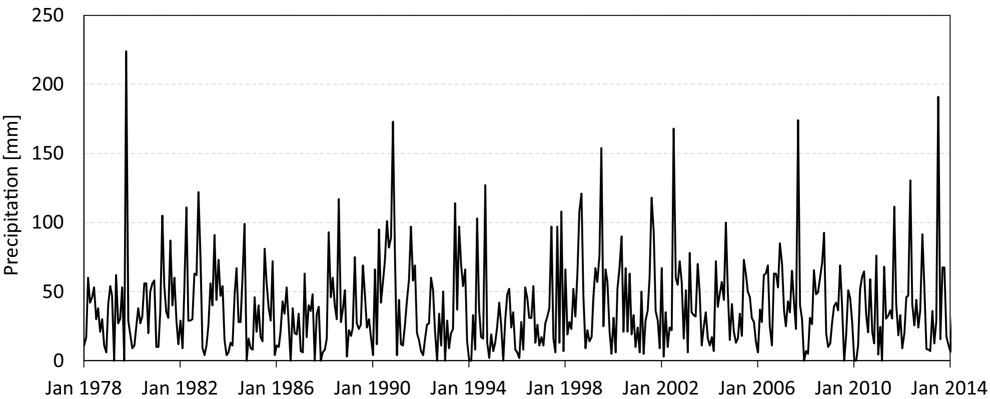


Fig. 4. Coastal profile changes obtained along transects A to E [see Fig. 3(e)]. The changes due to coseismic subsidence is removed.

From 2002 to 2011, the data indicate an enormous amount of tsunami-induced erosion of the Takata Coast and accumulation of sediment landward of the submerged breakwaters. The breakwaters (top heights, lengths, and widths were T.P.-2.9 m, 400 m, and 120 m, respectively), which were covered with riprap protections (see the coastal profile in winter 2002 shown in Fig. 4) [Inoue *et al.*, 2002], were damaged by the tsunami, as shown by the data from August 2011 [see Figs. 3(e) and 4]. The river mouth terrace was also eroded. The numerical simulations of Yamashita *et al.* [2016], who simulated the tsunami inundation height, sediment transport, and topographic change at the Rikuzen-Takata Coast, demonstrated that twice as much erosion resulted from the backwash compared to from run-up. Considering



(a)



(b)

Fig. 5. Time series of (a) significant wave-height at the nearest wave station (Kamaishi) and (b) monthly maximum daily precipitation at Sumita, which is located upstream of the Kesengawa River, from 1978 to 2013.

the distribution of the eroded and accumulated areas [Fig. 3(e)] and the results of Yamashita *et al.* [2016], the backwash from the coast to the sea must have been a main cause of the erosion. Furthermore, the volumes of sediment in the eroded and accumulated areas were 1.1 million m^3 in the beach area and 0.4 million m^3 in the landward area of the breakwaters, respectively [Fig. 3(e)]. According to the documents of the committee on nourishment at Takata beach, the median grain size on the foreshore surface changed from 0.26 mm in 2004 to 0.45 mm in 2012; this coarsening can also be attributed to the tsunami.

Aerial video frames at the times of tsunami arrival (around 15:20 JST), run-up (around 15:24 JST), and backwash (around 15:37 JST) are shown in Fig. 6 along with the satellite images (Google Earth) before and after the tsunami. The time stamp of the video was determined by elapse time from the time to start taking the video. The video editing time was not considered; thus, the time stamp was

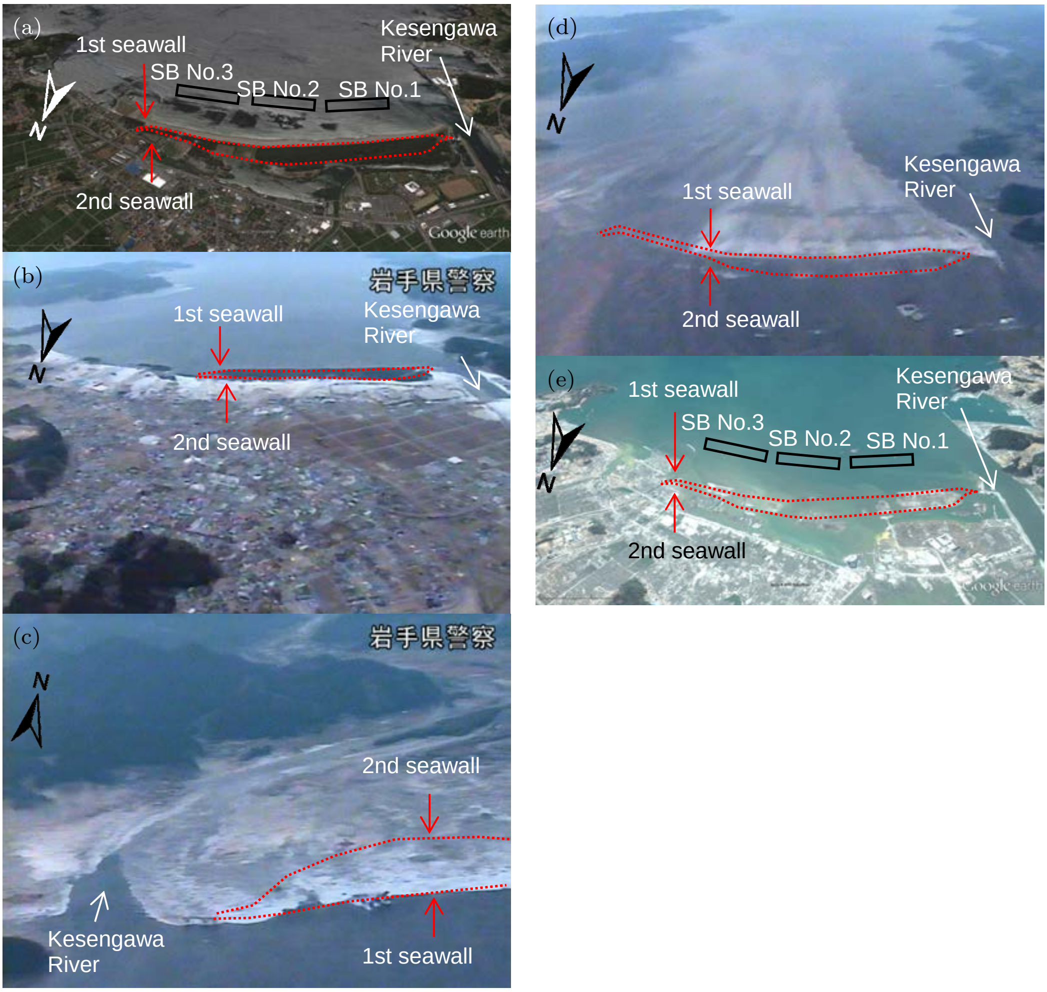


Fig. 6. Satellite images (Google Earth) of the Rikuzen-Takata Coast (a) on 23 July 2010 and (e) on 14 March 2011, and aerial video images taken by the Iwate Prefecture Police during the tsunami run-up at (b) around 15:20 JST, March 11 and (c) 15:24 JST, March 11, and the backwash at (d) 15:37 JST, March 11 [modified from Udo *et al.*, 2015].

earlier than that of Ushiyama and Yokomaku [2012]. For example, Ushiyama and Yokomaku [2012] reported that the tsunami arrival time was 15:24, whereas the arrival time in this study was 15:20. Figures 6(b) and 6(c) show the tsunami run-up into the area behind the seawalls and the Kesengawa River. Figure 6(d) shows the tsunami backwash and turbulent flow with air bubbles (the white sea area) at seaward of the first seawall or the coastal forest. During the backwash, the turbulent flow was also partly observed around the second seawall; it was not recognized in the forest area seaward of the second seawall, although it was recognized during the run-up. Breakwaters Nos. 1 and 2 are shown as dark areas in the white sea area, and the turbulent flow though No. 3 could not be recognized. These turbulent flows during the run-up and backwash were likely generated by the coastal structures (e.g. seawalls) or the forest.

The above findings indicate that the second seawall, the forest, and the eastward portion of the first seawall were damaged from around 15:20 JST to 15:37 JST, whereas the first seawall was damaged after 15:37 JST, resulting in significant erosion. On the contrary, part of the western coast, where the second seawall partly remained [see Fig. 2(e)], was not eroded. These facts demonstrate strong effects of the coastal structures on the tsunami behavior and sediment transport.

In 2013, the reconstruction of the Takata Coast began in order to restore the land and seawalls affected by the tsunami (see Appendix). At that point, the coast had not recovered [Udo *et al.*, 2015]. Based on the past wave climate, the topography in the study area had been relatively constant before the tsunami; thus, the possible drivers of the recovery were the supply of sediment from the Kesengawa River to the sea or crustal uplift. Significant floods caused by heavy rainfalls occurred once every few years [Fig. 5(b)]; however, the effects of these events were limited, as shown by the coastal profile before the 2011 tsunami (Fig. 4). The crustal uplift for five years after the coseismic subsidence (0.6 m) caused by the 2011 earthquake was approximately 0.2 m [Geospatial Information Authority of Japan, 2016]; and this effect is also limited so far by considering the present water depth ranged from 2 to 3 m at the past shoreline position before the tsunami.

5. Conclusions

This paper reports the coastal erosion of the Rikuzen-Takata Coast caused by the 2011 tsunami and the status of restoration five years after the tsunami. The field results demonstrated that the coast was eroded mainly due to the tsunami backwash, and the coastal structures had strong effects on the tsunami behavior and sediment transport. The seawalls partly prevented massive coastal erosion (land loss), and the submerged breakwaters trapped the seaward transport of sediment from the coast, reducing the transport of sediment to the deeper sea area. The results also indicated that the coast has not naturally recovered at a desirable rate since the 2011 tsunami.

Acknowledgments

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Appendix. Coastal Reconstruction Five Years after the Tsunami and Future Restoration Plan

The Department of Public Works, Ofunato Regional Development Bureau, Iwate Prefecture established a committee on the nourishment of Takata beach following the Basic Reconstruction Plan to discuss reconstruction measures. The committee's documents are open to the public on the department's website (http://www.pref.iwate.jp/engan/ofuna_doboku/022952.html) and are reviewed below.

The reconstruction of the Takata Coast began in 2013 to restore the land and seawalls (Fig. A.1). The landfill was finished in 2015 [Figs. 2(f)–2(j)], and the seawall

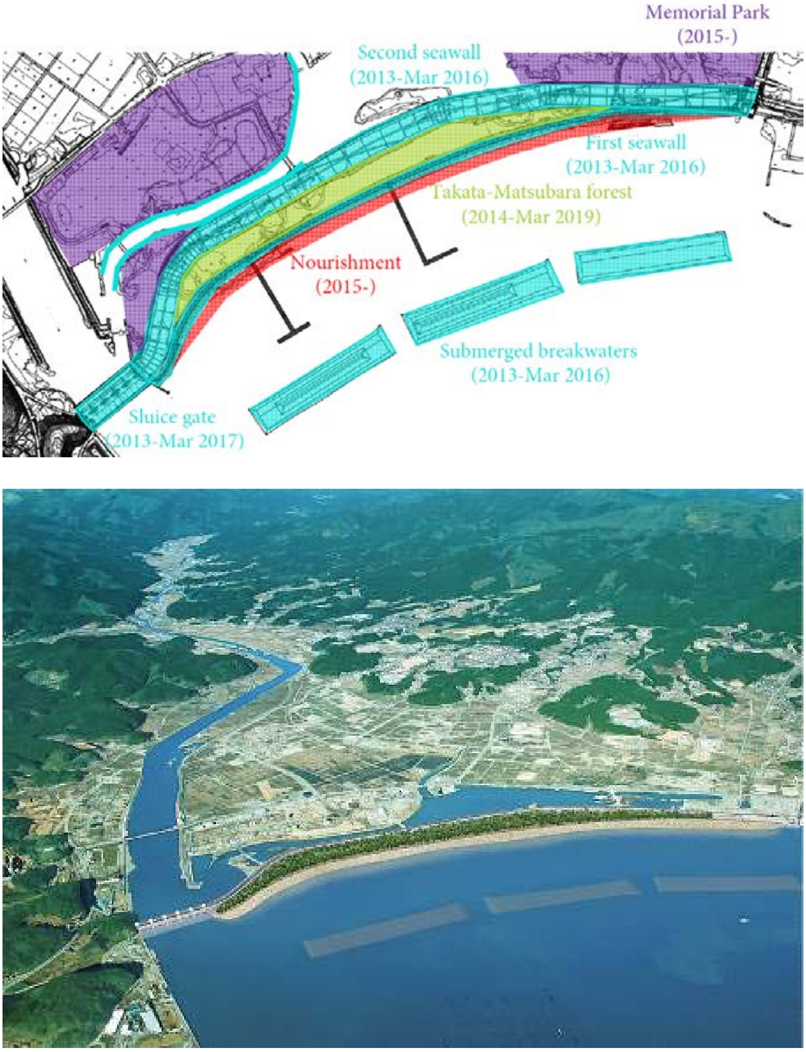
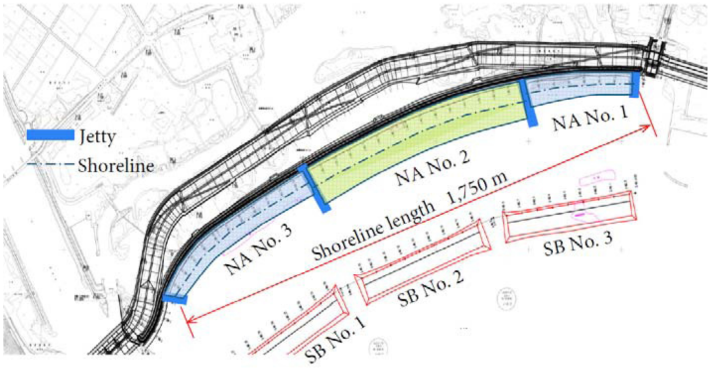


Fig. A.1. Reconstruction Plan and an image depicting its implementation on the Rikuzen-Takata Coast.

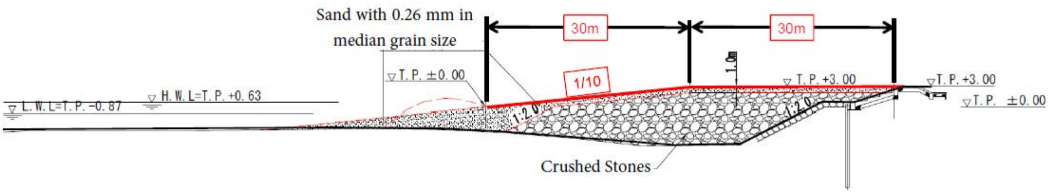
construction will be finished in 2016. The planned heights of the first and second seawalls are planned to be 3.0 m and 12.5 m, respectively; thus, the second seawall will be 7.0 m higher than the old one. The planned width of the second seawall is 60 m, which is around four times that of the old one. The purpose of the first seawall is to prevent the erosion of Takata beach and the Takata-Matsubara forest. The total cost of reconstructions of the seawalls, sluice gate, and submerged breakwaters was approximately 25.1 billion yen, as of June 2014 (http://www.pref.iwate.jp/engan/ofuna_doboku/010339.html [in Japanese]).

Materials such as the 30- to 200-kg ripraps and 1-ton riprap protections for both the first seawall and the three breakwaters and recycled stones for the foundation of the second seawall were supplied from three places: Muroran (Hokkaido Prefecture, northern Japan), Kawasaki (Kanagawa Prefecture, near Tokyo), and Shodoshima (Kagawa Prefecture, Western Japan). These materials were shipped to two temporary piers with the breakwaters shown in Fig. 2(i). A large volume of sediment is required for nourishment: 1.02 million m^3 for seawalls, 0.34 million m^3 for the Takata-Matsubara forest, and 0.51 million m^3 for the beach (as of November 2015). The eroded sand volume due to beach erosion [landward red polygon in Fig. 3(e)] was 0.58 million m^3 [Udo *et al.*, 2015]; therefore, the required sediment volume for nourishment is on the same order of magnitude as the eroded volume due to beach erosion. To accelerate reconstruction, sediment was carried by a conveyor belt [the so-called "Kibo no Kakehashi" (Bridge of Hope)]. The 3-km conveyor belt was placed over the reconstruction area including the Rikuzen-Takata Coast and began to carry sediments in March 2014; the conveyor belt completed its role in September 2015 and is to be removed by September 2016. The sediment carried by the conveyor belt was improved using cement.

As mentioned in Sec. 4, the topography of the study area was constant under the past wave and rainfall climates before the tsunami. Therefore, the eroded coast would not likely be naturally restored over a desirable time frame under the present climate. Uda *et al.* [2013] simulated future beach topography using a three-dimensional model based on Bagnold's concept, i.e. the BG model [Noshi *et al.*, 2009] and found that the beach will not recover after 50 years without nourishment. Their results also indicated that nourishment using coarse (1 mm) sand will be more effective than nourishment using finer (0.1 mm) sand. Similar simulations were also conducted for the Iwate Prefecture, and the results confirmed the effectiveness of nourishment using sand having a grain size of 0.5 mm. A committee was established to discuss the nourishment of Takata beach; three committee meetings were held in March 2014, October 2014, and January 2015. The committee decided to nourish the beach along the first seawall with the following characteristics: length is 1.75 km; width is 30–60 m; slope is 1/20–1/10; median grain size > 0.26 mm (Fig. A.1). The nourishment area is divided into three areas by two jetties, and the nourishment will begin at nourishment areas No. 2 (middle) and No. 3 (west) in 2017. Nourishment area No. 2 is planned to be a bathing beach.



(a)



(b)

Fig. A.2. Nourishment plan: (a) top view and (b) cross-sectional view of nourishment area No. 2. NA and SB in (a) indicate the nourishment area and submerged breakwater, respectively.

The committee also discussed where the nourished sand should be supplied from in view of sand availability, color, grain size, and cost. Before the tsunami, Takata beach was one of the most famous white beaches with pine forest; thus, the sand color and grain size are important elements. Sands at five places in Hokkaido, Aomori, Miyagi, Ibaraki, and Chiba Prefectures were evaluated as potential sources of sand for nourishment. Finally, the sand at Taiwa Town, Miyagi Prefecture [see Fig. 1(a)] with a grain size of 0.51 mm was selected due to its similarities with the natural sand of Takata beach. The nourishment cost was estimated to be 3.7 billion yen as of January 2015. The effects of nourishment, especially those on the ecosystems and fisheries, were also considered. To assess these effects, a test nourishment was carried out from November 2015 to December 2016 in the vicinity of the border between nourishment areas Nos. 2 and 3 (Fig. A.2). The changes in bathymetry, grain size, and turbidity in the test nourishment area and the environmental effects has been monitored.

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