LONG-TERM TOPOGRAPHIC CHANGES AROUND SAND SPIT AND IMPACT OF EXTRAORDINARY HIGH WAVES DURING TYPHOONS

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Around the Mihono-matsubara sand spit in Suruga Bay in Japan, the beach was eroded owing to the decrease in the fluvial sand supply from the Abe River triggered by excess riverbed mining before 1967, together with the discharge of sand into the deep sea via a steep slope near the tip of the sand spit. As a measure against beach erosion, an artificial headland (HL) composed of two detached breakwaters and the breakwaters (BWs) placed along the shoreline have been constructed along with beach nourishment, but the beach is barely maintained by these measures. In 2013, two large typhoons hit the coast, causing rapid beach changes around the structures, and these beach changes were superimposed on the long-term topographic changes that have occurred over a long time as a geomorphological process. In this study, their impact to the beaches was investigated on the basis of the field data.

Keywords: sand spit; Mihono-matsubara; typhoon waves; artificial headland; detached breakwater; beach changes; longshore sand transport

INTRODUCTION

A sand spit can be formed on a shallow seabed under the premise that a sufficient volume of sand is continuously supplied from upcoast by longshore sand transport. Thus, the decrease in sand volume supplied from upcoast has a considerable impact on the shoreline of a sand spit. A typical example can be seen around the Mihono-matsubara sand spit in Suruga Bay in Japan (Uda and Yamamoto 1994). Although this sand spit was formed by an abundant supply of sand, which was originally transported from the Abe River, the beach was eroded owing to the decrease in the fluvial sand supply from the Abe River triggered by excess riverbed mining before 1967, together with the discharge of sand into the deep sea a steep slope near the tip of the sand spit. As a measure against beach erosion, an artificial headland (HL) composed of two detached breakwaters and the breakwaters (BWs) placed along the shoreline have been constructed along with beach nourishment, but the beach is barely maintained by these measures at present. In 2013, two large typhoons hit the coast and extraordinary high waves were incident to the coast, causing rapid beach changes around the structures, and these beach changes were superimposed on the long-term topographic changes that have occurred over a long time as a geomorphological process as described in Miyahara et al. (2015). The understanding of these long-term and short-term topographic changes with different time scales is important in considering the conservation of the sand spit. In this study, this issue was investigated using field data measured around the Mihono-matsubara sand spit as an example.

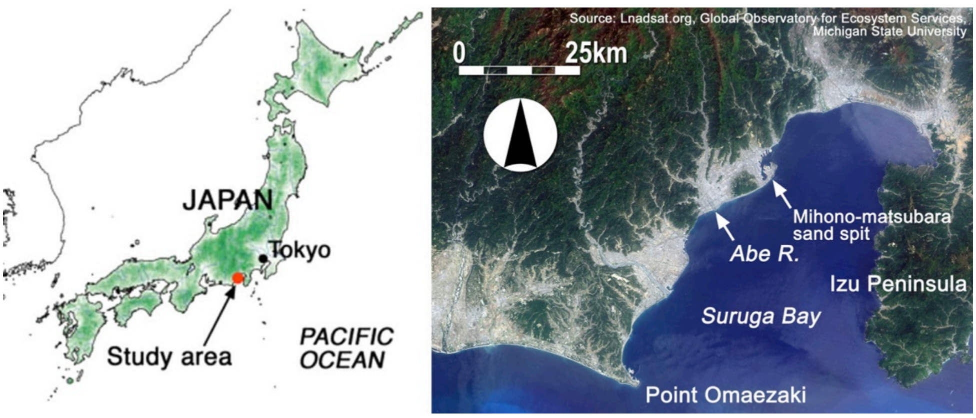

Figure 1. Location of study area.

GENERAL CONDITIONS OF STUDY AREA

The study area is the Shizuoka and Shimizu coasts including the Mihono-matsubara sand spit, extending northeast of the Abe River mouth flowing into Suruga Bay, as shown in Fig. 1. This sand spit was formed as a result of the successive deposition of sand, which was originally supplied from the

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Abe River and transported by northward longshore sand transport. The beach erosion of these coasts occurred because of the decrease in sand supply from the Abe River, and the erosion area expanded northward over time at a rate of 250 m/yr from the Abe River mouth (Itabashi and Uda 1998; Uda, 2010). As a measure against beach erosion, HLs composed of double detached breakwaters, an L-shape groin and four BWs were constructed from south to north, as shown in Fig. 2. Despite these measures, this beach is still being eroded at present, and a sandy beach is barely being maintained by not only these structures but also beach nourishment. In particular, these structures have been constructed using concrete armor units, and thus the wave-dissipating effect of these structures is assumed to be significantly reduced during the incidence of extraordinary high waves. However, such reduction effects have not yet been investigated, and this causes difficulty in the prediction of the long-term topographic changes of the coast.

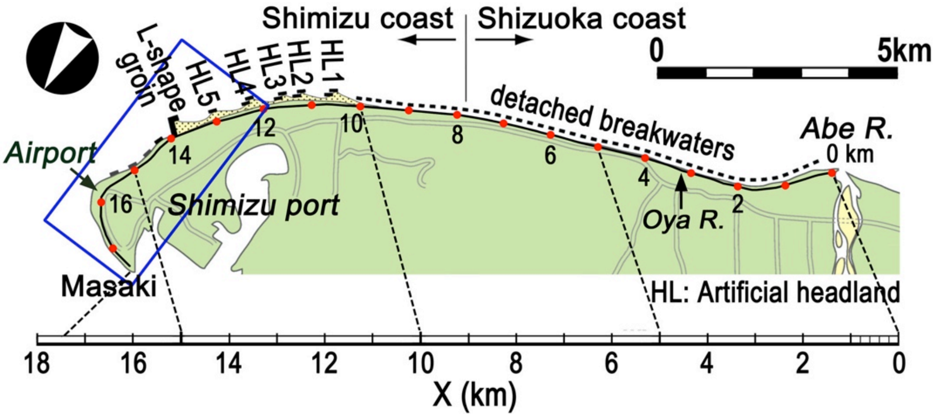

Figure 2. Shoreline configuration between Abe River mouth and tip of sand spit (Masaki) and expanded coordinate system.

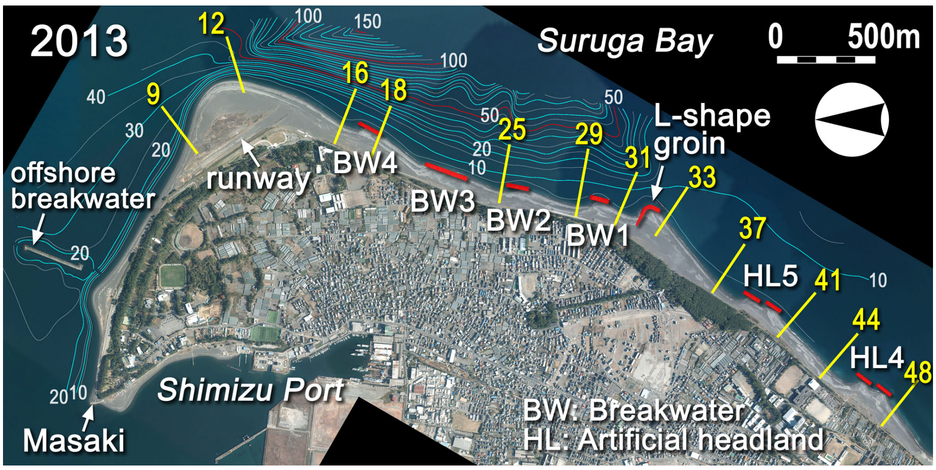

Figure 3. Aerial photograph in 2013 between HL4 and Masaki, location of structures and alignment of transects.

In the analysis of the beach changes of the study coast, expanded coordinates were selected, in which the origin was taken at the Abe River mouth and the distance X was taken alongshore, because the shoreline of the Shizuoka and Shimizu coasts is curvilinear, as shown in Fig. 2. Figure 3 shows an enlarged aerial photograph taken in 2013 of the rectangular area near the northern tip of the sand spit, as shown in Fig. 2, together with the bathymetry in 2013. The shoreline extending northward from the south turns at a right angle in the vicinity of the runway located at the north end of the sand spit, and then extends westward from the turning point. The shoreline in front of the runway has a semicircular shape with a radius of 280 m. The formation of the sand spit at this location clearly demonstrates the predominance of northward longshore sand transport. Because an L-shape groin was constructed and BWs were installed along the shoreline under such conditions, continuous longshore sand transport was blocked at these facilities, resulting in the formation of a hooked shoreline north of these facilities. It is clearly seen that an extremely steep slope was formed immediately offshore of the runway. Near the south end of the study area where HL4 and HL5 are located, an L-shape groin exists at the central part, and north of this groin, BW1 - BW4 are located. Beach profiles were measured at 100 m intervals, and longitudinal profiles along 12 transects between No. 48 and No. 9, as shown in Fig. 3, were compared.

OBLIQUE AERIAL PHOTOGRAPHS OF STUDY AREA

Oblique aerial photographs of the study area were taken on December 1, 2013. Here, coastal conditions in the study area were studied from south to north using these photographs. Figure 4 shows the shoreline condition between HL4 and HL5. Because northward longshore sand transport is predominant in this area, the shoreline significantly retreated immediately downcoast of HL4, resulting in the exposure of the seawall to run-up waves under storm wave conditions, as shown in Fig. 4. Figure 5 shows the coast between HL5 and the L-shape groin, where northward longshore sand transport was effectively blocked by the L-shape groin, so that a wide sandy beach was maintained south of L-shape groin. However, a hooked shoreline was formed downcoast of HL5, and it is clear that the beach downcoast of HL5 is prone to erosion.

Figure 4. Oblique aerial photograph between HL4 and HL5.

Figure 5. Oblique aerial photograph between HL5 and L-shape groin.

Figure 6. Oblique aerial photograph between L-shape groin and BW2.

Figure 7. Oblique aerial photograph between BW3 and BW4.

Downcoast of the L-shape groin, the coastline orientation markedly changes, and four BWs were installed on the shoreline to stabilize the shoreline by the headland control method (Silvester and Hsu 1993). A hooked shoreline was formed downcoast of each breakwater, as shown in Figs. 6 and 7. Finally, Fig. 8 shows the north end of the Mihono-matsubara sand spit and the runway. The shoreline in this area has a semicircular shape, as shown in Fig. 8, and along this shoreline, sand discharges into the deep sea via a steep slope, as mentioned later. Figure 9 shows the Shimizu Port offshore breakwater extended at the north end of the sand spit and a cuspate foreland on the lee of the breakwater as a result of the deposition of sand due to westward sand transport.

Figure 8. Oblique aerial photograph of tip of Mihono-matsubara sand spit.

Figure 9. Oblique aerial photograph of Shimizu Port breakwater and cuspate foreland.

WAVE CONDITIONS DURING T1318 AND T1326

In 2013, Typhoon Nos. 18 and 26 (T1318 and T1326, respectively) hit the study coast and extraordinary high waves were incident to the coast. Wave observation was carried out at a depth of 30 m at the Kuno wave observatory located 4.5 km offshore of the Shimizu coast, as shown in Fig. 10, and Fig. 11 shows the significant wave height and wave period in 2013 measured at this observatory. Although the significant wave height was lower than 2 m in almost all periods in 2013, a maximum significant wave height of 7.97 m and a wave period of 13.1 s were recorded when T1318 landed on the coast on September 16. In addition, T1326 hit the same coast on October 16, and the extraordinary high waves with a wave height of 9.28 m and wave period of 16.7 s were recorded. Since the Shimizu coast is located on the west coast in Suruga Bay with a steep slope, as shown in Fig. 10, predominant waves were incident from the south, causing northward longshore sand transport.

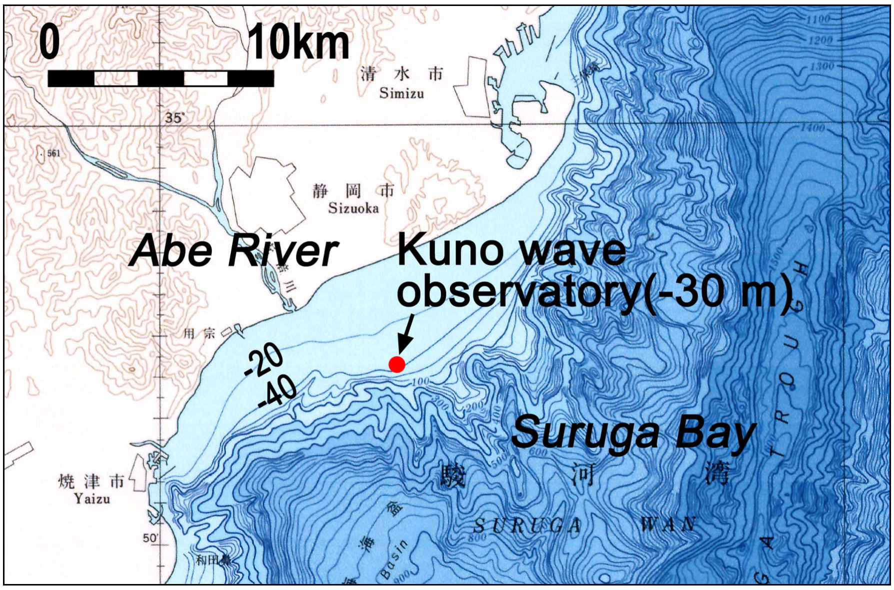

Figure 10. Location of Kuno wave observatory.

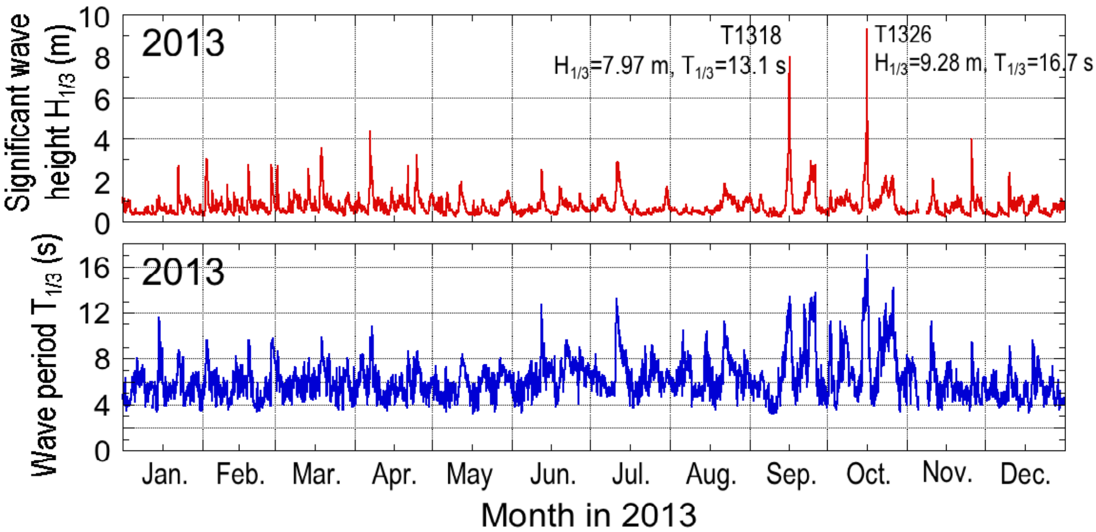

Figure 11. Significant wave height and wave period in 2013 measured at Kuno wave observatory.

Figures 12 and 13 show the detailed changes in wave height and wave period during the two typhoon events. During T1318, the duration of high waves with $H_{1/3}$ larger than 4 m was 14 h and waves with $T_{1/3}$ of 12 s were continuously incident to the coast. On the other hand, during T1326, the maximum wave height was 9.28 m with a period as long as 16.7 s, but the duration of high waves with the wave height of 4 m was 9 h, which is shorter than that during T1318. In the October 16 event, storm waves directly hit the seawall at transect No. 29 at 8:15 am, as shown in Fig. 14. The tide level at this time was +0.2 m above the mean sea level (MSL) and the maximum run-up height was much greater than the crown height of the seawall (+12 m above MSL), permitting wave overtopping over the seawall.

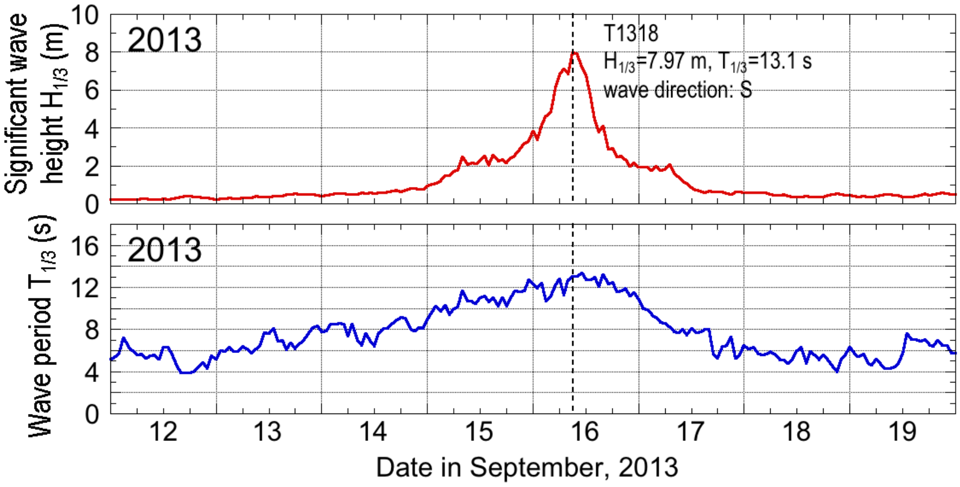

Figure 12. Significant wave height and wave period during T1318.

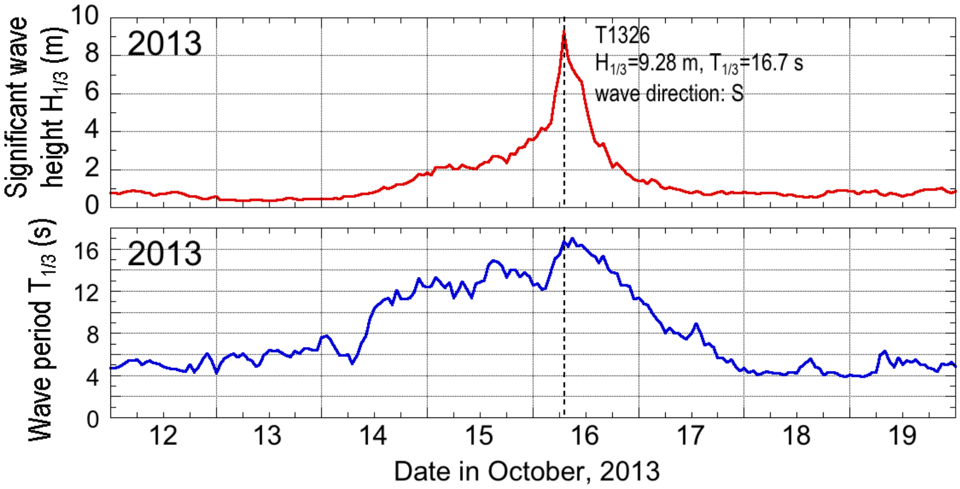

Figure 13. Significant wave height and wave period during T1326.

Figure 14. Run-up waves hitting seawall at transect No. 29 at 8:15 am on October 16, 2013.

BATHYMETRIC CHANGES

Figure 15 shows the bathymetry and bathymetric changes from 1998 to 2002, 2006, 2010, and November 2013, immediately after the typhoons, expressed on the expanded coordinates (*X*, *Y*) regarding the area between HL1 and Masaki. Here, *X* and *Y* are the longshore distance and offshore one from the seawall, and the blue and red colors correspond to erosion and accretion, respectively. In the study area, an impermeable L-shape groin was constructed near *X* = 14 km and five HLs (HL1 - HL5) composed of double detached breakwaters were installed south of the L-shape groin to control longshore sand transport. Additionally, four breakwaters (BW1 - BW4) were constructed along the shoreline north of the L-shape groin.

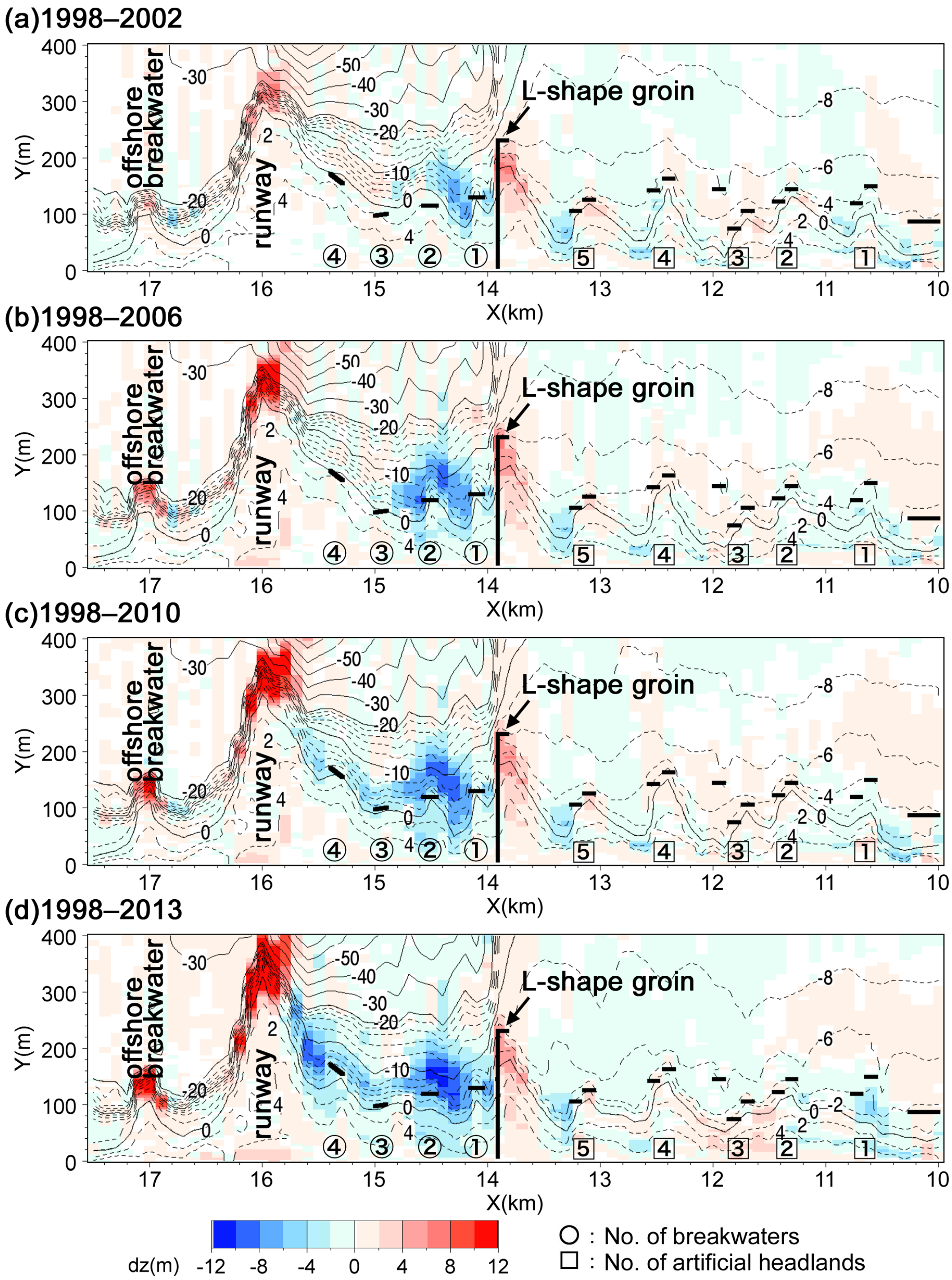

Figure 15. Planar distribution of topographic changes between HL1 and Masaki with reference to topography in 1998.

Because northward longshore sand transport prevails in the study area, and the L-shape groin significantly blocks the longshore sand transport, as shown in Fig. 5, erosion occurred between BW1 and BW2 north of the L-shape groin up to March 2002 with a slight deposition of sand immediately south of the groin. Furthermore, although sand was deposited in the offshore area up to -8 m south of *X* = 10.5 km, this offshore sand deposition zone gradually expanded northward over time. In contrast, at the tip of the sand spit (*X* = 16 km), sand was discharged into the deep sea via a steep slope.

By 2006, the offshore sand deposition zone observed in 2002 south of *X* = 10.5 km extended up to *X* = 11 km, a 0.5 km expansion in four years. North of the L-shape groin, the eroded zone expanded further north not only between BW1 and BW2 but also between BW2 and BW3, whereas a large amount of sand was deposited at the tip of the sand spit. Moreover, sand began to be deposited on the lee of the Shimizu Port offshore breakwater. The remarkable contrast in erosion immediately north of the L-shape groin and marked sand deposition offshore of the runway clearly demonstrated that the beach erosion was triggered by the blockage of northward longshore sand transport by the L-shape groin, and sand supplied from the erosion area was transported northward and discharged into the deep sea offshore of the runway.

In 2010, the distribution of the offshore sand deposition zone south of the L-shape groin and the sand deposition in the area immediately south of the L-shape groin are almost the same as those in 2006, but the erosion zone north of the L-shape groin further expanded to north of BW4. Offshore of the runway, the sand deposition zone expanded southward, and sand was discharged into the deep sea up to a maximum depth of 60 m. Also, sand was deposited to form a cuspate foreland on the lee of the Shimizu Port offshore breakwater by the successive sand supply from the south coast.

Concerning the topographic changes up to November 2013, the topographic changes that occurred up to 2010 were intensified, and the area between BW1 and BW2 was markedly eroded, and the area north of BW4, where beach erosion was not so severe in 2010, was also eroded. In contrast to the erosion, marked sand deposition occurred offshore of the runway. In the area south of the L-shape groin, although sand was deposited in the depth zone between -4 and -6 m south of *X* = 12.7 km by 2010, the sand deposition zone was significantly narrowed by 2013. It is assumed that sand originally supplied from the Abe River was deposited in this offshore zone, but such sand was rapidly transported northward around the tip of the L-shape groin from the area. In conclusion, it is found that beach changes have continuously occurred in the long term: erosion immediately north of the L-shape groin and deposition in front of the runway.

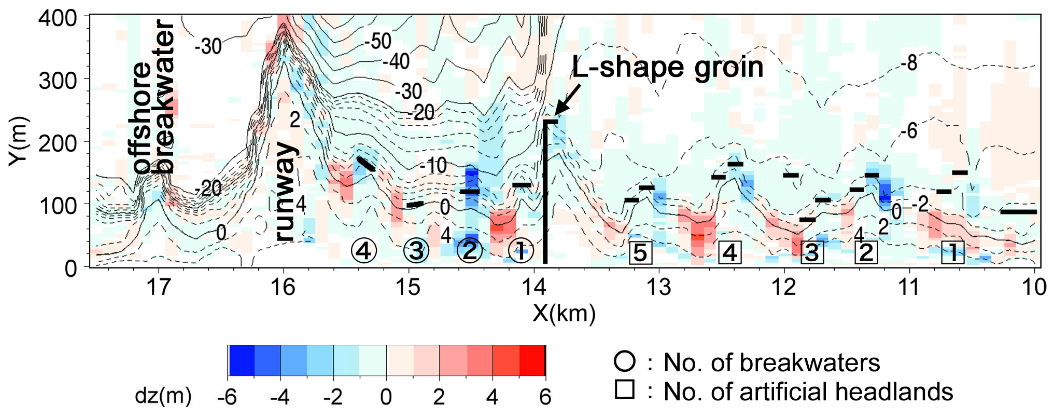

Figure 16. Planar distribution of topographic changes between HL1 and Masaki between September and November 2013, before and after T1318 and T1326.

Figure 16 shows the topographic changes of the same area as that shown in Fig. 15 from September 2013 before T1318 and T1326 to November 2013 after the typhoons. The areas on the HL1-HL5 south of the L-shape groin were eroded, whereas sand was deposited between HLs. The same topographic changes were observed between BW1 and BW4, implying that the wave-sheltering effect of various structures was reduced during extraordinary high waves, and deposited sand was discharged downcoast.

SHORELINE CHANGES

Figures 17 and 18 show the shoreline changes with reference to the shoreline in 1998 along the entire Shimizu coast and in the area north of HL4, respectively, calculated from the topographic survey data. The shoreline changes up to January 2012 and September 2013 before the two typhoons and up to November 2013 after the typhoons relative to 1998 are shown in these figures. In the long term, the shoreline advanced south of the L-shape groin, whereas it significantly retreated downcoast. However, shoreline advance can be seen in front of the runway. Between January 2012 and September 2013, although the shoreline receded downcoast of HL3, HL4 and HL5, and downcoast of BW1, BW3 and BW4, the shoreline in the bay downcoast of HLs and BWs all advanced by November 2013 by 28, 18 and 22 m downcoast of BW1, BW3 and BW4, together with shoreline advance by 35 m downcoast of HL4. In contrast, the shoreline receded behind and upcoast of each HL and the breakwater, with a maximum shoreline recession of 34 m behind BW2. On the other hand, the shoreline recession between the L-shape groin and BW1 was relatively small as little as 10 m. Except for these areas, the shoreline changes were relatively small and the shoreline slightly retreated in front of the runway and behind the offshore breakwater of Shimizu Port, where the shoreline had been advanced by the successive deposition of sand. Thus, in the short term during the period of storm waves, marked beach changes with shoreline recession and accretion upcoast and downcoast of the structures, respectively, were observed, which differ from the long-term changes.

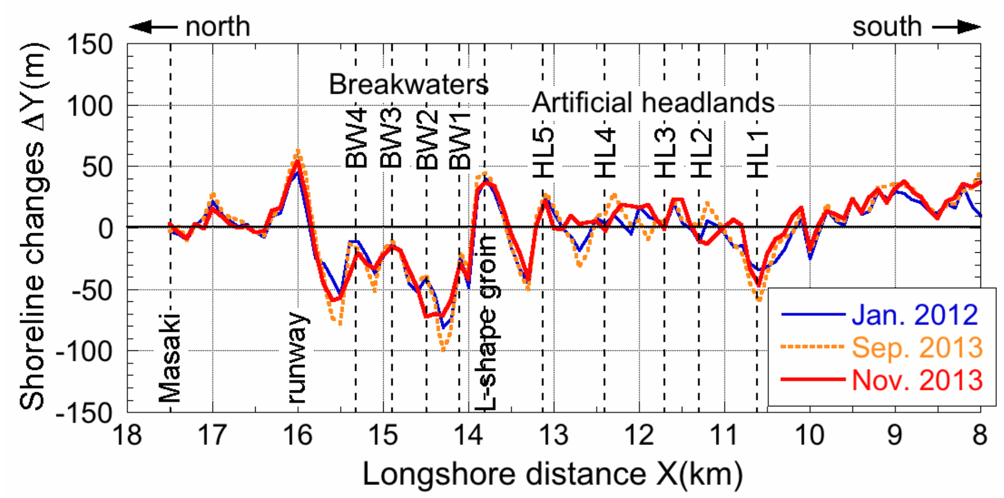

Figure 17. Shoreline changes along entire Shimizu coast relative to topography in 1998.

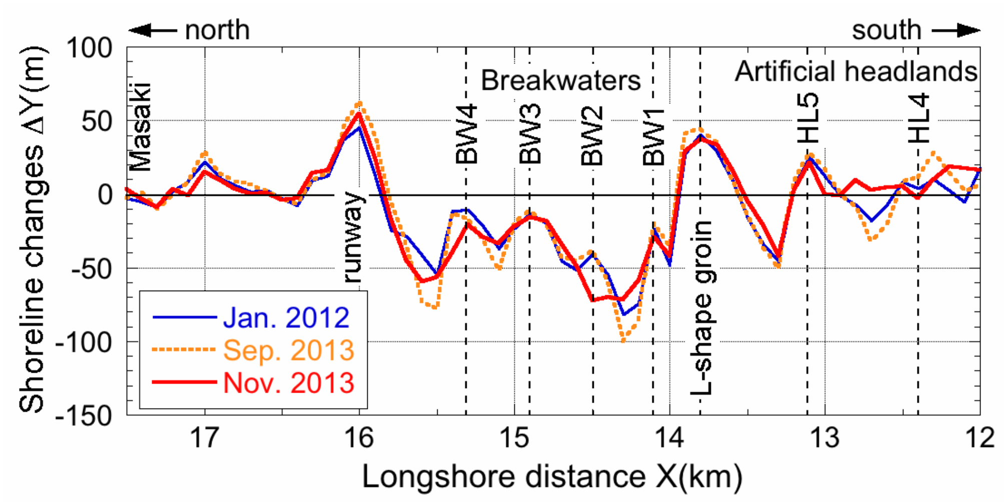

Figure 18. Shoreline changes between HL4 and Masaki relative to that in 1998.

CHANGE IN LONGITUDINAL PROFILES

Profile Changes in Area South of L-shape Groin

Longitudinal profiles along transects 48, 44, 41, 37, and 33 shown in Fig. 3 are shown in Fig. 19. In each figure, longitudinal profiles in January 2012 and September 2013 before the typhoon event, and in November 2013 after the event, as well as the reference profile in 1998 are shown. Along transect No. 48 upcoast of HL4, although sand was deposited in the zone shallower than -5 m between January 2012 and September 2013, while forming an upward convex profile, this sand deposition zone was eroded up to the same level as that in January 2012 by November 2013 after the typhoon. In contrast to this change, along transect No. 44 downcoast of HL4, the beach was eroded in the zone shallower than -4 m with the shoreline recession between January 2012 and September 2013, and then a large amount of sand was deposited and the shoreline advanced by 35 m between September 2013 and November 2013. Thus, it was confirmed that the beach changes of a reversed mode, i.e., erosion upcoast and accretion downcoast of HL4, occurred in the zone shallower than -4 m. Furthermore, the seabed was eroded in the zone deeper than -4 m by September 2013, and remained at the same level in November 2013.

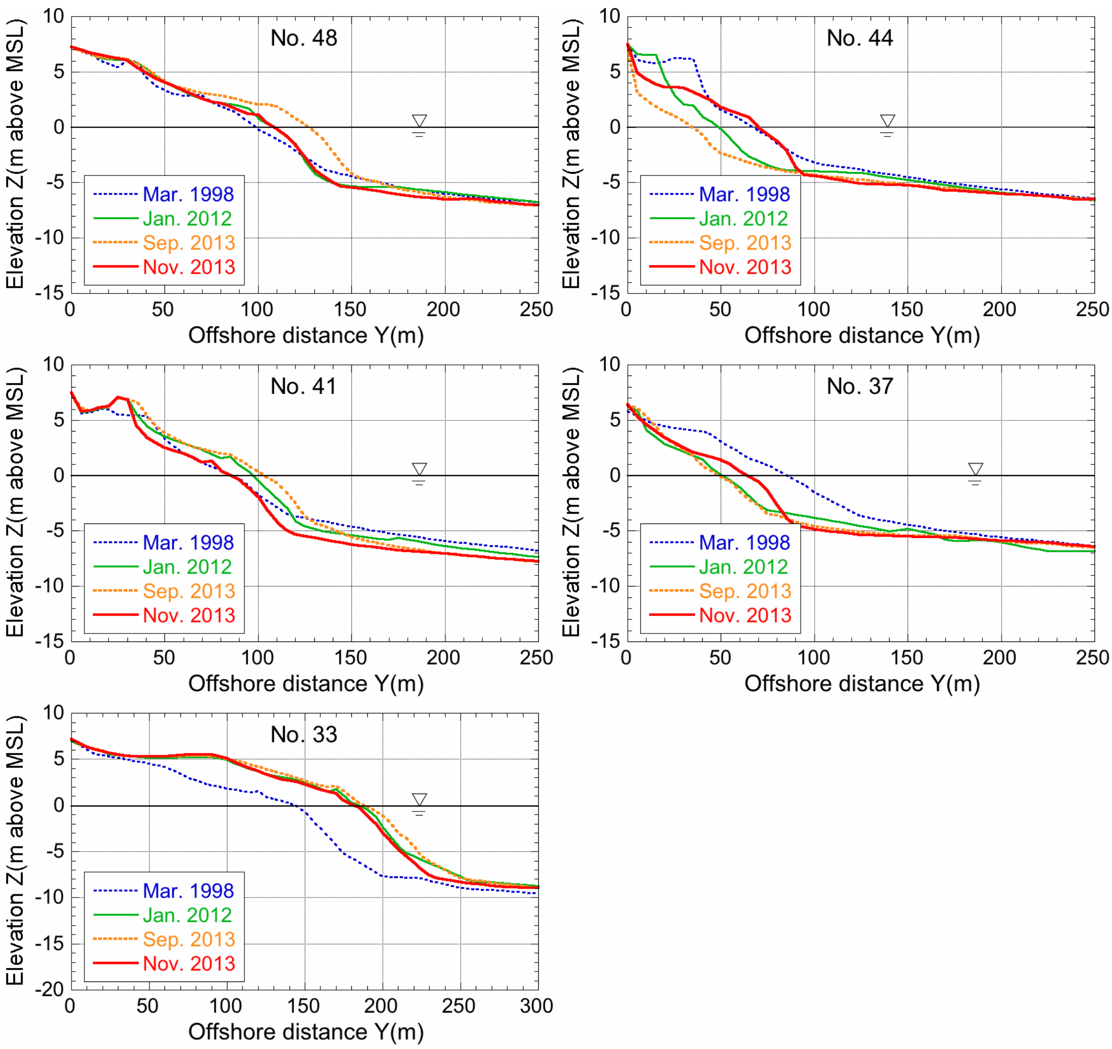

Figure 19. Longitudinal profiles along transect Nos. 48, 44, 41, 37, and 33 south of L-shape groin.

Transect Nos. 41 and 37 are located upcoast and downcoast of HL5. Along transect No. 41, although sand was deposited in the zone shallower than -5 m between January 2012 and September 2013, the beach was severely eroded and the profile retreated landward over the profile in January 2012 by November 2013. Along transect No. 37 downcoast of HL5, although the beach was erosive between January 2012 and September 2013, a large amount of sand was deposited on the foreshore by

November 2013. Thus, beach changes around HL5 had the same mode as that around HL4, demonstrating that the wave-dissipating effect of the detached breakwaters composed of HLs was reduced with increasing wave height, resulting in the increase in northward longshore sand transport.

In contrast to the beach changes on both sides of HLs, along transect No. 33 located upcoast of the L-shape groin, the changes in longitudinal profile were minimal between January 2012 and November 2013. However, the same change in longitudinal profile as those at HL4 and HL5 occurred, i.e., accretive between January 2012 and September 2013 and erosive between September 2013 and November 2013.

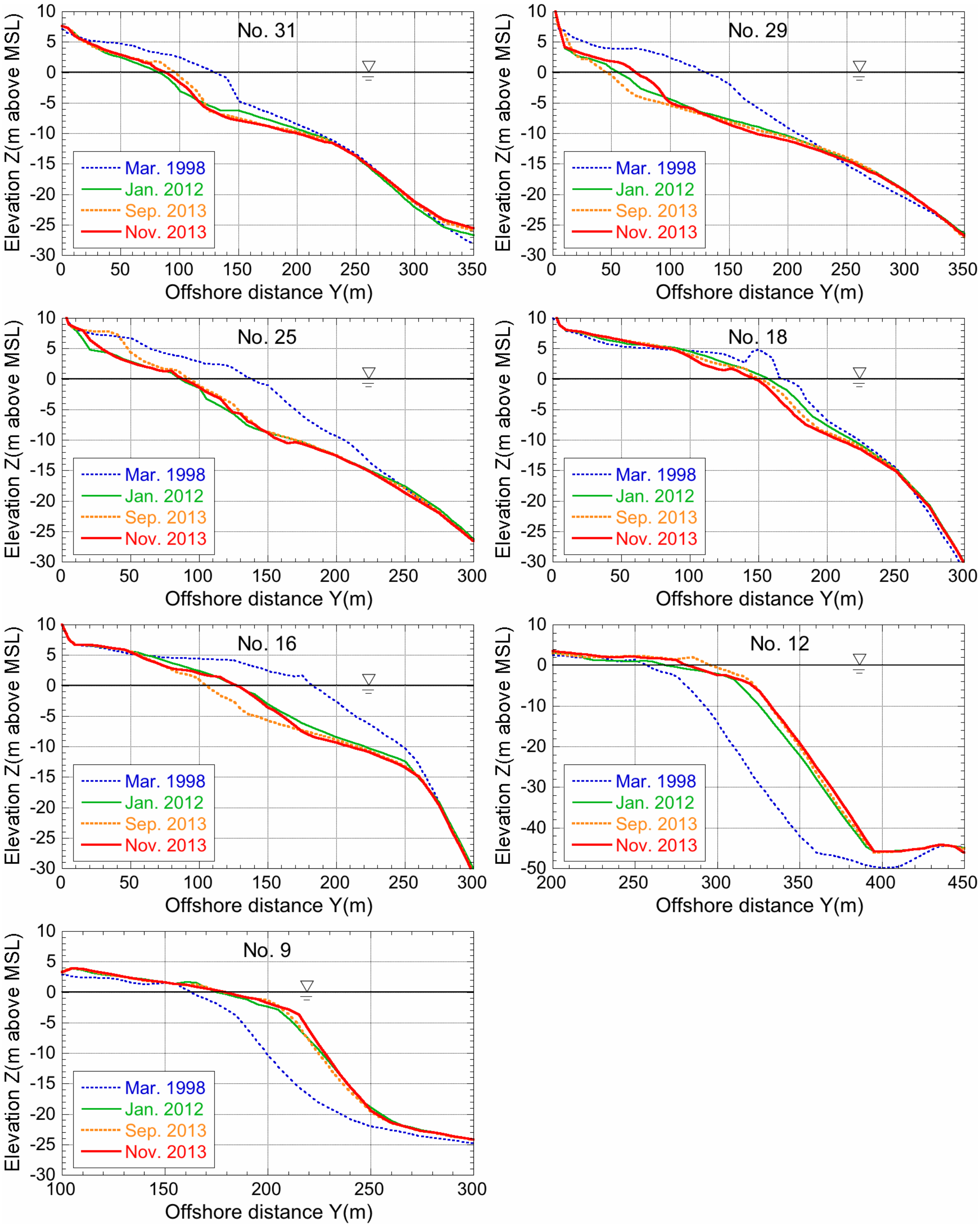

Figure 20. Longitudinal profiles along transect Nos. 31, 29, 25, 18, 16, 12, and 9 north of L-shape groin.

Profile Changes in Area North of L-shape Groin

Figure 20 shows the changes in longitudinal profiles along transect Nos. 31, 29, 25, 18 16, 12 and 9. Transect Nos. 31 and 29 and transect Nos. 18 and 16 are located upcoast and downcoast of BW1 and BW4, respectively. Although an upward convex profile was formed along transect No. 31 in 1998, the beach was severely eroded in the zone shallower than -12 m, implying that the depth of closure of the coast is 12 m, and a concave profile was formed with the shoreline recession of 50 m up to January 2012. The high storm waves were incident to this concave profile. Sand was slightly accreted from January 2012 to September 2013 along transect No. 31, and then eroded up to November 2013. Conversely, the beach was eroded from January 2012 to September 2013 along transect No. 29, where the shoreline had retreated by 75 m since 1998, and then a large amount of sand was deposited near the shoreline. Even though sand was deposited along transect No. 29, the accreted volume of sand was much smaller than the volume eroded between 1998 and 2012.

Along transect No. 25 located between BW2 and BW3, the beach was severely eroded with a shoreline recession of 57 m in the zone shallower than -15 m between 1998 and 2012. Before the erosion, an upward convex profile was formed, but it changed to almost uniform slope owing to the erosion up to January 2012. Beach nourishment at the backshore was carried out at this stage along this transect until September 2013, as shown in Fig. 20. Nourishment sand was assumed to be less stable because of the steeper slope and narrower foreshore. Nourishment sand was completely carried away by high run-up waves, and disappeared.

Along transect No. 18 located upcoast of BW4, although the beach had gradually retreated since 1998, it was slightly eroded between January 2012 and September 2013, and thereafter, the beach was further eroded. Along transect No. 16 downcoast of BW4, the recent erosion was severe: the profile changed from upward convex in 1998 to concave up to 2012. The seabed in a zone shallower than -12 m was eroded, and the shoreline receded by 74 m, resulting in the formation of a gentle seabed slope.

In contrast to the degradation of the seabed in a comparatively shallow zone in the erosion zone along transect No. 16, sand was deposited up to a depth of 45 m, which is 3.8 times greater than the depth of closure along transect No. 12, while maintaining a very steep slope of 1/2, and the profile moved offshore in parallel with each other, as studied by Miyahara et al. (2015). Along transect No. 9 west of the sandy beach with a semicircular shape, sand continued to be deposited, but the volume of sand deposition decreased because of the decrease in the water depth in the sand deposition zone compared with that along transect No. 12. From the finding provided, it is concluded that sand was deposited, and formed a very steep slope near the north end of the Mihono-matsubara sand spit.

EVALUATION OF LONGSHORE SAND TRANSPORT

Because the longshore sand transport at Masaki can be regarded as 0, the topographic changes were integrated southward using the bathymetric survey data, and the longshore sand transport rate was calculated by dividing the integrated volume of sand by the elapsed time between two periods. Longshore sand transport was evaluated in two periods between 1998 and 2006 when the L-shape groin was constructed but before the sand back pass at a rate of 3×10^4 m^3/yr, and between 2006 and 2013 after the initiation of the sand back pass from the tip of the sand spit. In the calculation, sand volumes of beach nourishment and sand back pass were taken into account to calculate the net longshore sand transport, assuming that nourishment sand can be effectively added to the sand volume with no loss of sand. Figure 21 shows the distribution of longshore sand transport. Between 1998 and 2006, longshore sand transport at the L-shape groin was as small as 1×10^4 m^3/yr, and increased northward to reach 8×10^4 m^3/yr near BW3 and BW4. Then, it markedly decreased offshore of the runway, demonstrating the offshore discharge of sand through the steep slope. Between 2006 and 2013, the longshore sand transport at the L-shape groin increased to 4.5×10^4 m^3/yr, because beach nourishment of $(3 - 5)\times10^4$ m^3/yr had been carried out south of the L-shape groin as a measure against erosion, and it increased to a maximum longshore sand transport of 1.1×10^5 m^3/yr at the location X = 1.5 km north of the L-shape groin. On the other hand, although the excavation of sand at the rate of 3×10^4 m^3/yr has been carried out as the sand back pass since 2007 in front of the runway, a large amount of sand had been lost at the tip of the sand spit.

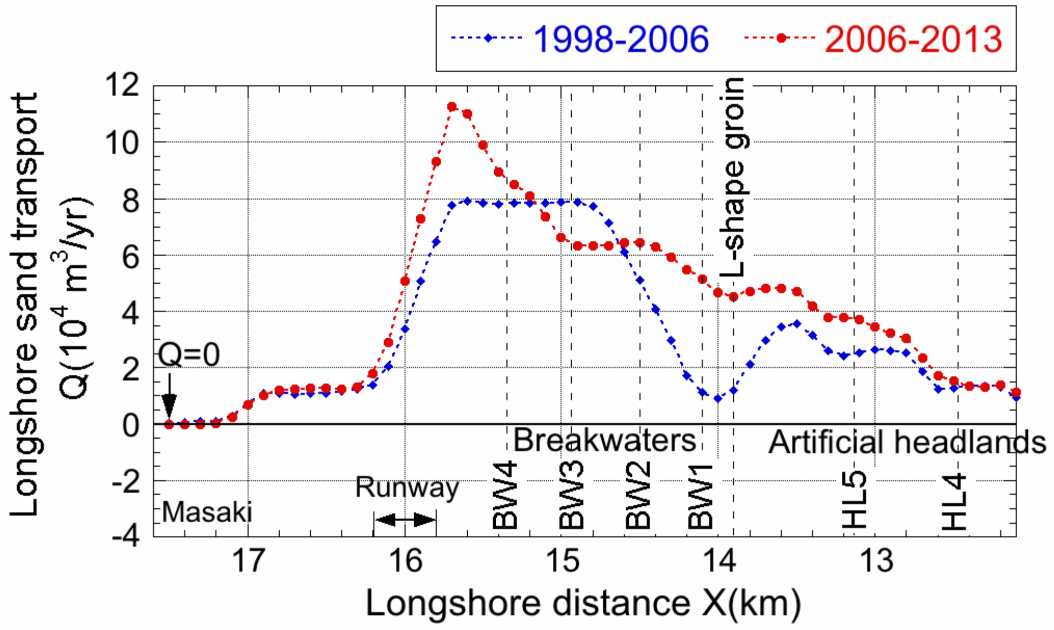

Figure 21. Distribution of longshore sand transport.

CONCLUSIONS

On the Shizuoka and Shimizu coasts including the Mihono-matsubara sand spit, severe beach erosion occurred owing to the excess sand mining in the Abe River before 1967. After the prohibition of such mining, however, sand discharge from the river increased, and the movement of a sand body began (Itabashi and Uda 1998; Uda 2010). Although the volume of sand supplied to the coasts has been increasing, natural longshore sand transport markedly decreased because of the installation of many detached breakwaters upcoast to prevent wave overtopping, and erosion is severe on the Shimizu coast near the tip of the sand spit. In the long term, natural sand supply from upcoast could be expected, but a long time is needed so that hard and soft measures were taken, namely, artificial headlands composed of double detached breakwaters, an L-shape groin and four breakwaters, as well as extensive beach nourishment of 7×10^4 m^3/yr using riverbed material of the Abe River and back pass of sand deposited at the tip of the sand spit at the rate of 3×10^4 m^3/yr. Beach erosion, however, has not yet been controlled, and it is rapidly expanding despite these countermeasures. Furthermore, short-period topographic changes superimposed on the long-term changes occurred during every occasion of extraordinary high waves during typhoons, and the wave dissipating effect of the detached breakwaters composed of HLs was reduced with increasing wave height, resulting in the increase in northward longshore sand transport and reduction in the effect of the structures. Moreover, owing to the beach erosion, the beach slope has been gradually increasing, resulting in an increasing severity of wave overtopping over the seawall, as shown in Fig. 14. Thus, for the conservation of the Shizuoka and Shimizu coasts, we must pay attention to not only the long-term topographic changes but also short-period events including topographic changes and wave run-up.

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