RECOVERY OF SANDY BEACH AFTER TYPHOON WAVES - CASE STUDY ON CHIGASAKI COAST

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Beach topography quickly changes in response to the action of storm waves, resulting in erosion of the foreshore with accretion under a calm wave condition after a storm. These seasonal beach changes may occur on beaches with protective measures or artificial beaches produced by beach nourishment. On these beaches, the shore protection function of a sandy beach is reduced when a trough is formed immediately offshore of the shoreline and the foreshore slope increases, indicating the importance of the study on topographic changes. Moreover, the time required for a beach recovery in response to wave conditions has not been sufficiently studied, along with the 3-D topographic changes associated with beach cycles. In this study, we aim to investigate these issues using the Narrow Multi-Beam survey data, wave data, and seabed materials data, taking the Chigasaki coast as an example. It was found that a seabed shallower than 2 and 3 m depths was eroded by rapid offshore sand transport during a storm event with the deposition of sand in a zone between 3 and 5 m depths, and then the beach recovered within 1–2 years after the storm. It was also confirmed that a bar and trough disappeared in 1–2 months under the conditions of H_E = 0.5 m, T_E = 8 s, and H/L = 0.005 when the crown depth of the bar was smaller than approximately 2 m. Thus, the topography after the storm waves recovers within several months or 1–2 years depending on wave conditions and the crown depth of the bar.

Keywords: storm waves; cross-shore sand transport; beach topography; NMB survey; Chigasaki coast

INTRODUCTION

Beach topography quickly changes in response to the action of storm waves on natural beaches, resulting in erosion of the foreshore with accretion under a calm wave condition after a storm. Davis and Fitzgerald (2004) clarified these beach cycles; when wave conditions are about equal to or less than the average energy conditions, such as a swell wave with a small wave height (generally < 1 m) and a period of 8-12 s, an accretionary beach is formed with other conditions of an erosive or storm beach. The storm beach is a temporary condition, and in the absence of successive storms the recovery period begins immediately after the storm ends. Over a period that ranges from as short as a week to as long as three months, the ridge repairs the beach, resulting in an accretional profile. These seasonal beach changes may occur on beaches with protective measures or artificial beaches produced by beach nourishment. On these beaches, the shore protection function of a sandy beach is reduced when a trough is formed immediately offshore of the shoreline and the foreshore slope increases because of the increase in the wave run-up height, indicating the importance of the study on nearshore topographic changes. Also, the response time required for the beach cycles has not been sufficiently studied, along with the 3-D topographic changes associated with the beach cycles. In this study, these issues were investigated using the Narrow Multi-Beam (NMB) survey data, wave data, and seabed materials data before and after storm events, taking the Chigasaki coast facing Sagami Bay in Japan as an example (Fig. 1).

COASTAL CONDITION OF CHIGASAKI COAST

The Chigasaki coast is located 1 km east of the Sagami River mouth, as shown in Fig. 1. This coast has been formed owing to the deposition of sand supplied from the Sagami River and transported by eastward longshore sand transport. The beach, however, has been eroded owing to a rapid decrease in fluvial sand supply from the Sagami River and the blockage of eastward longshore sand transport caused by the construction of the Chigasaki fishing port (Ishikawa et al., 2009). As a measure against beach erosion, an artificial headland was constructed 1 km east of the fishing port in 1990, and beach nourishment using materials composed of sand and gravel with grain sizes greater than those of the original seabed materials has been carried out at a rate of 3×10^4 m^3/yr on the Chigasaki-naka area since 2005 (Ishikawa et al., 2013; 2018). As a result, the shoreline has markedly advanced by 2019. However, storm waves of the largest level in observation history associated with typhoons hit this coast several times since 2007, causing the damage to the cycling road along the coastline. Figure 2 shows the occurrence of significant wave height and wave period in these typhoon events, measured at a 20 m

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depth at the Hiratsuka wave observatory 4.7 km west of Chigasaki fishing port. Storm waves associated with six typhoons had hit this area since 2007.

In the Chigasaki-naka area of the coast, the foreshore mainly composed of gravel was relatively stable during storms, but the nearshore zone was severely eroded, resulting in sand deposition in the offshore area. The shore protection function of a sandy beach is reduced when the foreshore slope increases near the shoreline because of the increase in wave run-up height, indicating the importance of the study on changes in nearshore topography. In this study, therefore, the topographic changes after storm events associated with typhoons were quantitatively analyzed using the NMB survey and wave observation data, together with the seabed material data.

Figure 1. Satellite image of Chigasaki-naka area.

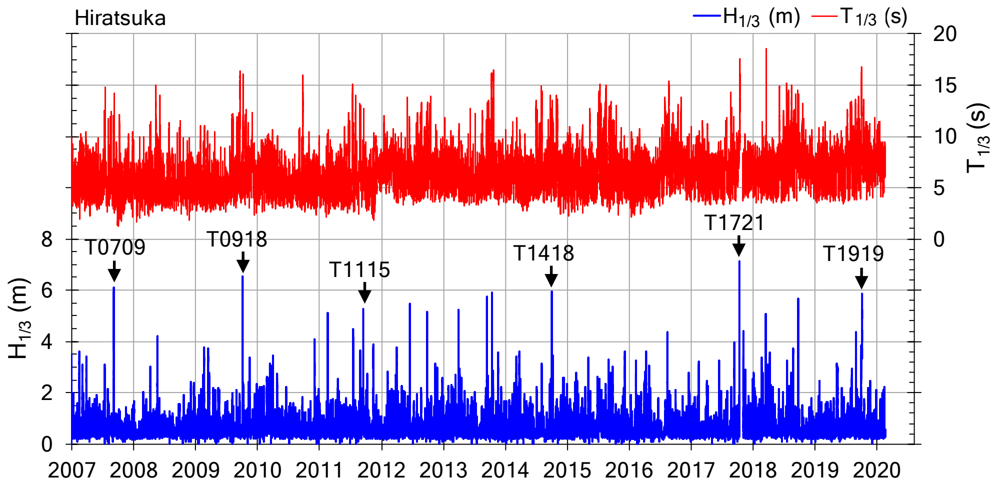


Figure 2. Wave height and wave period during six typhoon events since 2007 measured at Hiratsuka wave observatory.

DETAILED WAVE CONDITIONS IN STORM EVENTS

Since 2007, storm waves of the largest level in observation history associated with typhoons had hit the Chigasaki coast several times. In this study, four typhoons, as shown in Fig. 3, were adopted as typical typhoons: T0709 ($H_{1/3}$ = 6.1 m, $T_{1/3}$ = 10.4 s), T1115 ($H_{1/3} \geq$ 5.3 m, $T_{1/3}$ = 10.4 s), T1721 ($H_{1/3} \geq$ 7.1 m, $T_{1/3}$ = 11.2 s), and T1919 ($H_{1/3} \geq$ 5.9 m, $T_{1/3}$ = 13 s). In every storm, waves of a long period of over 10 s were observed.

In Fig. 3, part of wave observations is lacking during T1115, T1721, and T1919. For example, although wave data were not available after the observation of $H_{1/3}$ =7.1 m ($T_{1/3}$ =11.2 s) at the Hiratsuka wave observatory when T1721 hit on October 23, 2017, high waves with $H_{1/3}$ = 8.28 m ($T_{1/3}$ =11.1 s) was measured offshore of the Seisho coast 6 km west of the coast on the same day. Moreover, in these events, the duration of storm waves with a wave height over 2 m and a period longer than 10 s was extremely long compared with that in the other events, and the sea level significantly increased, as shown in Table 1. As a result, storm waves ran up to the backshore, and overtopping waves reached the cycling road. In the Hishinuma area, the cycling road was destroyed during T1721, as shown in Figs. 4(a) and 4(b).

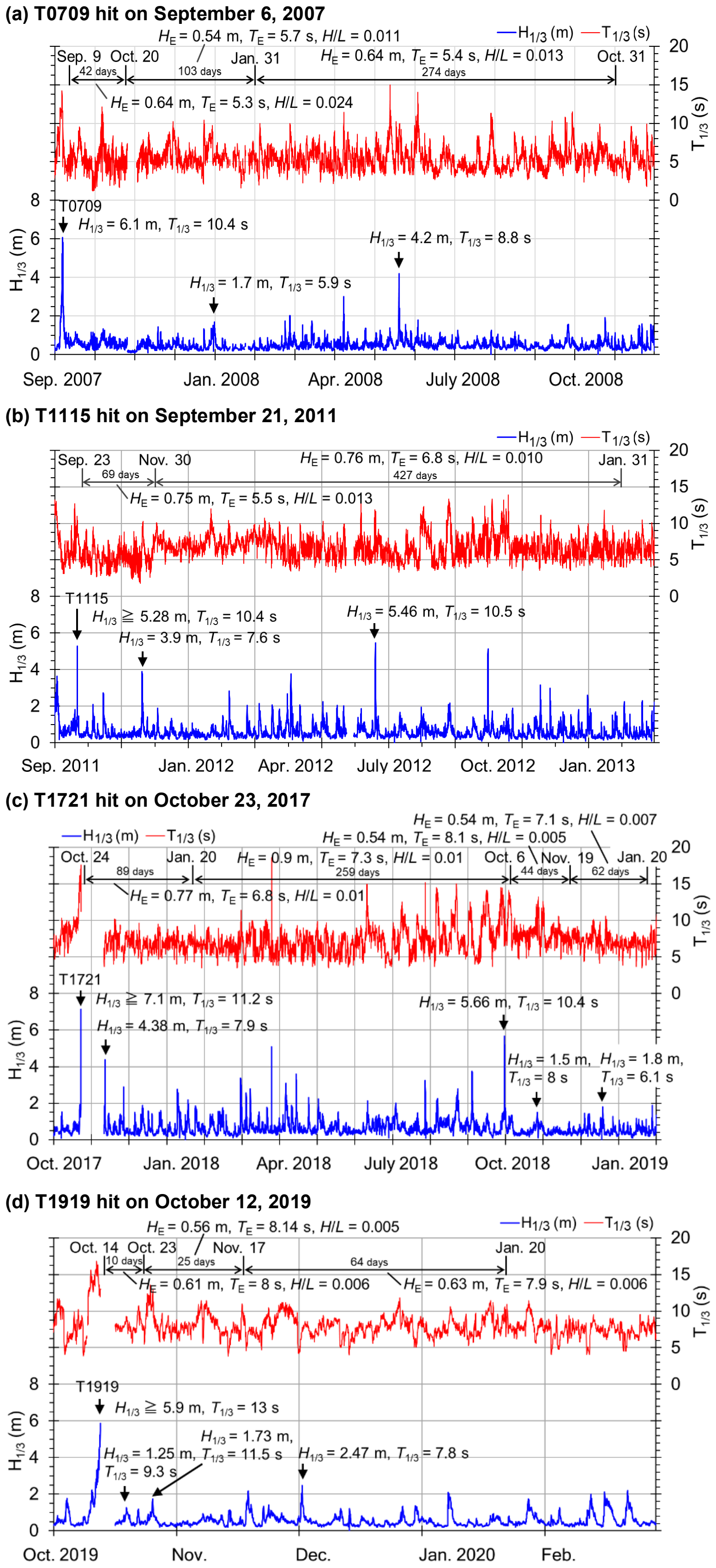


Figure 3. Wave height and wave period during T0709, T1115, T1721, and T1919 and in subsequent periods after each typhoon event.

Table 1. Wave conditions during four typhoons measured at Hiratsuka wave observatory.

	T0709	T1115	T1721	T1919
$H_{1/3}$ (m)	6.1	≧5.3	≧7.1	≧5.9
$T_{1/3}$ (s)	10.4	[10.4]	[11.2]	[13.0]
H/L	0.036	[0.031]	[0.036]	[0.022]
H_{max} (m)	9.2	≧6.9	≧9.4	≧7.0
T_{max} (s)		[12.6]	[21.9]	[13.1]
Time of occurrence of maximum wave height	Sep. 6, 2007 23:00	Sep. 21, 2011 15:00	Oct. 23, 2017 4:00	Oct. 12, 2019 19:00
Duration of wave height over 2 m (hrs)	53	≧5	≧6	≧31
Duration of wave period longer than 10 s (hrs)	57	≧10	≧144	≧76
Tide at Odawara observatory (m, above MSL)	+0.47	+0.49	+0.7	+1.07

[ ]: Maximum value of observed data because of lack of observation

Table 2. Wave characteristics in each duration after typhoon events.

Typhoon	Duration [days]		Energy-mean wave		Mean wave steepness	Maximum significant wave height		
			H_E (m)	T_E (s)	H/L	$H_{1/3}$ (m)	$T_{1/3}$ (s)	Date
T0709	Sep. 9, 2007–Oct. 20, 2007	[42]	0.64	5.3	0.024	1.3	10.1	Oct. 7, 2007
	Oct. 21, 2007–Jan. 31, 2008	[103]	0.54	5.7	0.011	1.7	5.9	Dec. 31, 2007
	Feb. 1, 2008–Oct. 31, 2008	[274]	0.64	5.4	0.013	4.2	8.8	May 20, 2008
T1115	Sep. 23, 2011–Nov. 30, 2011	[69]	0.75	5.5	0.013	3.9	7.6	Nov. 19, 2011
	Dec. 1, 2011–Jan. 31, 2013	[485]	0.76	6.8	0.010	5.5	10.5	June 20, 2012
T1721	Oct. 24, 2017–Jan. 20, 2018	[89]	0.77	6.8	0.010	4.4	7.9	Nov. 11, 2017
	Jan. 1, 2018–Oct. 6, 2018	[259]	0.90	7.3	0.010	5.7	10.4	Oct. 1, 2018
	Oct. 7, 2018–Nov. 19, 2018	[44]	0.54	8.1	0.005	1.5	8.0	Oct. 27, 2018
	Nov. 20, 2018–Jan. 20, 2019	[62]	0.54	7.1	0.007	1.8	6.1	Dec. 19, 2018
T1919	Oct. 14, 2019–Oct. 23, 2019	[10]	0.61	8.0	0.006	1.3	9.3	Oct. 19, 2019
	Oct. 24, 2019–Nov. 17, 2019	[25]	0.56	8.1	0.005	1.7	11.5	Oct. 25, 2019
	Nov. 18, 2019–Jan. 20, 2020	[64]	0.62	7.9	0.006	2.5	7.8	Dec. 2, 2019

TOPOGRAPHIC CHANGES IMMEDIATELY AFTER STORM EVENTS AND RECOVERY AFTER STORMS

The long-term topographic changes of the Chigasaki coast were analyzed in a previous paper using the data set measured between 1999 and 2015 by the NMB surveys (Ishikawa et al., 2018). In this study, short-term topographic changes before and after typhoon events were studied together with the investigation using the data set obtained by the routine surveys conducted several times a year along transect No. 18 located in the middle between the artificial headland and the Chigasaki fishing port, as shown in Fig. 1. Then, the energy-mean wave height, mean wave steepness, and maximum significant wave height in each duration after typhoon events are summarized in Table 2.

Topographic changes after T0709

Figure 5(a) shows the topographic changes measured between February 2007 before T0709 and January 2008 four months after T0709. In this period, the seabed shallower than 2 and 3 m depths was eroded by rapid offshore sand transport in the entire area, whereas sand was deposited in the offshore zone between 3 and 5 m depths immediately after the typhoons. When examining the topographic changes at the tip of the headland, the east side of the headland was eroded, whereas sand was deposited immediately west of the tip of the headland, implying the occurrence of westward longshore sand transport turning around the tip of the artificial headland. This was because storm waves were hit the coast from the easterly direction in T0709.

Figure 5(b) shows the topographic changes between January 2008 and February 2009, 17 months after T0709. In contrast to the topographic changes shown in Fig. 5(a), the offshore zone between 3 and 4 m depths was eroded with accretion near the shoreline, i.e., shoreward sand movement occurred. Figure 5(c) shows the change in longitudinal profile along transect No. 18 located in the middle of the Chigasaki-naka area. In October 2007 immediately after T0709, a bar with a crest of 3.4 m depth was formed along this transect, and then, this bar moved landward, and finally, a bar with a crest of 2.8 m depth was formed until January 2008.

In this period, the energy-mean wave height was H_E = 0.54 m with T_E = 5.7 s, and the wave steepness was as small as H/L = 0.011 with a maximum significant wave height of $H_{1/3}$ = 1.7 m ($T_{1/3}$ = 5.9 s). Although a trough remained in January 2008, the trough was completely buried, forming a seabed with a gentle slope until October 2008. The energy-mean wave height in this period was the same magnitude of that in the previous period as H_E = 0.64 m (T_E = 5.4 s), but the maximum significant wave height was as large as $H_{1/3}$ = 4.2 m and $T_{1/3}$ = 8.8 s. Thus, approximately 1 year was necessary for the beach topography to recover after T0709.

(a) At 6:38 **(b) At 6:42**

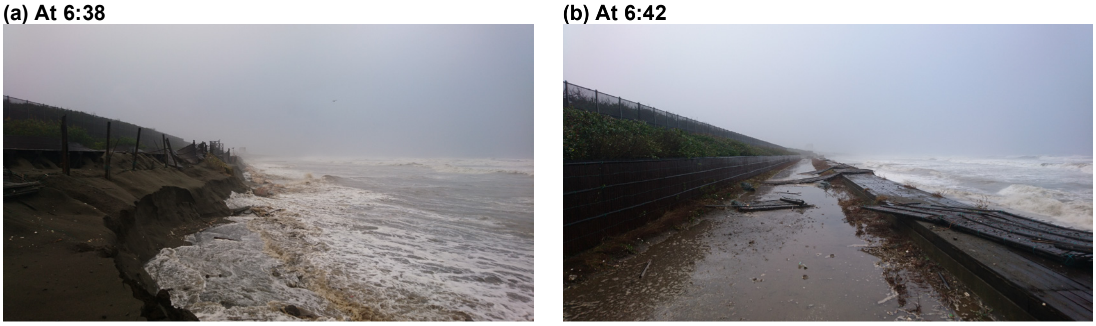
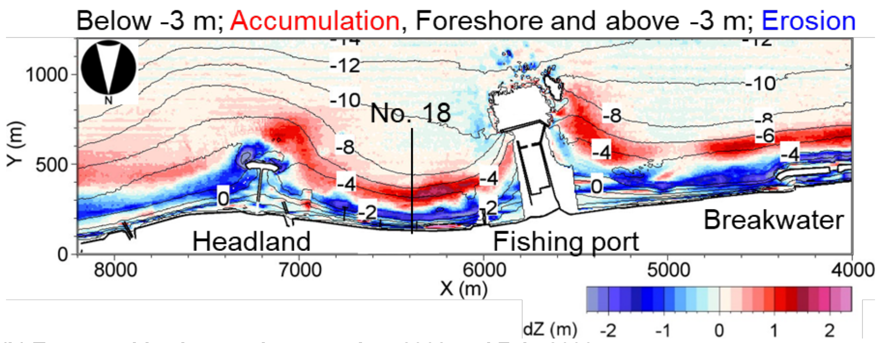
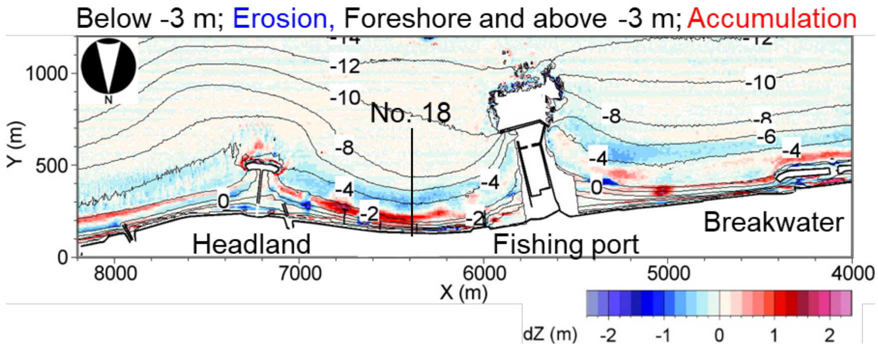


Figure 4. Erosion of sand mound along the coastline and wave overtopping to walkway in Hishinuma area during T1721 measured at 6:38 and 6:42 on October 23, 2017, respectively.

(a) Topographic changes between Feb. 2007 and Jan. 2008



(b) Topographic changes between Jan. 2008 and Feb. 2009



(c) Changes in longitudinal profile along transect No. 18

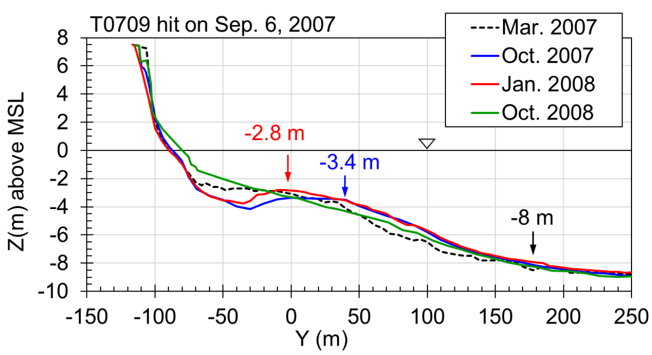


Figure 5. Topographic changes immediately after T0709 hit on September 6, 2007 and change in longitudinal profile along transect No. 18.

Topographic changes after T1115

Figure 6(a) shows the topographic changes between October 2010 before T1115 hit the coast on September 21, 2011 and November 2011 two months after the storm. The topographic changes occurred in the entire areas, such that the seabed shallower than 2 and 3 m depths was eroded and deposited in the zone between 3 and 4 m depths, although the topographic changes were smaller than those in the case of T0709. Moreover, a sand deposition zone was formed along a 4 m depth contour west of Chigasaki fishing port because of the blockage by the fishing port breakwater. Furthermore, the topographic changes between November 2011 and January 2013, 16 months after the storm waves, are shown in Fig. 6(b). In this case, the seabed between 3 and 4 m depths was eroded again with the accretion near the shoreline, similarly to those in the case of T0709. When examining the change in longitudinal profile along transect No. 18, as shown in Fig. 6(c), a bar with a crown depth of 3.7 m was formed by November 2011, two months after T1115. The depth of closure in this event was 7.2 m, shallower than the 8 m depth in the case of T0709. Then, part of the bar was eroded, and the trough was refilled until January 2013. The energy-mean wave height in this period was H_E = 0.76 m (T_E = 6.8 s), and H/L = 0.01, the maximum significant wave height was as large as $H_{1/3}$ = 5.5 m and $T_{1/3}$ = 10.5 s. Thus, approximately 1.5 years were necessary for the recovery of the beach topography under a calm wave condition after T1115.

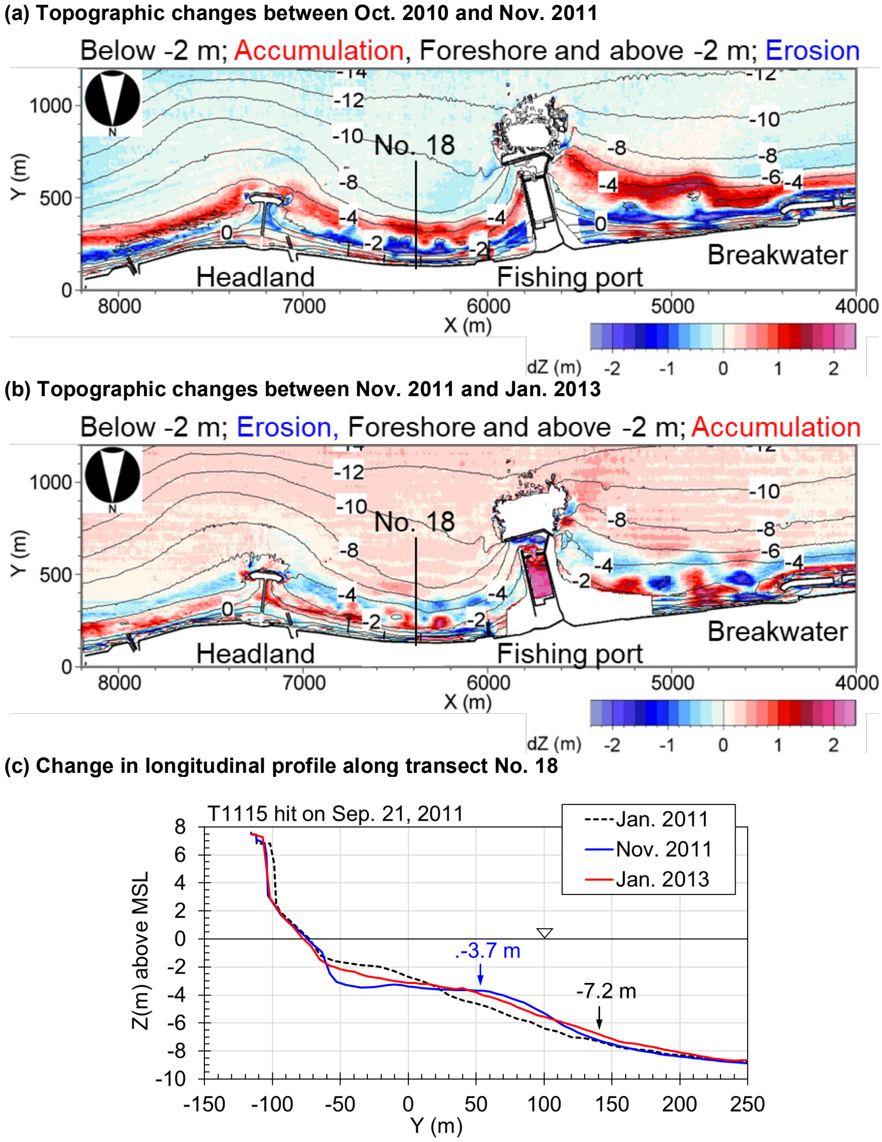


Figure 6. Topographic changes immediately after T1115 hit on September 21, 2011 and change in longitudinal profile along transect No. 18.

Topographic changes after T1721

On October 23, 2017, T1721 hit the coast, causing damage to the walkway along the coastline and the fences for preventing windblown sand. Figures 7(a) and 7(b) respectively show the images of the coast on October 6, 2017 before T1721 and October 27, immediately after T1721, taken from a fixed point on the Chigasaki-naka area. After the rough waves of over $H_{1/3}$ = 7.1 m and $T_{1/3}$ = 11.2 s during T1721, concrete armor units composing a groin buried under the beach surface were exposed by a relative height of approximately 1 m, indicating erosion of the backshore during the storm. Moreover, the fences for preventing windblown sand to the walkway were severely damaged by run-up waves. On the other hand, beach cusps composed of gravel were formed on the beach face within three days immediately after the storm waves.

Figure 7. Images of the coast taken from a fixed point before and after T1721 and T1824.

Figure 8(a) shows the topographic changes between December 2016 before T1721 and January 2018, approximately three months after the storm. Similarly to the previous typhoon events, the seabed was eroded in a zone shallower than 2 m depth, whereas sand was deposited in a zone between 3 and 4 m depths in the entire area, although beach changes were relatively small. Furthermore, Fig. 8(b) shows the topographic changes between January 2018 and January 2019, approximately 15 months after T1721. In this event, the seabed was eroded in the zone near 3 and 4 m depths and deposited near the shoreline, similarly to the previous events.

Figure 8(c) shows the change in longitudinal profile along transect No. 18. Although a bar with a crown depth of 3.2 m was formed on January 20, 2018, approximately 3 months after T1721, this bar moved shoreward with the formation of a bar with a crown depth of 2.3 m until October 6. At this time, a trough remained as it was, but the trough was completely buried by November 19, and the longitudinal profile of a gentle slope recovered until January 20, 2019. Although a bar and trough were formed immediately after T1721, a gentle slope topography was reformed again within 1–2 years after the typhoon (Fig. 8). Approximately one year was needed for the recovery of the longitudinal profile of a gentle slope, a smooth profile was formed from that with a bar and trough in 44 days between October 6 and November 19, 2018. In this period, the energy-mean wave height was H_E = 0.54 m with T_E = 8.1 s, and the steepness was as small as H/L = 0.005, which was smaller than H/L = 0.01 in the previous period between October 24, 2017 and October 5, 2018. Moreover, the maximum significant wave height was $H_{1/3}$ = 1.5 m and $T_{1/3}$ = 8 s. Although the longitudinal profile became a gentle slope within 62 days between November 20, 2018 and January 20, 2019, as shown in Fig. 8(c), a calm wave condition continued during this period namely $H_{1/3}$ = 0.54 m, $T_{1/3}$ = 7.1 s, and H/L = 0.007 (Table 2). Also, the energy flux after October 6 was smaller than that in the previous period, as shown in Fig. 9.

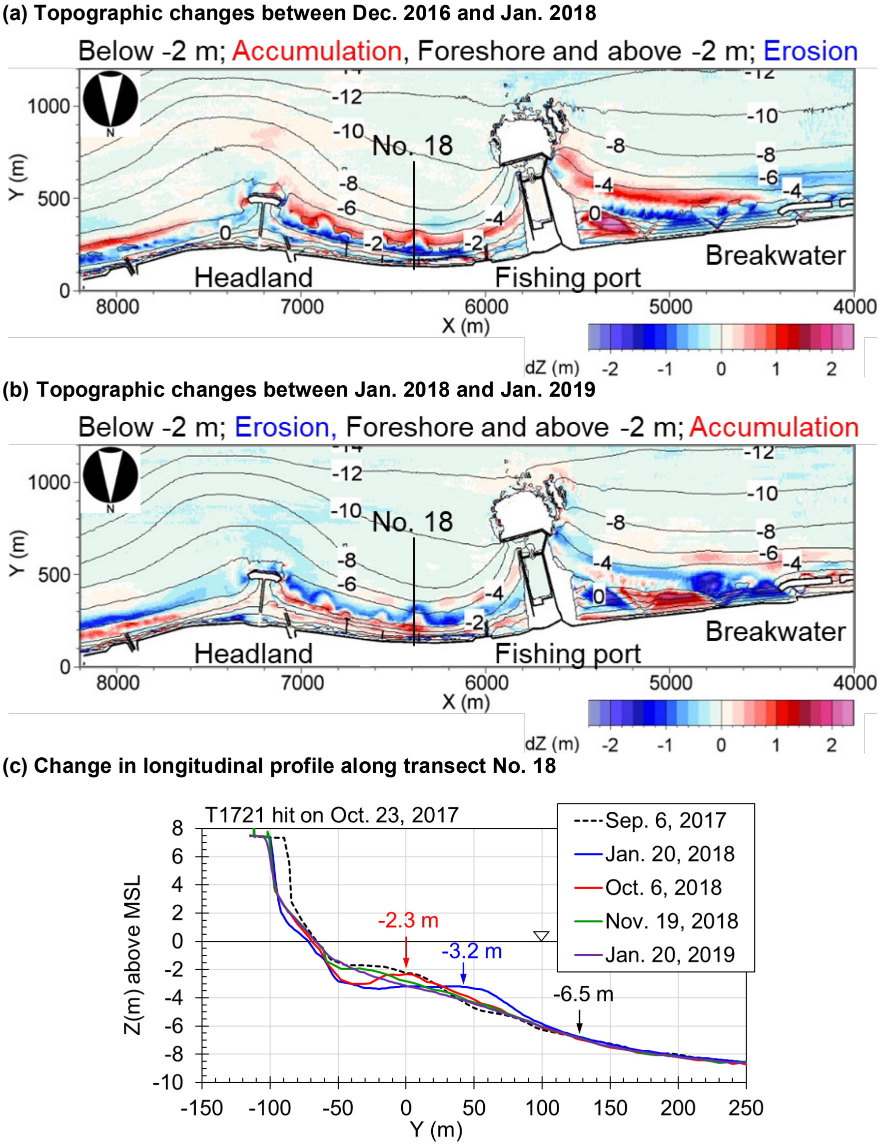


Figure 8. Topographic changes immediately after T1721 hit on October 23, 2017 and change in longitudinal profile along transect No. 18.

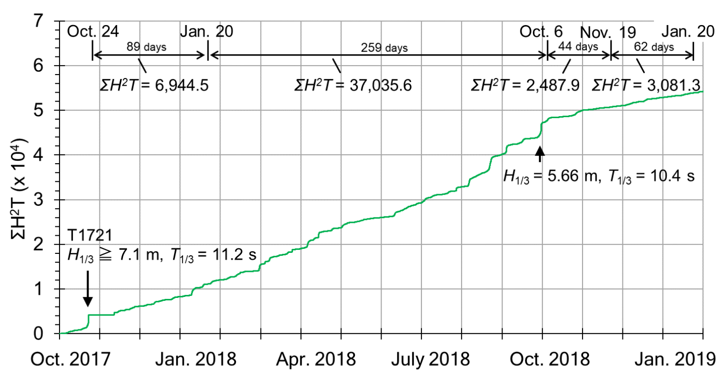


Figure 9. Cumulative energy flux after T1721.

In 2018, another typhoon T1824 hit on October 1 with rough waves of $H_{1/3}$ = 5.7 m and $T_{1/3}$ = 10.4 s, as shown in Fig. 3(c). Figures 7(c) and 7(d) show the foreshore and backshore changes before and after T1824 respectively. On September 19 before T1824, large amounts of sand and gravel were deposited on the shoreline, and the second layer of the groin composed of concrete armor units was invisible on the backshore because of the sand deposition. However, on October 3 after T1824, the backshore was eroded similarly to the event immediately after T1721, as shown in Fig. 7(b). Although a trough remained on October 6, 2018 with the change in longitudinal profile, as shown in Fig. 8(c), the effect of storm waves during T1824 have partly remained.

Figure 10 shows the depth distribution of the seabed material along transect No. 18. The seabed material was mostly composed of fine and medium-size sand, although the gravel content was as high as 60-70% in the zone of 1-2 m depths in September 2017 before T1721, whereas coarse material composed of gravel remained near 1 m depth and the gravel content increased on the foreshore until November 2017 immediately after the typhoon. This corresponds well to the foreshore changes shown in Fig. 7(b). Although a bar was formed in the zone between 3 and 5 m depths after T1721, as shown in Fig. 8, the grain size composition of this depth zone was 7% gravel, 8% coarse sand, 57% medium-size sand, and 28% fine sand. Moreover, the composition of medium-size sand showed increases in contents from 4% gravel, 3% coarse sand, 49% medium-size sand, and 42% fine sand, as shown in Fig. 10. The composition on November 2018, when a bar was eroded and a trough was refilled, was 0% gravel, 1% coarse sand, 52% medium-size sand and 45% fine sand, and the contents of gravel, coarse sand, and medium-size sand decreased, whereas the content of fine sand increased, while recovering the grain size composition before T1721. From this, it was found that mainly medium-size sand was transported offshore and was deposited, forming a bar during a storm event.

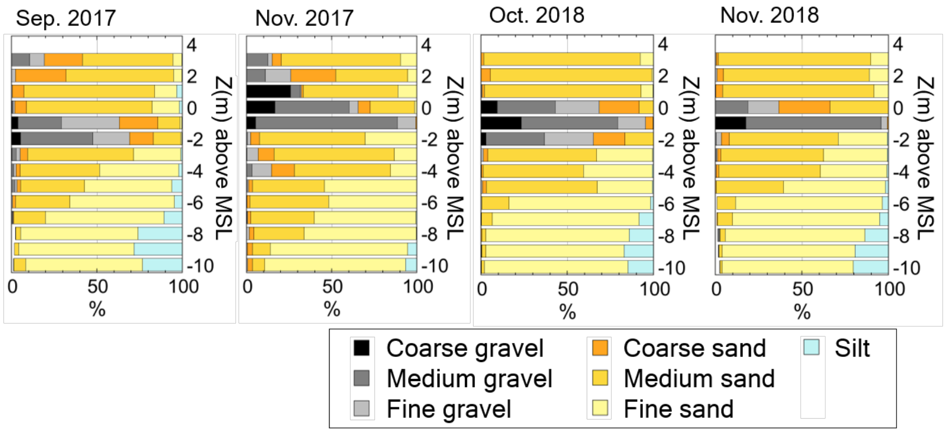


Figure 10. Depth changes in composition of sea bed material before and after T1721.

Topographic changes after T1919

During T1919 that hit the Chigasaki coast on October 12, 2019, storm waves of $H_{1/3}$ = 5.9 m at maximum and $T_{1/3}$ = 12.2 were measured at the Hiratsuka wave observatory, although the wave measurement was stopped after 6 p.m. In the Hishinuma area, the walkway along the coastline over 400 m was destroyed. Figure 11(a) shows the topographic changes between January 2019 and January 2020 three months after T1919. Topographic changes, such as the seabed in the zone shallower than 3 m depth was eroded and sand was deposited in the zone between 3 and 6 m depths, occurred in the entire area. In the longitudinal profile change shown in Fig. 11(b), a bar with a crown depth of 3 m was formed on October 23 immediately after the storm event, but part of the trough was refilled with sand until November 17, 25 days after the storm event. The energy-mean wave height was H_E = 0.56 m with T_E = 8.1s, the steepness was small as H/L = 0.005, and the maximum significant wave height was $H_{1/3}$ =1.7 m, $T_{1/3}$ =11.5, as shown in Fig. 3(d) and Table 2. Although the wave condition in this period was the same as that between October 7, 2018 and November 19, when a trough was refilled in 44 days, the beach changes were minimal. It was considered to be due to the fact that the crown depth of the bar on October 23, 2019 was deeper than that on October 6, 2018. Also, a gentle slope topography was formed again by August 2020.

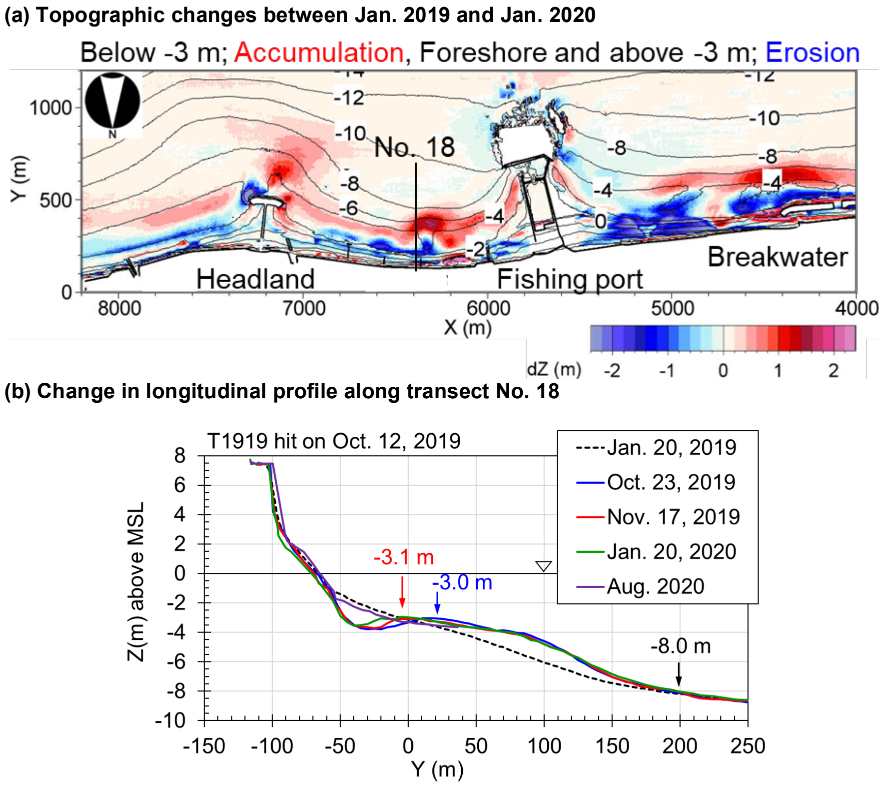


Figure 11. Topographic changes between January 2019 and January 2020 and change in longitudinal profile along transect No. 18.

CONCLUSIONS

Topographic changes in terms of beach cycles, i.e., accretion caused by storm waves and subsequent beach recovery after storm events, were investigated using the data sets of wave observation, the NMB survey, and grain size distribution, taking four typhoons that hit the Chigasaki coast as examples. It was found that a seabed shallower than 2 and 3 m depths was eroded by rapid offshore sand transport during a storm event with the deposition of sand in a zone between 3 and 5 m depths, and then the beach recovered within 1-2 years after the storm wave. The result of the grain size analysis of the seabed material indicated that medium-size sand was mainly transported offshore and was deposited, forming a bar during the storm wave. It was also confirmed that a bar and trough disappeared in 1-2 months under the conditions of H_E = 0.5 m, T_E = 8 s, and H/L = 0.005 when the crown depth of the bar was smaller than approximately 2 m. Thus, the topography after the storm wave recovered within several months or 1-2 years depending on the wave conditions and the crown depth of the bar. On the Chigasaki coast, beach nourishment at a rate of 3×10^4 m^3/yr has been carried out over 10 years (Ishikawa et al., 2013), and a large amount of sand was nourished. During the storm events, part of the nourishment sand was transported away from the foreshore, resulting in beach narrowing. However, the volume of beach sand recovered within several months or 1-2 years, so it is concluded that beach nourishment on this coast was successful when we consider the effect on the long-term basis while permitting the seasonal variation.

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