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Coastal Erosion Caused by Construction of an Artificial Island and Performance of Beach Nourishment

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ABSTRACT

It is well known that the littoral drift carries much sand into a sheltered area caused by the presence of coastal structures such as detached breakwaters. As a result, the shoreline in the sheltered area advances, whereas the shoreline of the neighboring coast recedes to balance a sand budget of the coast. An artificial island for storage of crude oil was constructed off the Kashiwabara coast, Shibushi, Kagoshima Prefecture, Japan since 1985. The island has a rectangular shape roughly 1.5 km long and 1.5 km wide. This paper describes coastal processes related to the construction of the artificial island, and proposes a new dredging and beach fill scheme including a groin to decrease the coastal erosion due to the sheltering effect by the artificial island.

INTRODUCTION

When coastal structures such as detached breakwaters and artificial reefs are constructed, sheltered areas are created. The littoral drift carries much sand into these sheltered areas. As a result, the shoreline in the sheltered area advances, whereas the shoreline of the neighboring coast recedes. The sand from the neighboring shoreline becomes the sediment source for the sheltered area. A plan view of the shoreline configuration changes significantly after the construction of sheltering coastal structures in a nearshore region. These kinds of engineering issues in Japan are documented by Uda (1997) in detail. To overcome this problem, it is proposed that a single groin should be set at the boundary of the sheltered and non-sheltered beaches to block the excess longshore sediment transport into the sheltered area. This scheme will also ideally prevent additional coastal erosion along the non-sheltered beach.

An artificial island for storage of crude oil was constructed off the Kashiwabara coast, Shibushi, Kagoshima Prefecture, Japan since 1985 (see Figure 1). The construction of outer facility of the island was completed in 1987 and then the island was reclaimed by dredged material from the nearshore area in front of the island. The island has a rectangular shape roughly 1.5 km long, 1.5 km wide, and the size of

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the island is 192 ha. The length of the island is nearly eighteen times longer than the wave length of mean energy wave and 3.8 times longer than the observed longest significant wave length, respectively in this area of the Pacific Ocean. The refraction and diffraction patterns are modified by the shape of the borrow site for reclamation and the presence of the island to cause an uneven wave height distribution along the shoreline. Because of its size, this artificial island generated a large sheltered area as shown in Photograph 1 and caused significant beach and dune erosion on the neighboring coasts. Thus, monitoring projects in terms of a shoreline configuration, bathymetry, dune and beach scarp, and incident wave climate have been conducted since the construction of the island at the Kashiwabara coast. This study aims at the investigation of coastal processes related to the construction of the artificial island and a beach nourishment scheme involving a single groin based mainly on the monitoring data.

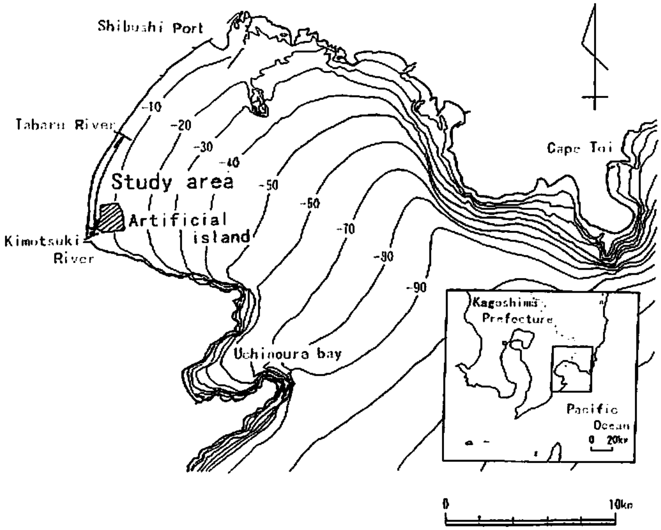
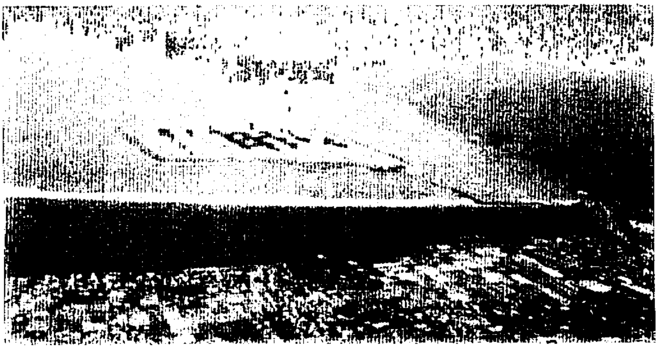


Figure 1 Location of study area.



Photograph 1 Aerial view of the artificial island.

SUMMARY OF STUDY AREA

Location of study area

The Kashiwabara coast is located on the south side of Shibushi Bay which opens to the southeast direction as shown in Figure 1. Shibushi Bay is 16.8 km long and faces to the Pacific Ocean. Shibushi Port and the artificial island lie on the northeast and southwest sides of the bay, respectively. The sandy beach extends nearly 14.2 km along the coast. Five rivers, i.e. Mae, Anraku, Hishida, Tabaru and Kimotsuki Rivers, run into the coast and supply the sediment to the beach. However, the length of each of these rivers is only 14.5, 27.1, 49.3, 14.7 and 34.0 km, respectively, therefore the sand discharge from the river mouths are probably minimal. For instance, the annual mean water discharge of the Kimotsuki River is only 35.12 m^3/sec. The Kimotsuki and Tabaru Rivers run into the southwest and northeast side of the study area, respectively.

Wave climate

The entire coast in the bay opens to southeast direction and both sides of the coast are surrounded by the capes as shown in Figure 1. Therefore, the incident wave direction is limited nearly to the southeast direction with some seasonal fluctuation. The incident wave conditions have been monitored by an ultrasonic type of wave gauge which is installed at the -35m water depth and located just off the Birou island. The monthly mean energy wave conditions is shown in Table 1, where as of the highest significant wave since 1980 are shown in Table 2. The incident angles are positive to clockwise from southeast. As can be seen in Table 1, the mean energy wave height during the winter season (December to February) is smaller than that in summer season (July to September). In addition, mean incident wave angle in June, July and August is slightly southward compared to that during the period from September to May, because the mean wind directions in winter and summer are from landward and seaward, respectively. Moreover, high waves generated by typhoons approach to the coast in the summer season.

Table 1. Mean energy wave conditions obtained at Birou wave station from Jan. 1992 to Dec. 1996. (h = -35m)

Month	$H_{1/3}$ (m)	$T_{1/3}$ (sec)	Angle (° SE=0)	Deviation (°)
Jan.	0.45	6.48	1.8	-1.54
Feb.	0.54	6.40	2.7	-0.64
March	0.70	6.99	2.6	-0.74
April	0.69	6.64	1.6	-1.74
May	0.77	6.87	-1.4	-4.74
June	0.68	6.65	5.5	2.16
July	1.01	7.40	8.8	5.46
Aug.	1.45	7.98	6.8	3.46
Sep.	1.17	8.24	2.4	-0.94
Oct.	0.92	8.14	2.5	-0.84
Nov.	0.90	8.30	2.7	-0.64
Dec.	0.53	7.17	4.1	0.76
Mean	0.89	7.29	3.34	

Table 2. The highest significant wave conditions

Date	$H_{1/3}$ (m)	$T_{1/3}$ (sec)	Climate
2:00 Sep. 11, 1980	7.39	13.1	Typhoon 8013
10:00 Oct. 22, 1981	3.73	14.0	Typhoon 8124
22:00 Aug. 26, 1982	7.88	12.3	Typhoon 8213
14:00 Aug. 14, 1983	3.65	12.8	Typhoon 8305
0:00 Aug. 19, 1984	3.54	9.9	Typhoon 8410
2:00 Aug. 31, 1985	4.70	12.1	Typhoon 8512,8513
0:00 Aug. 26, 1986	4.59	13.2	Typhoon 8613
0:00 Aug. 31, 1987	3.86	8.8	Typhoon 8712, Depression
18:00 June 2, 1988	2.64	7.5	Combined depression
18:00 July 27, 1989	4.28	13.1	Typhoon 8911
2:00 Sep. 18, 1990	7.48	13.8	Typhoon 9019
10:00 Sep. 23, 1991	5.91	11.9	Typhoon 9119
8:00 Aug. 8, 1992	4.99	11.3	Typhoon 9210
2:00 Aug. 10, 1993	8.30	12.8	Typhoon 9307
12:00 Aug. 13, 1994	6.52	12.2	Typhoon 9414
16:00 Sep. 16, 1995	5.24	15.9	Typhoon 9512
14:00 July 18, 1996	6.02	10.5	Typhoon 9606
14:00 July 18, 1997	7.17	13.1	Typhoon 9719

Characteristics of bed material

Sediment samples were taken from the beach face to the nearshore. A transect for the sediment sampling was set in the middle of the eroded coast where shoreline recession by the presence of island was the most significant. The median diameter of the sediment on a beach during the summer season is of the order of 0.5 mm and is larger than that during the winter season, whereas the median diameter in the shallow water area is of the order of 0.19 mm. The average density of sediment is nearly 2.55 g/cm^3 with a variation between 2.35 and 2.7 g/cm^3.

OVERVIEW OF THE COASTAL PROCESSES BY AERIAL PHOTOGRAPHS

Aerial photographs have been regularly taken at Kashiwabara Coast since 1984. An overview of coastal processes will be given first based on these photographs. Photograph 2 taken in 1984 shows the natural condition of the Kashiwabara coast before the construction of the island. The mouth of the Kimotsuki River and parallel jetties can be seen on the left side of photograph. The curved breaker line in front of the river mouth shows that there is a shallow water area. This river mouth terrace was generated by the sediment deposition discharged from the Kimotsuki River. In addition, the shorelines during a high and a low water levels are easily recognized as dry and wet beaches, respectively. The width of wet beach near the north jetty is narrow implying that the beach face is steep compared to the northern beach, because this area is highly depositional.

The outer facility of the island was completed in 1987. After that, a large tombolo was formed in the sheltered area by the refracted and diffracted waves. The major sediment source for the depositional features are neighboring northern sandy beach. The shoreline retreated nearly 80 m compared to the shoreline before the construction of island.(in November 1984). The steepening and narrowing of beach face caused pronounced dune and beach scarps. The highest dune scarp attained to

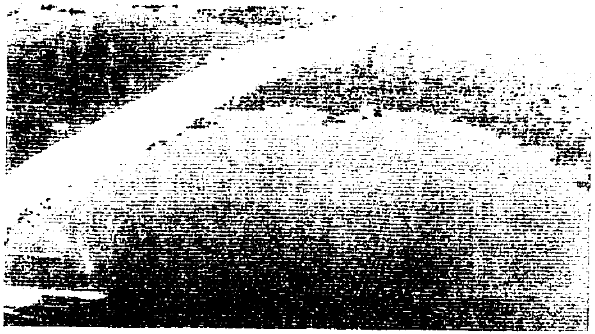


Photo 2. Kashiwabara coast in natural condition (1984).

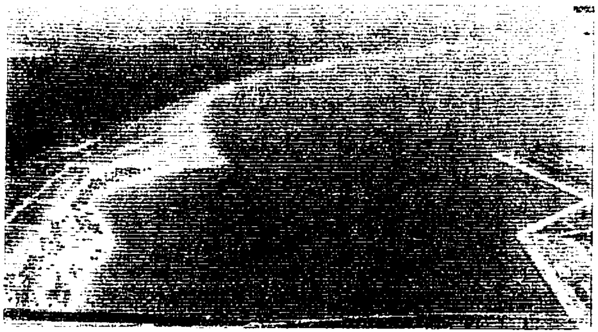


Photo 3. Plan view before the beach nourishment
(Sept. 27, 1992).

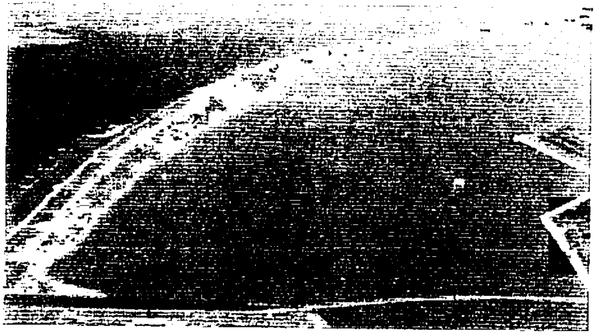


Photo 4. Plan view after the beach nourishment
(May 13, 1993).

Photo 5. Coastal damage after the first typhoon season
(Feb. 16, 1994).

nearly 7 m at that time. To prevent further coastal erosion and shoreline recession, a beach nourishment project with single groin was carried out. Photograph 3 dated on May 27, 1992 is the situation just before the beach nourishment.

Photograph 4 shows the plan view just after the beach nourishment. The sand for the nourishment had been taken from two borrow sites between a groin and Hami fishery harbor. Therefore the sandy beach behind the island is somewhat uniform. The non-sheltered beach north to the groin was filled by the sand from the sheltered area, and thus the beach was widened nearly 80 m offshore. As a result, the shoreline configuration became more straight. In addition, a T-shaped single groin was installed between the sheltered and non-sheltered beaches to block the excess southern longshore sediment transport.

Photograph 5 shows the shoreline configuration of nourished beach just after one typhoon season. As seen in the photograph, the shoreline in the entire nourished beach receded and scarp generation had initiated. The profile adjustment after the beach nourishment is accelerated by two of the largest typhoon since 1980. It was observed that foot of scarp exists at an elevation of berm height at that time. So it is expected that the scarp generation can be avoided if the elevation of nourished beach is kept to be the natural berm height in the design.

LONGSHORE PROCESSES

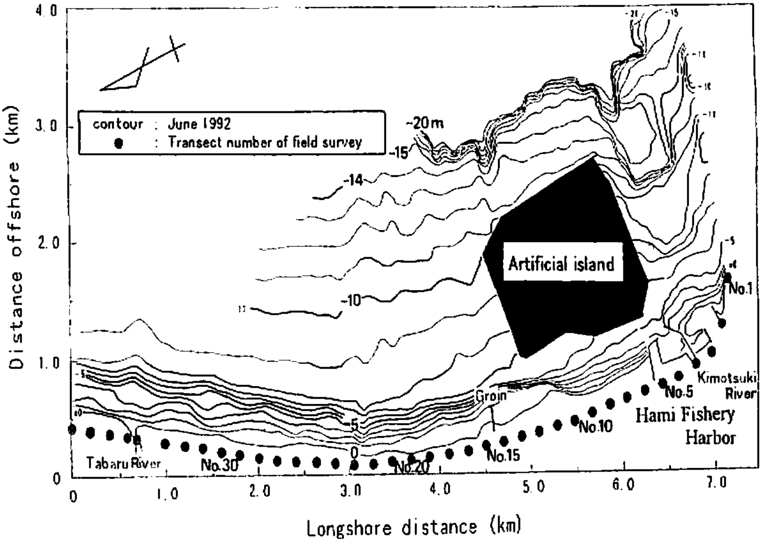


Figure 2. The orientation of coastal structures and transects.

The orientation of artificial island, groin, fishery harbor is shown in Figure 2. The incoming waves are refracted and diffracted by the island and tend to transport much sediment into the sheltered area located just behind the island. The bathymetry and shoreline data have been collected twice a year since 1984, and wave data is collected since 1980. The bathemetry survey covers the region from the southwest end of the bay, where the Kimotsuki River runs into, to beyond the Tabaru River.

The length of this study area extends to 7.5 km. The origin of the x-coordinate for a survey is set to the northeast end of the study area. The number of survey transects increases from the Kimotsuki River to the Tabaru River as shown in Figure 2. The borrow sites for the reclamation sand were in front of the island and te Kimotsuki River mouth.

Shoreline Change (Plan View) after the Construction of Artificial Island

Shoreline configurations of the Kashiwabara coast after the construction of artificial island are shown in Figure 3. The reference shoreline is set to be the shoreline in July 1985. As seen in the shoreline in June 1986, when an outlying facility of the artificial island was being constructed, the wave sheltering effect on the sandy beach had initiated especially in further south area than x = 4.3 km. It is clearly seen that sediment had been deposited in the sheltered area, and the shoreline configuration showed quasi-double-tombolo features. The peaks in the shoreline were located at x = 4.9 km and x = 6.3 km in June 1987. The migration of southern quasi-tombolo along a shore was blocked by an outer facility of the Hami fishery harbor, but the size of this depositional area had continued to grow. The sediment supply from the Kimotsuki River partially contributed to the generation of the south depositional feature. The north tombolo had shifted south along shore and the size of the tombolo had enlarged year by year.

Regarding the growth of the north tombolo, where significant amount of sand had been deposited, the offshore distance of peak of the tombolo had advanced from 40 m in June 1986 to 170 m in June 1992. The maximum shoreline advance in this period was 130 m, resulting the mean advance speed 21.7 m/yr of the shoreline. In addition, the peak of the tombolo was migrated from x = 4.75 km in 1986 to x = 5.25 km in 1992 to south direction, hence the tombolo had been shifted 500 m in this period. The mean migration speed was 83 m/yr after the construction of island. Once the tombolo generation was initiated by the diffracted waves in the sheltered area, the water depth at the tip of the tombolo was getting deeper according to its offshore growth. As a result, more diffracted waves with higher wave energy flux tend to act toward south direction in the sheltered area. Therefore, the peak of the tombolo migrated southwards while the size of tombolo was increasing in the sheltered area. As seen in the figure, the boundary of northern tombolo and southern quasi-tombolo had been also shifted 270 m to south with an annual mean speed of 45 m/yr. In accordance with the migration of tombolo behind the island, the boundary of depositional and erosional areas of this coast shifted 132 m toward the sheltered area.

The sandy beach in the sheltered area had widened, but the neighboring sandy beach in non-sheltered area had suffered severe coastal erosion after the construction of artificial island. As can be seen in the first and second rows of the figure, there is little shoreline recession in 1988 and 1989. The shoreline recession in non-sheltered area seems to be delayed two years compared to the quick shoreline advance in sheltered area. The shoreline started to retreat over 1360 m stretch from 1988, and then the total length of shoreline recession had become nearly 2.5 km by June 1992. The maximum shoreline recession was nearly 100 m at that time. The northern boundary of erosional area had shifted from x = 2.8 km to x = 1.8 km in June 1992, while the peak of erosion has shifted from x = 4.1 km to x = 3.2 km with an annual speed of 200-250 m/yr. The shoreline recession triggered the dune erosion and scarp generation as well. Because the shoreline is located closed to the upper beach face and dune face, the steeper the cross-shore profile, avalanching tends to occur on the steep slope to cause the scarp. Following the severe dune and beach erosion, a beach nourishment project with single groin had been carried out to prevent further coastal erosion. The project was completed in May 1993.

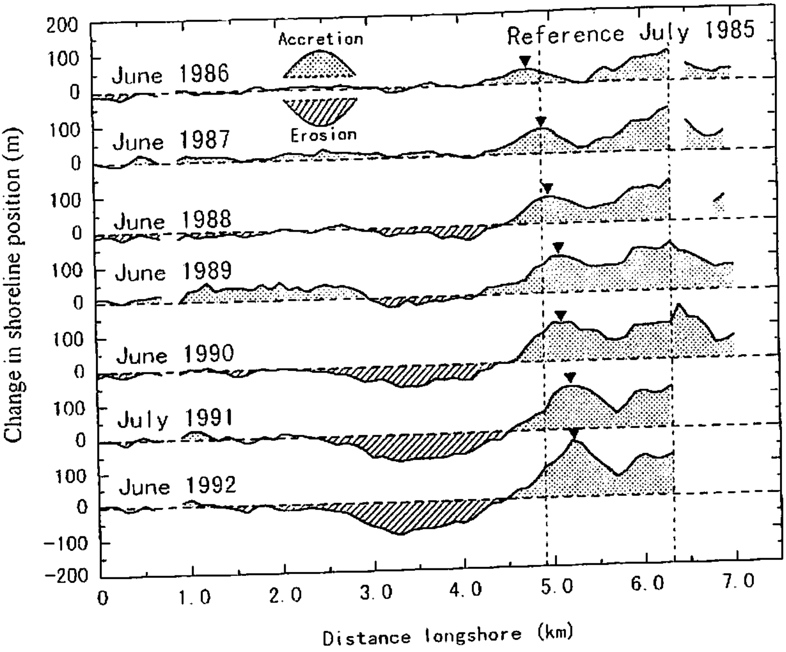


Figure 3. Shoreline change after the construction of the island.

Shoreline Change after the Beach Nourishment

A volume of 1.15 x 10^6 m^3 of sand was dredged from two borrow sites just behind the island and filled into the eroded beach. The two borrow sites for the beach nourishment were deployed between x = 5.3 km and x = 6.24 km, respectively. The shoreline changes after the beach nourishment is shown in Figure 4. The reference shoreline is set to be the shoreline in June 1992 when the nourishment project had conducted thereafter. As seen in the figure, the shoreline advanced in a region from x = 4.94 to 6.3 km (= 1.36 km extension) in June 1992. The maximum shoreline advance was 152 m at x = 5.34 km. On the other hand, the shoreline receded in the region from x = 1.43 to 4.75 km (= 3.32 km extension) with a convex plan view in June 1992 before the beach nourishment. This maximum shoreline retreat in November 1992 was nearly 80m at x = 3.74 km.

To prevent further erosion and property damage, sand was filled in the non-sheltered area in May, 1993 as shown by the shoreline in Nov. 1993. The nourished shoreline around x = 2.63 km was smoothly connected to the natural shoreline at x = 2.43 km. The shoreline was advanced 80 to 100 m in the eroded section of the beach by the beach nourishment.

A single T-shaped groin 230 m long was extended from the beach face to the water depth of -2.3 m at x = 4.6 km. The function of this groin is to block the excess longshore sediment transport into the sheltered area from the northern neighboring beach. In addition, beach and dune scarps were scraped by bulldozers to guarantee safe accessibility and utilization of the beach. Then a mild-slope revetment with 200 m extension was installed at x = 3.5 km.

Following the beach fill project in May 1993, the largest typhoon since 1980 generated a maximum significant wave with $H_{1/3}$ = 8.3 m and $T_{1/3}$ = 12.8 sec period on August 10, 1993. Then unfortunately the third largest significant wave caused by Typhoon 9313 approached the shore with 7.72 m wave height and 11.2 sec wave period on September 3, 1993. As a result, the filled shoreline quickly receded nearly 50 m in the first six months just after the beach fill project as shown by solid line in Nov. 1993. Following this shoreline recession in the first six months, successive shoreline recession including a crescentic shoreline configuration between x = 3.27 km and x = 4.68 km occurred until 1995. In contrast, the shoreline in the non-sheltered area was advanced in Nov. 1996, because the Typhoon wave condition in this year was smaller than previous years. However, Typhoon 9713 which lasted three days (in terms of the significant wave height condition higher than 3.0 m) and Typhoon 9719 caused the shoreline recession in the entire region except the river mouth of the Tabaru River and the sheltered area. Finally, the shoreline configuration became as shown by the solid line in December 1997.

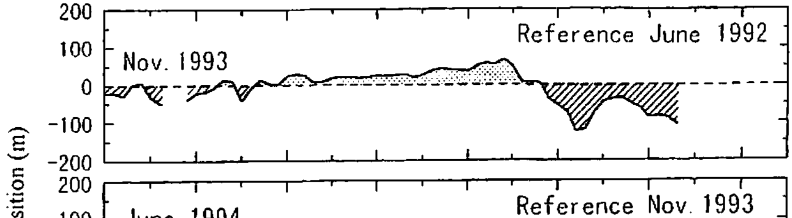
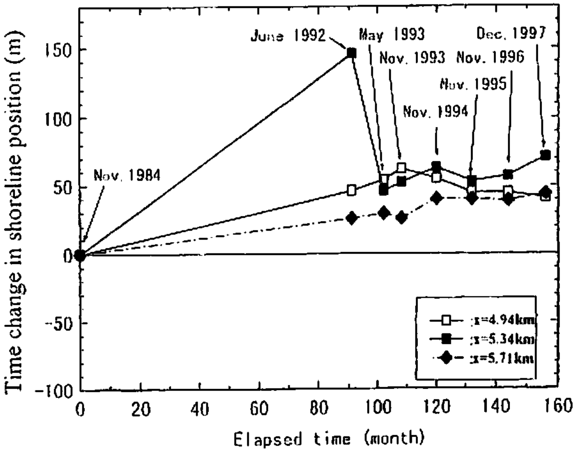


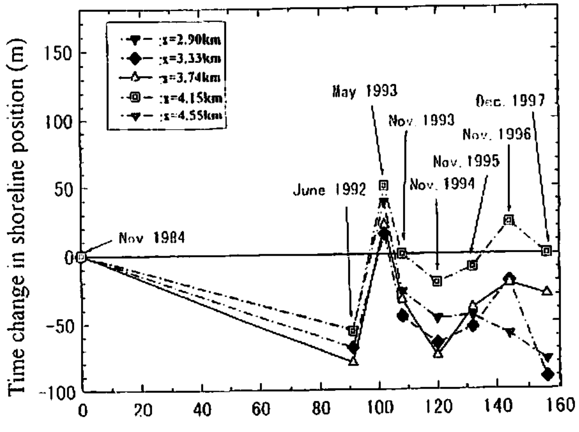
Figure 4. Shoreline change after the beach nourishment.

Figs. 5 (a), and (b) show the time series of shoreline position at representative transects. The mean shoreline changes at x = 5.34 km and x = 3.74 km were nearly +19.3 m/yr and -10.5 m/yr, respectively. In contrast, the shoreline changes in the sheltered area after the beach nourishment show either small positive trend or stabilization.

The shoreline changes on the nourished beach were accelerated during the first 2.5 years after the nourishment due to attack of two of the three largest typhoons in the wave record in 1993 and profile adjustment relating to the overfill. For instance, an annual rate of shoreline change at transect x = 3.74 km was 60.2 m/yr. Following this period, the shoreline change seems to have stabilized or shows some positive trend except the shoreline position in Dec. 1997.



(a) Time change in shoreline position in the sheltered area.



(b) Time change in shoreline position in the non-sheltered area.

Figure 5. Shoreline changes of each transect.

The inverse exponential behavior of the shoreline changes on the nourished beach (on non-sheltered beach) clearly means that a single groin installed between sheltered and non-sheltered beaches functions to block an excess longshore sediment transport into the sheltered area.

SAND BUDGET ALONG THE COAST

A time series of the change in sand volume over the entire Kashiwabara coast is shown in Figure 6. The change in sand volume along the shore is calculated by multiplying the cross-sectional change by the transect spacing. The volumetric change beyond the -9 m water depth was not taken into account for the estimation, since the sounding survey was conducted to this water depth. The profile analysis which will be shown later and the cross-shore distribution of sediment diameter show that the critical water depth for profile change in this study area is nearly -8 m. Therefore the change in sand volume in Figure 6 can be used as the first approximation. The change in total sand volume in the sheltered area x=4.55 to 6.30 km was nearly 600 x 10^3 m^3, thus the annual depositional rate in this area was 160 x 10^3 m^3/yr after the construction of the island (June 1986 to November 1990). On the other hand the change in total sand volume in the erosional area from x = 2.68 to 4.55 km was roughly 970 x 10^3 m^3. Thus, the annual erosional rate in this area was -220 x 10^3 m^3/yr.

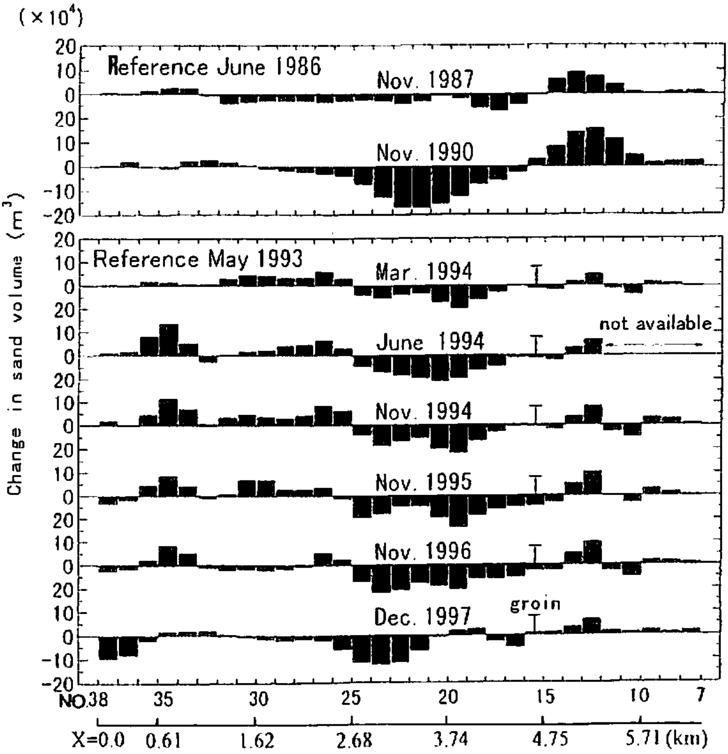


Figure 6. Change in sand volume in the study area.

The beach nourishment project with the single groin was completed in May 1993. The change in sand volume in the area from x = 4.75 to 5.71 km was +220 x 10^3 m^3 after the beach nourishment, and thus the annual depositional rate in this area is 50x10^3 m^3/yr. This means that the transmission rate of this groin for longshore sediment transport is estimated by comparison of depositional rate before and after the beach nourishment as follows;

$$P_{tr} = \frac{50\times10^3(m^3/yr)}{130\times10^3(m^3/yr)}\times100(\%) = 38\%$$

Volumetric change in the northern area from the groin after the beach nourishment was –830 x 10^3 m^3, thus the annual erosion volume was -200 x 10^3 m^3/yr.

CROSS-SHORE PROCESSES

The profile variations in space during the post-construction period, beach nourishment period, and post-nourishment period are examined here. Figure 7 shows the change in profile along shore from November 1984 to June 1992. The coordinate x = 4.94 km is located in the sheltered area and x = 3.53 km is located in the middle of erosional area. In addition, an entire profile at x = 3.53 km is lowered by more than 1.4 m.

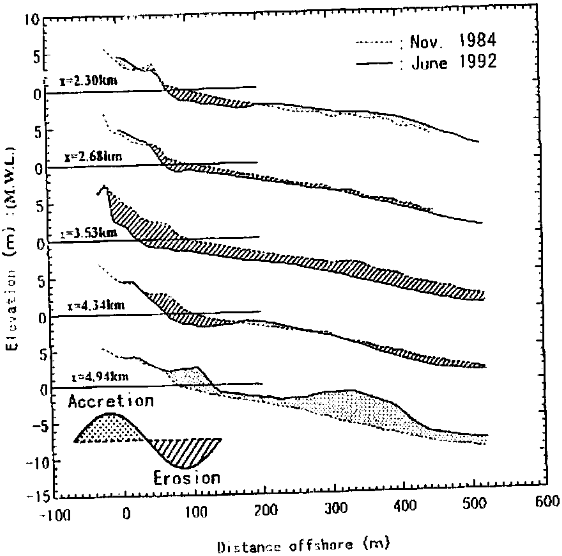


Figure 7. Profile change along the shore after the construction of the island.

Figure 8 shows the profile change along the coast before and after the beach nourishment. The nourished sand was filled from a landward boundary of erosional area to –4 m water depth. As can be seen in the figure, the profile was designed to have composite slopes. The beach slopes higher than 1m elevation are 1/25, 1/29, 1/27 and the offshore slopes are 1/60, 1/59 and 1/51 at x = 2.68, 3.53 and 4.34 km, respectively.

Figure 9 shows that the profile changes along the coast in the first typhoon season struck on the shore during this period, the nourished beach had been extensively damaged and scarp generation has commenced again. Typhoons 9307 and 9313 produced 8.3 m and 7.72 m significant wave height, respectively. The elevation of the scarp base is nearly 2 m along the shore.

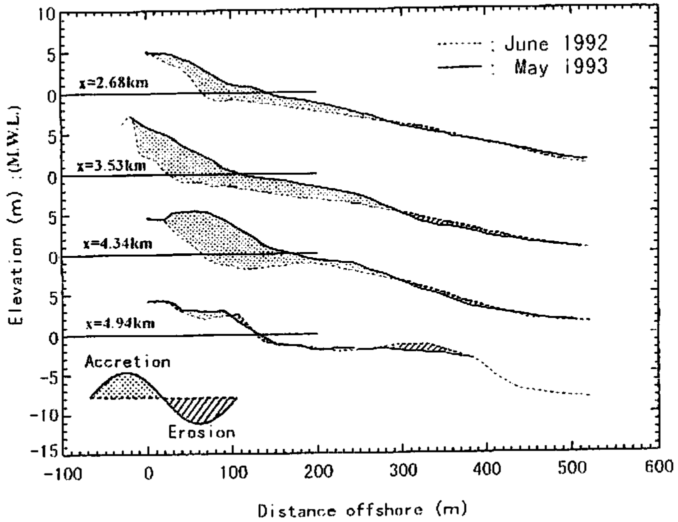


Figure 8. Profile change along the shore during the beach nourishment.

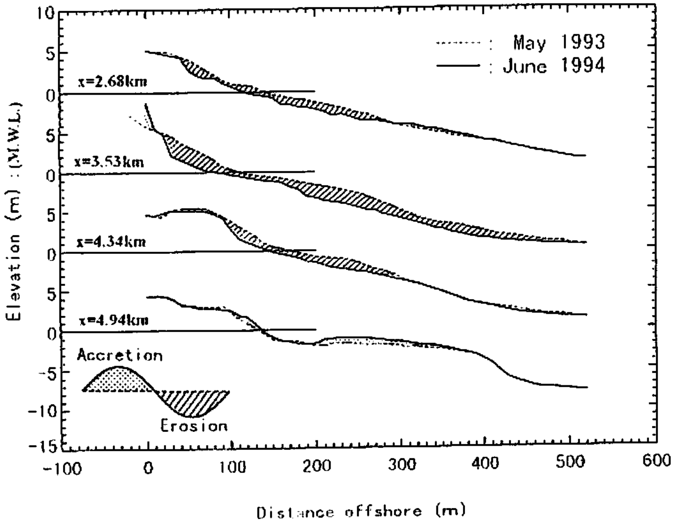


Figure 9. Profile change along the shore after the beach nourishment

CONCLUSIONS

Field observations were carried out to study the mechanism of coastal erosion due to the presence of artificial island, and to access the performance of new beach nourishment scheme as well as develop database for future numerical work. The main conclusions are as follows;

(1) A quasi-double-tombolo feature was generated by the sheltering effect of the artificial island at the Kashiwabara coast. The northern tombolo moved into the sheltered area with the speed of 75m/year due to the wave refraction and diffraction. Sediment was supplied from the northern neighboring coast. As a result, the neighboring coast eroded over a 2.0km stretch.

(2) A single groin, which was set between the sheltered and non-sheltered areas, decreased the southward longshore sediment transport. The transmission rate of the groin is estimated to be 38% in terms of annual transport rate. Despite rapid shoreline recession due to profile adjustment and severe typhoon conditions during the first 2.5-year period after the beach nourishment, shoreline position tends to be stabilized or slightly progressed in the last few years. It can be concluded that the nourished beach close to the groin tends to be partially stabilized.

(3) Part of the nourished sand has been transported still beyond the single groin, because the water depth at the tip of groin was set to be -4m and thus it is shallower than the depth of closure which is roughly -8m in this area. In addition, a large amount of nourished sand, which exceeded the equilibrium berm height has been transported to north direction due to the excess longshore slope of nourished beach, and partially to offshore beyond a typical closure depth due to severe typhoons.

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