FIELD OBSERVATION OF EROSION AND ACCRETION WAVES ON SHIZUOKA AND SHIMIZU COASTS IN SURUGA BAY IN JAPAN

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ABSTRACT

A distinct propagation of erosion and accretion waves was discovered along the Shizuoka and Shimizu coasts facing Suruga Bay in Japan. Their propagation velocities were 270m/yr and 250m/yr. "Hagoromo-no-matsu", a scenic beach famous in Japan, where, along the shoreline, people can see Mt. Fuji in the distance, sandy beaches and pine trees, will be eroded in two years, whereas it takes 30 years for longshore sand supply to reach this beach. Countermeasures must be taken, without relying on natural sand supply from the upcoast by longshore sand transport which will take for at least 30 years. Severe beach erosion began at the time of large-scale river bed excavation conducted before 1967 in the Abe River which is the source of littoral sand, and beach erosion has a propagation mode of erosion waves. Measures combining the construction of headlands to stabilize the natural sandy beach with beach nourishment should be taken immediately.

I. INTRODUCTION

In recent years, shoreline change of a wavy mode has been extensively studied. Such shoreline changes are classified into the longshore sand waves discussed by Thevenot and Kraus (1995) and a type in which the wavelike shoreline propagates alongshore while keeping its form. In addition, there are various names for the longshore sand waves. Sonu (1968) called them cusp-type sand waves, Bruun (1954) and Grove et al. (1987) migrating sand humps, Inman (1987) accretion and erosion waves, and Verhagen (1989) simply sand waves. In particular, the accretion and erosion waves reported by Inman (1987) are produced when a coastal structure such as a groin is installed or the sediment supply from a river or the source of littoral drift is sharply increased due to flooding, and they propagate along the coastline, accompanied by weak diffusion. Uda and Yamamoto (1994) and Uda et al. (1996) investigated this phenomenon of a longshore movement of a large mass of sediment (hereinafter called sand body), analogous to a soliton, along the Shizuoka coast in Japan and concluded that this sand body movement was triggered by the trapping effect of sand supplied from the Abe River by detached

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breakwaters built along this coast, by using a contour line change model.

On the other hand, before the propagation of this positive wave along the Shizuoka coast, it was also found that an erosion wave with the phase velocity of 0.5-0.8km/yr propagated (Uda and Yamamoto, 1994). Presently, this erosion wave is approaching the northeastern end of the Shimizu coast, the famous viewpoint called "Hagoromo-no-matsu" where a sandy beach with pine trees and a backdrop of Mt. Fuji provides a scenic view. "Hagoromo-no-matsu" means a pinc tree on which a young lady has draped her clothes. This study is aimed at investigating beach changes associated with the propagation of these erosion and accretion waves occurring along the Shizuoka and Shimizu coasts, with special attention paid to the preservation of this beach.

II. FIELD OBSERVATION OF EROSION AND ACCRETION WAVES ALONG SHIZUOKA AND SHIMIZU COASTS

(1) General

Figurc 1 shows thc location of the Shizuoka and Shimizu coasts situated on the outer margin of the Mihono-matsubara sand spit on thc west shore of Suruga Bay. Suruga Bay opens south to the Pacific Ocean and rough waves are incident from the south. Sinee the coastline runs southwest to northeast, as shown in Fig.1,

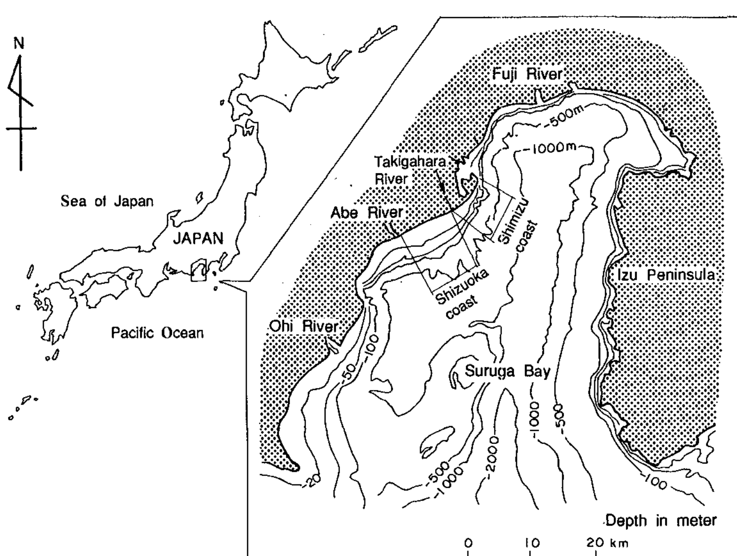

Fig.1 Location of thc Shizuoka and Shimizu coasts in Suruga Bay facing the Pacific Ocean.

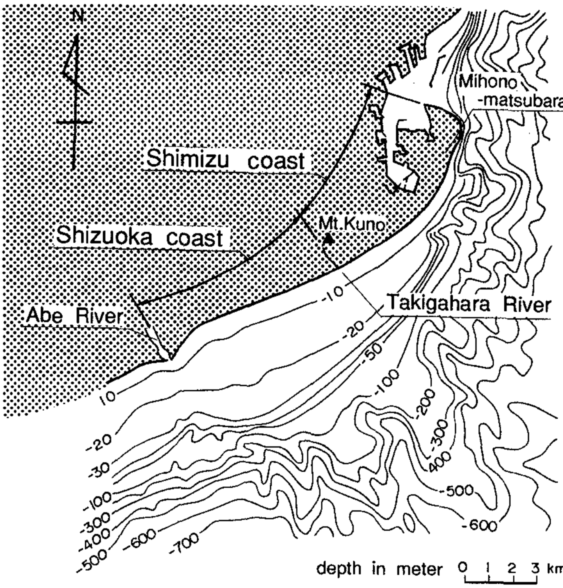

Fig.2 Sea bottom contours off Shizuoka and Shimizu coasts.

northeastward longshore sand transport prevails along these coasts. The Shizuoka coast extends 7.8km northeastward from the Abe River mouth to the mouth of the Takigahara River and the 9.8km coastline from this river mouth to the tip of the sand spit is called the Shimizu coast. Figure 2 shows the sea bottom contours off the Shizuoka and Shimizu coasts. Here, the beach slope near the shoreline is as steep as 1/10. A continental shelf of mild slope of 1/150 is spread along the offshore zone ranging from 10m to 30m in depth, but the sea bottom slope at the tip of the Mihono-matsubara sand spit is steep at about 1/5.

It is considered that during the Jomon Transgression of the sea level about 6,000 years ago, erosion of the side of Mt. Kuno, as shown in Fig.2, supplied sediment to the Mihono-matsubara sand spit, but at the present sea level, the only source of sediment to the sand spit is the Abe River. River bed excavation was carried out extensively before 1968 in the Abe River, causing a sharp decrease in fluvial sand supply from this river, and the dynamic balance of longshore sand transport was lost, giving rise to the northeastward extension of the eroded area from the river mouth. Uda and Yamamoto (1994) revealed that the erosion wave propagated at 0.8km/yr in the period between 1975 and 1983 and 0.5km/yr between 1983 and 1988 along the Shizuoka coast. At present, the most severely eroded portion of the beach is near the tip of the Mihono-matsubara sand spit at the northeastern end of the Shimizu coast. Most of the sediment transported by northeastward longshore sand transport discharges into the submarine canyon located at the northeastern end of the Shimizu coast.

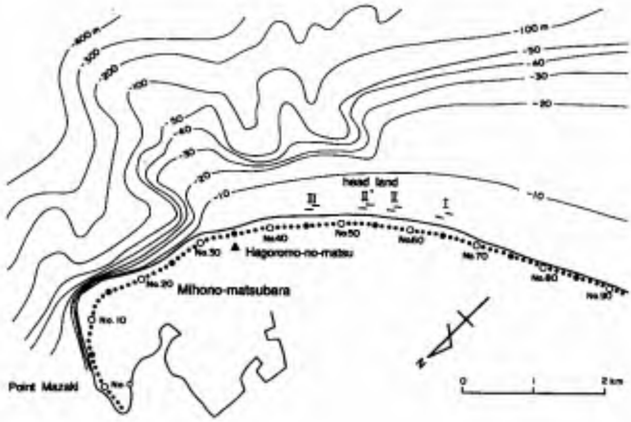

Fig.3 Detailed sea bottom contours off Shimizu coast and alignment of measuring lines.

Photo.1 Sandy beach, Mt. Fuji and pine trees at Hagoromo-no-matsu on February 10, 1995 taken at a point No.35.

Figure 3 shows the sea bottom topography around the tip of the Mihono-matsubara sand spit, as well as the alignment of measuring lines on the Shimizu coast. In this area, sea bottom surveys have been conducted once a year in March since 1988. The interval of measuring lines is 100m. The origin of the measuring lines is located at a point No.0 at Mazaki at the tip of the sand spit and measuring lines are set alongshore southwestward. In Fig.3 the turning point of the shoreline is located at a point No.12, and there exists a submarine canyon between points No.12 and No.30. The beach slope is very steep around this submarine canyon. Hagoromo-no-matsu, as shown in Photograph 1, is located at a point No.35. According to the sampling test of bottom materials conducted at nine points at 1km intervals alongshore from the Abe River mouth on February 20, 1989, the median diameter of beach materials near the shoreline of the Shizuoka coast is around 7.5mm.

(2) Changes in Shoreline Configuration and Sand Volume of Shizuoka and Shimizu Coasts

Figure 4 shows the shoreline change of the Shizuoka and Shimizu coasts with reference to the shoreline position in 1983 obtained from the sea bottom surveys. The Abe River mouth is located at the right end of the figure, and the left end is the tip of Mihono-matsubara sand spit called Masaki Point. The Shizuoka and Shimizu coasts are separated by the mouth of the Takigahara River. Along the Shizuoka coast, a sand body formed by sand accumulation moves northward (leftward in the figure) with time and its propagation velocity is around 250 m/yr, as shown in Fig.4. Uda et al. (1996) showed that the propagation velocity of the leading edge of this sand body between 1984 and 1993 was 233m/yr. The value obtained in the present study is slightly larger due to the selection of a longer comparison period.

The shoreline of the Shizuoka coast was totally covered by concrete armor units before the propagation of the sand body and there existed no sandy beaches, which means an absence of littoral sand to be transported alongshore. The sand body was considered to be moving northeastward, while sand was also covering the concrete armor units set along the shoreline, since a large amount of sediment was supplied from the mouth of the Abe River located at the southwestern boundary of the coast. Furthermore, Uda et al. (1996) revealed, by numerical simulation using "the contour line change model", that the movement of the sand body was triggered by

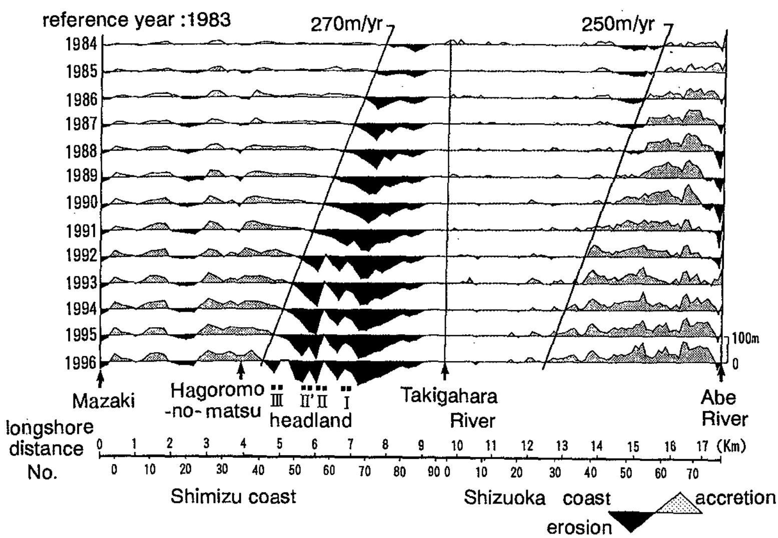

Fig.4 Shoreline changes along the Shizuoka and Shimizu coasts showing the propagation of erosion and accretion waves. The propagation velocities of erosion and accretion waves are around 270m/yr and 250m/yr, respectively.

Photo.2 Coastline totally covered by seawall and concrete armor units on the Shimizu coast. This picture was taken in July, 1995. The river flowing into the sea is the Takigahara River, which separates the Shizuoka and Shimizu coasts. These coastal structures were built to protect farmland just behind the seawall.

Photo.3 Coastline protected by a continuous seawall, concrete armor units and a number of detached breakwaters further north of the location shown in Photograph 2 on the Shimizu coast.

the blocking effect of longshore sand transport due to the presence of a number of detached breakwaters constructed off the coastline.

Along the coast between the location of longshore distance of around 12.5km, which the leading edge of the sand body reached in 1996, and the location around 0.5km north of the mouth of the Takigahara River, no shoreline change is observed because this area is totally covered by concrete armor units, as shown in Photographs 2 and 3.

Along the Shimizu coast, beach erosion has clearly occurred since 1983. Shoreline recession first began from the location of around 9km and extended northeastward with time, approaching Hagoromo-no-matsu in 1996. Beach erosion along the Shizuoka coast was originally triggered by a sharp decrease in fluvial sand supply from the Abe River due to large-scale river bed excavation to obtain construction materials in the period around 1970, and it propagated from the Shizuoka coast to the Shimizu coast (Uda and Yamamoto, 1994). Presently it is approaching the tip of the Mihono-matsubara sand spit. Shoreline change of a zigzag type have occurred after the construction of headlands using two sets of detached breakwaters built as a countermeasure against beach erosion, as shown in Photographs 4, 5 and 6. The eroded zone is monotonously extending northward and its propagation velocity is around 270 m/yr. This propagation velocity is comparable to the propagation velocity (250m/yr) of the sand body on the

Photo.4 The shoreline around detached breakwaters I. A couple of detached breakwaters were built alongshore. The offshore distance of the detached breakwater downcoast is close to the original shoreline. Large cuspate foreland was formed behind the upcoast detached breakwater.

Photo.5 The shoreline downcoast of detached breakwaters II'. Downcoast erosion was so severe that beach nourishment is being conducted, as shown in the photograph of the most severely eroded location.

Photo.6 The shoreline around detached breakwaters III. In this area, the foreshore is still fairly wide.

Shizuoka coast, but with an excess of about 8%. Since the distance between the tip of the eroded zone (No.40) and Hagoromo-no-matsu (No.35) was only 500m in 1996, only two years remain before severe beach erosion reaches Hagoromo-no-matsu, if the propagation velocity of the erosion zone remains unchanged. Uda et al. (1994) determined that the rate of extension of the erosion zone was about 271m/yr on an average in the period between March 1990 and March 1993; this means that the same propagation velocity of the erosive zone has been maintained thereafter.

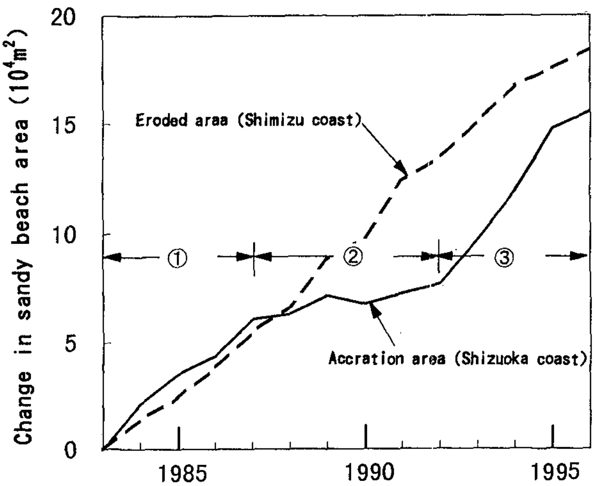

Fig.5 Change with time in eroded and accretion areas along Shizuoka and Shimizu coasts.

Table 1 Flood discharge of Abe River.

year	month	day	average discharge (m^3/s)	maximum discharge (m^3/s)
1982	August	2	1,129	3,857
1982	August	3	1,466	
1982	September	12	1,723	
1983	August	2	1,731	2,981
1985	July	2	1,523	–
1990	August	10	1,005	–
1991	September	2	1,396	2,511

In addition, the north end of the erosive zone was located at a point No.46 in 1993.

The change in foreshore area in the accretion area of the Shizuoka coast and erosion area of the Shimizu coast compared to that in 1983 was calculated and is shown in Fig.5. Along the Shizuoka coast, the rates of increase of the accretion area during each of the three periods shown in Fig.5 differ; the rate of increase was $1.42 \times 10^3 m^2/yr$ in the first period between 1983 and 1987, which decreased by one order of magnitude to $0.44 \times 10^3 m^2/yr$ in the second period between 1987 and 1992, and in the last period between 1992 and 1995, the rate increased to $1.98 \times 10^3 m^2/yr$, larger than that in the first period. The only sand supply to the Shizuoka coast is from the Abe River. In addition, the shoreline north of the tip of the sand deposition zone is covered by a large number of concrete armor units and there are no sandy beaches. This means that this artificially protected coast suffers from a shortage of sand before the arrival of the tip of sand body. Accordingly the only reason for the accretion zone increase as shown in Fig.5 must be due to the sand supplied from the Abe River mouth. Table 1 shows the records of large floods since 1980 at location 4.7km upstream from the river mouth. Daily average flood discharges of $1{,}000 m^3/s$ or larger occurred seven times between 1980 and 1993, as shown in Table 1, and particularly, on September 12, 1982 the flood with the largest discharge of 3,857m^3/s occurred, but thereafter, large-scale floods have rarely occurred. This indicates that the variation in the rate of increase of the foreshore area in the accretion zone of the Shizuoka coast mainly corresponds to the occurrence of large floods that supply largc amounts of sediment to the coast.

Along the Shimizu coast, the eroded area monotonously increased from 1983 to 1996 at the rate of 1.42x10^3m^2/yr, as shown in Fig.5. This rate is approximately equal to that in the first period along the Shizuoka coast. The long-term rate of increase of the foreshore area of the Shizuoka coast between 1983 and 1996 became 1.21x10^3m^2/yr, although there are short-term variations in this rate, as shown in Fig.5. This value is only 14% smaller than that obtained on the Shimizu coast. This indicates that the foreshore area exhibits a large variation along the Shizuoka coast in the area next to the river mouth depending on the variation in the amount of river sediment discharge, but along the Shimizu coast located far from the river mouth, such a variation is minimal and monotonous change is dominant, resulting in a smooth shoreline change.

Along the Shizuoka and Shimizu coasts, the shoreline change correlates well with the change in cross-sectional area of the beaches, and the regression coefficient between these parameters gives characteristic heights of beach changes of 7.7m and 7.2m on the Shizuoka and Shimizu coasts, respectively (Uda and Yamamoto, 1994). The changes in foreshore area were multiplied by the characteristic height of beach changes to calculate the change in sand volume due to erosion and accretion. Since the coast near the boundary between the Shizuoka and Shimizu coasts is totally covered by concrete armor units and there exists no sandy foreshore as shown in Photographs 3 and 4, longshore sand transport passing this location is assumed to be 0. Accordingly, calculated change in sand volume is approximately equal to the inflow or outflow rate of longshore sand transport to the examination zone from the continuity condition of sand mass. Table 2 is the results of the calculation in each period. Inflow rate of longshore sand transport to the Shizuoka coast has a considerably large variation and it varies from 3.4x10^4 m^3/yr to 15.2x10^4m^3/yr. Average rate of longshore sand transport is found to be 10.1x10^4m^3/yr. In contrast, the rate of longshore sand transport on the Shimizu coast has an approximately constant value of 10.2x10^4m^3/yr.

Figure 6 shows temporal change in sand volume calculated by multiplying the decrease of the foreshore area in the region between No.55 and No.85 by the characteristic height of beach changes of 7.2m. The reference year is taken in 1983 the same as that in Fig.5. In

Table 2 Longshore sand transport rates on Shizuoka and Shimizu coasts.

coast	duration	change in foreshore area ($\times 10^4 m^2/yr$)	characteristic height of beach changes (m)	longshore sand transport rate ($\times 10^4 m^3/yr$)
Shimizu	1983~1996	1.42	7.2	10.2
Shizuoka	1983~1987	1.53	7.7	11.8
	1987~1992	0.44		3.4
	1992~1995	1.98		15.2
	1983~1996	1.21		9.2

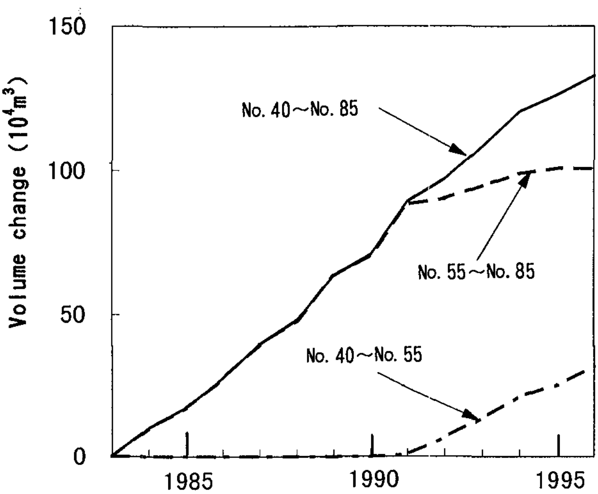

Fig.6 Change in sand volume with time in the regions between No.55 and No.85, and between No.44 and No.55 along the Shimizu coast.

Fig.5 it was clear that total volume of sand in the erosion zone on the Shimizu coast had increased monotonously since 1983. However, precise examination of the change in sand volume in each zone in Fig.6 gives another features. Eroded sand volume in the region between No.55 and No.85 attains to an equilibrium state after it increased up to 1991, wbereas the eroded sand volume in the zone between No.40 and No.55 increased after 1991 at a rate of increase equal to the increase rate of the eroded area along the entire Shimizu coast. This means that the construction of a headland using a couple of detached breakwaters prevents further beach erosion at tbe site but instead, the erosion zone extends further downwards.

In short, accretion and erosion waves were triggered by the imbalance in these longshore sand transport rates. In Fig.4, Hagoromo-no-matsu was about 7.9km from the tip of the sand body (x=12.5km) in 1996 and therefore it should take 30 years for thc tip of the sand body to reach the most severely eroded location of Hagoromo-no-matsu, if the movement of the sand body takes place in an unchanging manner. During this period, natural sand supply by longshore sand transport cannot be expected along the Shimizu coast and tberefore, it is necessary to effectively utilize the sand existing along the coast. This period is a long time compared with tbat required for erosion waves to reach north tip of the Shimizu coast. During this period, measures to stabilize the shoreline must be taken without relying on sand supply from upcoast. Beacb nourisbmcnt is onc of the possiblc measures, but the longshore sand transport along this coast is around $10x10^4m^3/yr$, with ultimatc discharge into the deep ocean tbrougb tbe submarine canyon locatcd at the tip of sand spit, implying that beach nourishment only is not a sufficient mcasure.

III. BEACH PROFILE CHANGES ALONG SHIMIZU COAST

Beach profile changes are investigated in detail along several measuring lines where large shoreline recession was observed in Fig.4. As typical measuring lines, four lines are selected: No.44 located north of the group of detached breakwaters III very close to Hagoromo-no-matsu, No.50 located between detached breakwaters II and II', No.55 located north of detached breakwaters II, and No.62 to the north of detached breakwaters I which was built the earliest.

Figure 7 shows the beach profile changes along No.44. The beach profile in 1985 is selected as a reference and beach profiles after this year are shifted along the vertical axis. At this location, accretion prevailed until 1995, corresponding to the shoreline advance in comparison with the beach profile in 1985, but beach erosion became dominant in 1996 in the zone shallower than -4m. At No.50 0.6km south of survey line No.44, intense beach erosion has taken place since 1992, as shown in Fig.8. In this case it should be noted that the beach profile change at around 1994, as shown in Fig.8, is very similar to that in 1996 in Fig.7, implying that recession of the beach extended gradually alongshore while maintaining almost the same profile.

Figure 9 shows the beach profile changes along No.55. As shown in Fig.4, the shoreline retreated considerably until 1994 in the vicinity of this measuring line (No.55) because detached breakwaters II' were constructed between detached breakwaters II and III. Depending on this shoreline change, the beach was eroded until 1994 but thereafter, sand accumulated again until 1996 and almost the same beach profile as in 1993 was recovered. Re-accretion occurred at No.55 due to the sand accumulation effect of the detached breakwaters constructed immediately downcoast.

Figure 10 shows the beach profile changes at No.62. Severe beach erosion can be observed in the profile after 1989, corresponding to the extensive shoreline recession shown in Fig.4. It is noted that the time when beach erosion became dominant at this location was 8 years before the initiation of beach erosion at No.44 located 1.8km north of No.62. In addition, it is found that an upward convex profile near the shoreline reduced to a concave profile, because the sea bed in the zone shallower than -6m was eroded as a result of beach erosion.

The beach profile changes mentioned above are similar to each other except in terms of the initiation time of beach erosion. As mentioned earlier, only two years remain before the shoreline recession zone reaches Hagoromo-no-matsu. After that, the shoreline profile is predicted to become steep, as shown in Figs.8, 9 and 10.

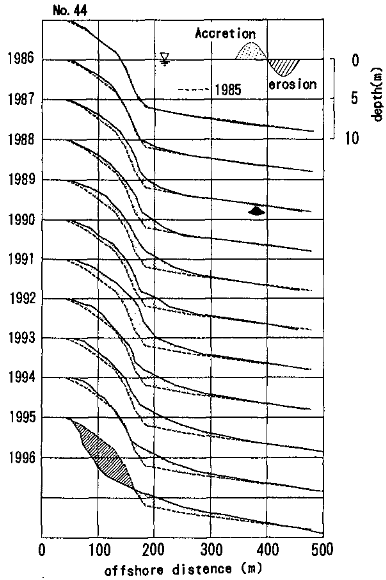

Fig.7 Profile changes along No.44.

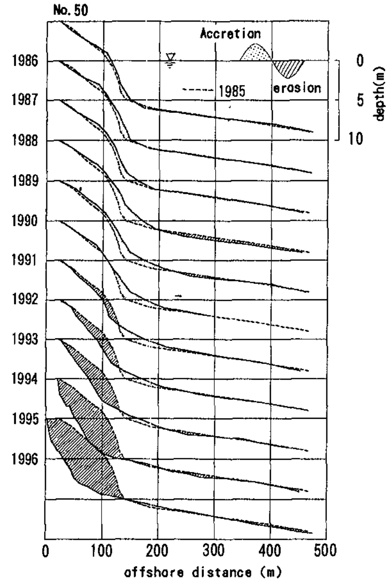

Fig.8 Profile changes along No.50.

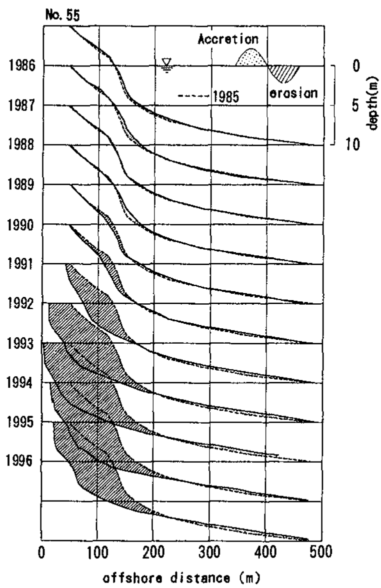

Fig.9 Profile changes along No.55.

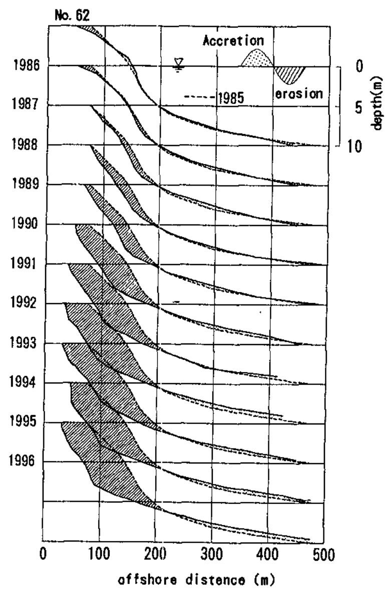

Fig.10 Profile changes along No.62.

IV. TOPOGRAPHIC CHANGES AROUND DETACHED BREAKWATERS

Since dominant beach changes along the Shimizu coast can be observed in the area between No.40 and No.60, as shown in Fig.4, beach changes in this area from March 1992 to March 1996 are invcstigated in detail through a comparison of bathymetric survey maps. Figure 11(a) shows the sea bottom topography in March 1992. At this time, northeastward longshore sand transport was partly blocked by detached breakwaters II located at around No.57 and No.58 and therefore, sea bottom contours shallower than -3m became concave at the northeast end of the detached breakwaters, whereas the contours far from this area were straight. In contrast, on the southwest side of the detached breakwaters, the shoreline connects smoothly to the detached breakwaters and offshore contours hetween -4m and -6m protrude off the detached breakwaters, implying that some longshore sand transport is discharged downdriftward while passing around the detached breakwaters, since longshore sand transport is blocked by the detached breakwaters.

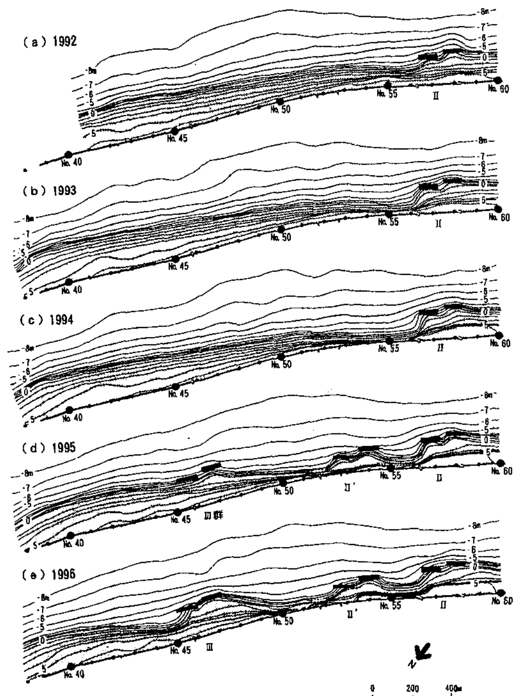

Fig.11 Sea bottom changes around the detached breakwaters between March 1992 and March 1996.

In March 1993, as shown in Fig.11(b), sea bottom contours in the vicinity of No.55 became further concave and the foot depth in front of the seawall considerably increased. In March 1994, as shown in Fig.11(c), according to the dense contours near the shoreline, the seawall was directly exposed to sea waves in the vicinity of No.55, and also, a steep scarp between No.55 and No.51 was formed. Beach erosion near No.55 was so severe as to cause the failure of the seawall such that not only the detached breakwaters III were set in the vicinity of No.46 but detached breakwaters II' were also constructed at No.53 to prevent further beach erosion. As a result, the foreshore was widened near No.53, as shown in Fig.11(d) and the seawall was protected against scouring. The shoreline north of detached breakwaters II' is considerably stable because the shoreline is fixed at detached breakwaters III. By contrast, shoreline recession has begun northeast of detached breakwaters III.

Figure 11(e) shows the sea bottom topography in March 1996. A stepped shoreline was formed due to the construction of detached breakwaters. However, the contours northeast of detached breakwaters III are still unstable because of the open boundary condition and therefore, urgent measures to stabilize the shoreline in front of this area should be adopted by constructing a facility to stabilize the shorelinc, such as a groin or detached breakwaters downcoast of this point. As shown in Photograph 1 taken at a point No.35, a snowcapped Mt. Fuji in the distance beyond the sandy beach and pine trees produce a beautiful scene, so that the disappearance of the sandy beach is considered to be a definite damage to this coast.

V. CONCLUSIONS

Distinct propagation of crosion and accretion waves was revealed along the Shizuoka and Shimizu coasts facing Suruga Bay. Their propagation velocities are 270m/yr and 250m/yr, respectively. It was found that the famous scenic beach called "Hagoromo-no-matsu", will be eroded in two years, whereas it takes 30 years for longshore sand supply to reach this bcach. Therefore, countermeasures must be taken without relying on natural sand supply from upcoast by longshore sand transport for at least 30 years. Furthermorc, taking into consideration that such severe beach erosion dates from the large-scale river bed excavation of the Abe River conducted before 1968 and that it has a propagation mode of an erosion wave, it can be said that beach erosion along the Shimizu coast is inevitable. Measures combining the construction of headlands to stabilize the natural sandy beach, with beach nourishment should be adopted immediately.

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