BEACH EROSION AROUND A SAND SPIT
–An Example of Mihono-Matsubara Sand Spit–

Takaaki Uda[1] and Koji Yamamoto[2]

Abstract

Topographic changes around Mihono-Matsubara Sand Spit were studied based on bottom sounding data and aerial photographs. On the Shizuoka and Shimizu coasts located upcoast of the sand spit, erosion waves are generated due to interruption of longshore sand transport by the construction of coastal structures. The propagating velocity of these erosion waves was found to range from 0.5 to 0.8km/yr. This agrees considerably well with the theoretically estimated value of 0.47km/yr. Comparison of beach profiles showed that the dominant beach changes take place at depths shallower than $-7m$, and this provides the closure depth for profile changes on this coast. The longshore sand transport rate was evaluated to be $1.3 \times 10^5 m^3/yr$ at specific locations on the Shizuoka and Shimizu coasts, and it was found that this transported sand discharges into submarine canyons, forming a steep slope of around 1/2, thus resulting in the net loss of sand from this coast.

1. INTRODUCTION

In general, sand spits form where obliquely incident waves are dominant and a large amount of sediment is supplied from rivers or coastal cliffs to the channel or the bay. Johnson (1919) and Zenkovich (1967) studied the formation process of various kinds of sand spits, focusing on the change in shoreline configuration. In their studies, spit forms were well classified, but the consideration of the relationship between spit formation and ambient bottom profiles, which is of vital importance to wave refraction, was not adequate. From this point of view, Uda and Yamamoto (1986, 1988, 1989, 1991) studied the formation process of sand spits along with the deformation mechanism by comparing data obtained from coasts, lake shores and model experiments with particular emphasis on the relationship between sea bottom topography and sand spit formation.

On the western coasts of Suruga Bay there are several well developed sand spits;

[1]D. Eng., Coastal Eng. Div., Public Works Res. Inst., Ministry of Construction, Ibaraki 305, Japan.
[2]Research Engineer, Ditto.

examples are Mihono-Matsubara Sand Spit and Wadabana Sand Spit on the Suruga coast. Mihono-Matsubara Sand Spit is one of the most famous compound spits, being the largest in Japan, together with the Notsukezaki Spit in eastern Hokkaido. This sand spit was originally formed by northward longshore transport carrying a large amount of sediment supplied from the Abe River. The decrease in sand supply from the river as a result of the excavation of the river bed to obtain construction material caused serious beach erosion around the Abe River mouth after 1965. The area of erosion rapidly expanded northeastward after 1977 and reached further downcoast (Shimizu coast) in 1982 (Toyoshima et al., 1981; Toyoshima, 1984). After 1979 various countermeasures against beach erosion were adopted and related construction work is still underway. No fundamental solution to the erosion problem, however, has yet been obtained. Beach erosion has also in recent years started at the tip of the Mihono-Matsubara Spit. Similar beach changes have been commonly observed at other coasts near sand spits in Japan.

In order to solve the above-mentioned coastal erosion problem, it is necessary to fully understand the topographic characteristics and deformation process of the sand spit. Such beach changes are considered to be different from those of straight coastlines with a gentle bottom slope. From this viewpoint, the present study aims at the investigation of beach erosion and accretion around a sand spit, taking the Shizuoka and Shimizu coasts as typical examples. The results of this case study will be useful when considering measures against beach erosion on other coasts suffering from similar problems. For this purpose, the topographic characteristics and beach deformation around the Mihono-Matsubara Sand Spit are studied using bottom sounding data and aerial photographs (Uda and Yamamoto, 1992).

2. TOPOGRAPHIC CHARACTERISTICS AND WAVE CONDITIONS

The Mihono-Matsubara Sand Spit, a typical compound sand spit in Japan, is located on the west coast of Suruga Bay (Fig. 1). Within the study site, the area of about 7km from the Abe River mouth to the Takigahara River mouth is referred to as the Shizuoka coast, and the 10km from the end of the Shizuoka coast to the tip of Mihono-Matsubara Sand Spit as the Shimizu coast. Suruga Bay is very deep, having the Suruga Trough in the center, and the bottom slope on each shore of the bay is steep. Narrow continental shelves develop only near the alluvial fans of the Abe and Ohi Rivers. The continental shelf off the Abe River mouth has a water depth of about 100 m at its offshore end.

The sea bottom topography near Mihono-Matsubara Sand Spit is illustrated in Fig. 2. The bottom slope at the tip of the sand spit is very steep; it falls to –400m with a slope of about 1/5, and several submarine canyons exist very close to the shoreline. Between the base of the sand spit and the Abe River mouth a gentle slope is found between –10m and –30m depths. The shape of bottom contours deeper than –50m is complicated, and several submarine canyons develop. Figure 2 also shows the arrangement of survey lines. Point No. 0 is located at the tip of the spit, No. 175 is at the left bank of the Abe River mouth, and the survey lines are arranged at 100m intervals from east to west. It is seen from the figure that the shoreline configuration is convex seaward between No. 0
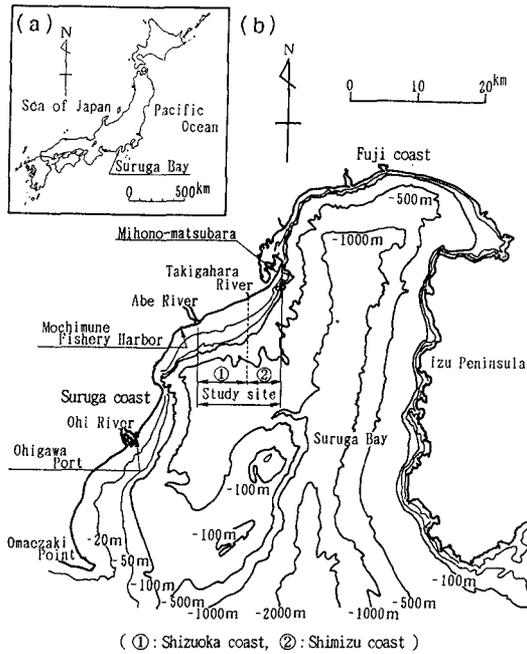
(① : Shizuoka coast, ② : Shimizu coast)

Figure 1. Location of Shizuoka and Shimizu coasts on the western shore of Suruga Bay.

(No.175~No.97 : Shizuoka coast, No.96~No.0 : Shimizu coast)
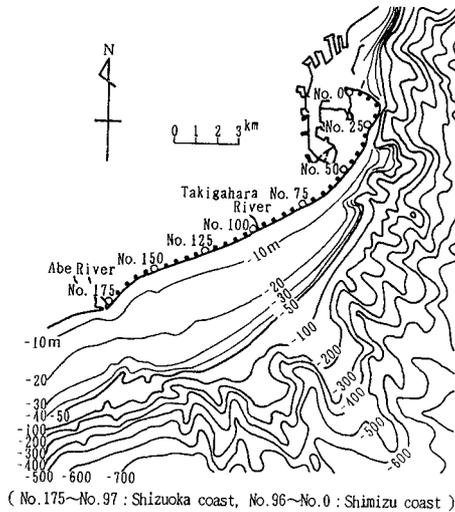
Figure 2. Bottom contours off Shizuoka and Shimizu coasts and alignment of survey lines (No. 0 - No. 175). No. 0 is located at the tip of the sand spit and No.175 at the left bank of the Abe River mouth.

and No. 75, straight between No. 75 and No. 150, and concave seaward between No. 150 and No. 175.

Since no wave observation is performed off this coast, the distributions of wave directions with the classification of wave height obtained by wave observation off Mochimune Fishery Harbor and Ohigawa Port are shown in Fig. 3. These observatory stations are respectively located about 2.5km WSW and 20km SSW from the Abe River mouth, as shown in Fig. 1. It can be seen from Fig. 3 that the predominant wave direction is SSE at Mochimune Fishery Harbor and SE at Ohigawa Port. The energy-averaged significant wave height estimated from Ohigawa Port data from 1967 to 1979 is 0.82m, the mean period is 9.0s, and the dominant wave direction is SE. The direction of the normal to the coastline on the Shizuoka and Shimizu coasts runs SSE through ESE. Therefore, waves from S to SSE are obliquely incident to the coasts, causing northeastward longshore sand transport. According to foreshore sampling conducted in 1989, beach material has a median diameter in the range of 0.3mm to 20mm and specific gravity between 2.67 and 2.72. As for the tide condition, the mean monthly highest water level is T.P. + 0.806m and the mean monthly lowest water level is T.P. –0.733m, where T.P. is the abbreviation of the Tokyo Peil (mean tide level in Tokyo bay).
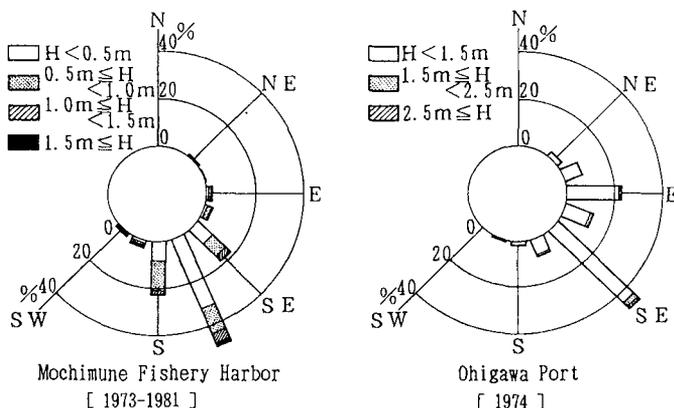

Figure 3. Directional probability of wave occurrence measured off Ohigawa Port and Mochimune Fishery Harbor (For location, see Fig. 1).

3. TOPOGRAPHIC CHANGES OF THE COAST
3.1 Long-Term Change in Shoreline Configuration

Long-term change in shoreline position in the study area was investigated by comparing aerial photographs taken in 1948 and 1987 (Fig. 4). Shoreline position was read from the aerial photographs enlarged to the scale of 1/10000. The beach slope near the shoreline is from 1/5 to 1/10, which is steep enough to neglect shoreline change due to change in tide level. On the Shizuoka coast (No. 175 to No. 97) the shoreline retreated
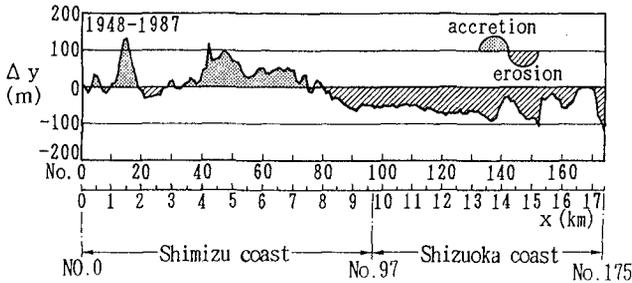
Figure 4. Change in shoreline position between 1948 and 1987 observed from aerial photographs.

approximately 50m on average during the 39 years, while the shoreline apparently advanced on the Shimizu coast located to the east. The shoreline configuration fluctuates considerably between No. 140 and No. 170 because of the accretive effect of the offshore breakwaters built in this area.

The longshore distribution of the annual change in shoreline position determined from soundings off the Shizuoka and Shimizu coasts is shown in Fig. 5, where all soundings were carried out in March unless otherwise indicated in the figure. The longshore distribution of cumulative shoreline change during the entire survey period is also shown at the bottom of the figure. Arrows in the figure indicate the position of the eastern end of the area where wave-dissipating structures were adopted as countermeasures against beach erosion. The area has been extended eastward along the shore from the Abe River mouth.

In 1975, beach erosion began between No. 144 and No. 159. The area where the shoreline retreated moved eastward with time and reached the Shimizu coast in 1983. The mean propagation velocity of the erosion wave, in which the eroded zone propagates downdrift (Inman, 1987), was about 0.8km/yr between 1975 and 1983. In 1988, the eroded area reached the area between No. 59 and No. 80. The propagation velocity of the erosion wave decreased between 1983 and 1988 compared to that between 1975 and 1983, but the area of erosion still extended at a rate of about 0.5km/yr. Inman (1987) suggested that the propagation velocity of the accretion wave, referring to the propagation of the opposite perturbation caused by the sudden release of sand, ranges from 0.5 to 1.5km/yr near Santa Cruz and 0.6 to 1.1km/yr at San Onofre in California. These values are on the same order as in the present study, although the nature of the waves is quite different. It is noted in Fig. 5 that the maximum change in shoreline position at the moving center of mass is around 25m. It should be further noted that, together with the extension of the eroded area, the area covered by the wave-dissipating structures apparently extended. The erosion waves seem to have propagated as a result of the extension of the wave-dissipating measures, but this is not true. In fact, these measures were undertaken at least one year after the onset of beach erosion. This indicates that the countermeasures followed the propagation of the erosion waves.
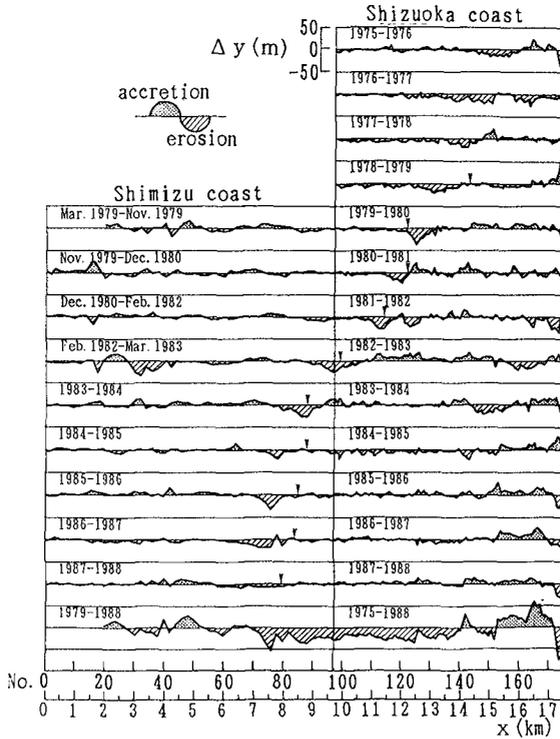
Figure 5. Longshore distribution of annual change in shoreline position between 1975 and 1988 calculated by bottom sounding data. An erosion wave defined by the longshore propagation of the eroded area (shaded zone in the figure) can be observed and its propagation velocity is about 0.8km/yr in the period between 1975 and 1973, and about 0.5km/yr between 1983 and 1988.

3.2 Longshore Changes in Sea Bottom Topography

In order to investigate the topographic features of the Shizuoka and Shimizu coasts, the longshore distribution of the offshore distance from the reference point to 0 to −10m contour lines was obtained from the bottom sounding data taken in 1988 and is summarized in Fig. 6.

Between No. 75 and No. 175, the intervals between 0 to −5m contour lines are considerably narrow, and the bottom slope of this area is 1/10 to 1/15. The intervals between −5 to −10m contour lines further offshore are much wider, the bottom slope being gentler at 1/90 to 1/125. The gentle bottom slope in the offshore zone is considered to have formed as a result of erosion of a region shallower than the closure depth for profile changes, which is associated with shoreline recession. On the other hand, the shoreline configuration is very similar to the shape of contour lines up to −7m. This suggests that the beach profiles near the shoreline move in parallel and that the profile
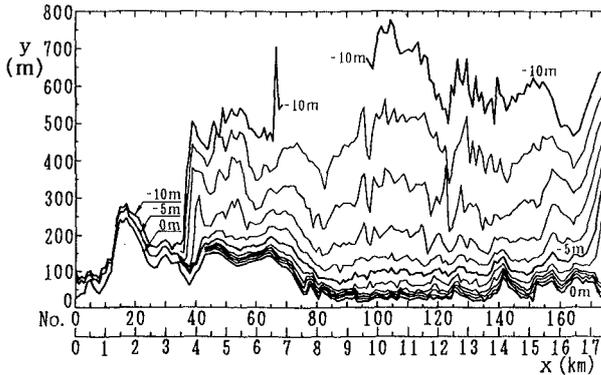
Figure 6. Longshore distribution of offshore distance from a reference point to some contour lines along the study area observed in 1988.

changes are caused by longshore sand transport.

Between No. 35 and No. 75 close to the Mihono-Matsubara Sand Spit, the intervals between 0 to −5m contour lines are narrow, similarly to the case of the western coast, and the bottom slope is about 1/10, whereas the intervals between −5 to −10m contour lines suddenly decrease from No. 40. The intervals between 0 to −10 m contour lines at the tip of the Mihono-Matsubara Spit (No. 0 to No. 35) are very short, and the bottom slope is steep at about 1/5.

The comparison of the bottom topography of these three areas with the change in shoreline configuration between 1948 to 1987, as shown in Fig. 4, explains that the topographic features of the sea bottom and the change in shoreline configuration correspond well to each other; that is, a gentle offshore slope is formed between No. 75 and No. 175, where the shoreline retreated in recent years, and a steep slope is formed between No. 10 and No. 20 near the tip of the sand spit, where the shoreline greatly advanced. From these characteristics it should be noted that Fig. 6 shows not only the present topography, but also contains information relating to the topographic changes during beach deformation.

3.3 Comparison of Beach Profiles

Two typical profiles along survey line Nos. 122 and 142 on the Shizuoka coast were selected for investigation of long-term profile changes. First, the profile changes at No. 142 are shown in Fig. 7, in which the reference year is selected as 1975. The beach had been severely eroded by 1980 to yield the concave profile upward. Thereafter, sediment accumulated and the beach slope became gentle. Because a group of detached breakwaters was constructed east of this survey line after 1980, eastward longshore sand transport was blocked. This is the cause of accretion on the survey line. Figure 7 indicates that the closure depth for profile changes associated with beach erosion or accretion is about −7 m.
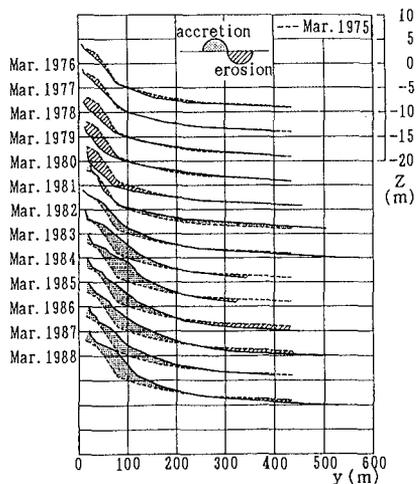
Figure 7. Temporal changes in beach profiles at No. 142. Beach was eroded severely up to 1980, leading to a concave profile near the shoreline, and beach slope became gentle due to sand accumulation.
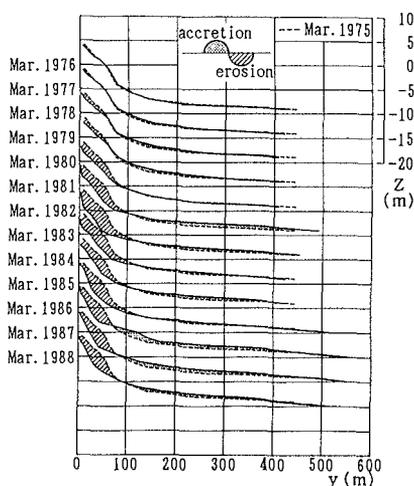
Figure 8. Temporal changes in beach profiles at No. 122. This beach was also eroded severely and a concave beach profile was formed.

The profile change at No. 122 located 2km east of No. 142 is shown in Fig. 8. Along this line, erosion progressed rapidly from 1975 to 1982, and the beach profile became concave upward. It is revealed that the location of the shoreline in 1975 was at a depth of 3~4m in 1982 as a result of the erosion. Two profiles, as mentioned above, show the characteristic features of a very gentle slope existing in the offshore zone. Such a flat bottom was formed by the erosional effect of waves, since the water depth over the slope is almost equal to the closure depth for profile changes. Furthermore, when sand accumulates on the beach, the profile near the shoreline becomes convex; it becomes concave when erosion occurs. This agrees well with the profile characteristics around a sand spit obtained in previous studies by Uda and Yamamoto (1986, 1991).

4. ESTIMATION OF THE LITTORAL TRANSPORT RATE AND PROPAGATION VELOCITY OF EROSION WAVES

Figure 5 reveals considerable advance and retreat of the shoreline position west of No. 42 and wide, gentle offshore slopes were well developed below −7m. Thus, in these areas the closure depth for profile change is considered to be approximately constant. At the tip of the sand spit, sand discharges into the deep ocean, and it is difficult to define the closure depth. Eight survey lines were therefore selected between No. 42 and No. 161; variation in cross sectional area, $\Delta A(m^2)$, and the change in shoreline position, $\Delta y(m)$, were calculated for each profile. The data were examined by means of regression analysis to obtain the following relationship between ΔA and Δy with the

correlation coefficient R=0.87:

$$\Delta A = 11.0\,\Delta y - 19.0 \tag{1}$$

The regression coefficient of ΔA and Δy gives the characteristic height of beach change, h, when topographic change is caused by longshore drift. Figure 9 illustrates the definition of the characteristic height of beach change due to longshore sand transport, where h_C is the closure depth for profile change and h_R the wave run-up height. The characteristic height is often used in the one-line model for shoreline change to relate the change in cross-sectional area to the change in shoreline position. The characteristic height for this coast is thus evaluated as h= 11m.

Based on the above definition, the volume change of the beach can be calculated by multiplying the change in beach area by the characteristic height of beach change. Furthermore, the littoral transport rate can be estimated from the temporal change in sand volume taking into account the continuity condition of littoral transport. With reference to Fig. 5, the littoral transport rate is estimated by selecting the area between No. 70 and No. 85, where the eroded region simply extended from 1984 to 1988 and the area between No. 151 and No. 166, where the accretion progressed in the same period, each area having a length of 1,500m. A great number of wave-dissipating structures were installed west of No. 85, so that sand supply from upcoast is considered to be greatly decreased. On the other hand, between No. 151 and No. 166, the discharge of longshore drift is considered to have been interrupted by the group of detached breakwaters and the jetty of the floodway located at No. 151. Figure 10 shows the cumulative change in beach areas of accretion and erosion since 1984. The area of erosion between No. 70 and No. 85 simply increased with time, and the total increase in four years was $4.5 \times 10^4 \mathrm{m}^2$. The rate of increase is therefore $1.1 \times 10^4 \mathrm{m}^2/\mathrm{yr}$. Similarly, an increase of $5.2 \times 10^4 \mathrm{m}^2$ occurred between No. 151 and No. 166, the rate of increase being $1.3 \times 10^4 \mathrm{m}^2/\mathrm{yr}$. Here
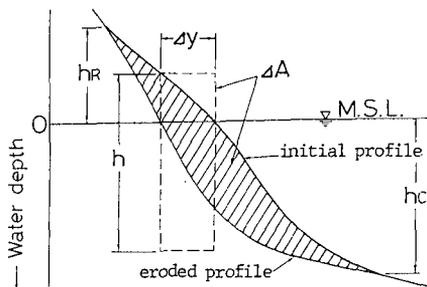

Figure 9. Definition of characteristics height of beach change due to littoral transport (ΔA: increase in cross-sectional area, Δy: the change in shoreline position).
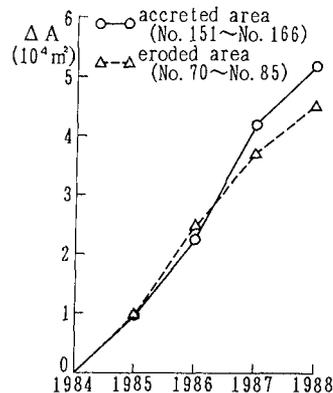

Figure 10. Temporal changes in accreted (No. 151–No. 166) and eroded (No. 70–No. 85) beach areas since 1984.

assumptions that the total amount of sand supplied from upcoast is deposited in the accretion zone and that a constant amount of sand discharges out of the erosion zone without any sand supply were made. The rate of change in Fig. 10 multiplied by the characteristic height of beach change then gives the littoral transport rate. Multiplying by h=11m determined from Eq.(1), the littoral transport rate across No. 70 is evaluated as $1.2 \times 10^5 m^3/yr$ and across No. 166 as $1.4 \times 10^5 m^3/yr$, the average being $1.3 \times 10^5 m^3/yr$. These values are very close, and this indicates that no erosion or accretion occurred as long as continuous longshore drift took place in this range of the coast. This also implies that erosion will begin in the future at the tip of the sand spit because of significant decrease in sand supply.

Inman (1987) defined the propagation velocity of accretion or erosion waves, V, in terms of the longshore sand transport rate Q (m^3/yr) and the volume change q associated with the moving center of mass as

$$V=Q/q. \tag{2}$$

As mentioned above, here, $Q = 1.3 \times 10^5 m^3/yr$ on average. Furthermore, the relation of $q = h \Delta y_{max}$ holds where Δy_{max} is the maximum shoreline change in terms of the moving center of mass. Substituting h=11m and $\Delta y_{max} = 25m$ as obtained from Fig. 5 into this relation, we obtain V= 0.47km/yr, which is comparable to the measured velocity (0.5–0.8km/yr). As shown in Fig. 6, between Points No. 150 and No. 100 the foreshore width is so narrow that the maximum shoreline retreat (y_{max}) is reduced owing to the restriction of the sea wall. This may cause a higher velocity of erosion waves. On the other hand, between Points No.100 and No.60 the foreshore width is sufficiently wide, and this is a possible reason for the agreement between measured and calculated velocities. It is finally concluded that the extension of the area of erosion can be explained well by introducing the concept of erosional waves.

5. BEACH CHANGES IN VICINITY OF TIP OF SAND SPIT

Figure 11 shows sea bottom contours and alignment of survey lines at 100m intervals around the tip of the Mihono-Matsubara Sand Spit. The origin of the survey lines is set at No. 0 at the tip of the sand spit. Steep submarine canyons develop at locations No. 12 through No. 30, No. 36 through No. 44, and No. 48 through No. 54, as shown in Fig. 11, in strong contrast to the development of a wide continental shelf with a gentle bottom slope west of No. 55.

First, the change in shoreline position between No. 47 and No. 71 is shown in Fig. 12 with reference to the shoreline form in 1988. In 1988 the shoreline extended straight north of No.71, where a coastal revetment had been installed to protect the coastline. The shoreline had started to retreat north of this revetment by 1989. The shoreline retreat takes a maximum value at a location beside this revetment, and it gradually decreases eastward with negligibly small change at No. 58. The shoreline change up to 1990 is similar to that measured to 1989, but the shoreline change increased west of No. 62 with a slight recession of the shoreline between No. 50 and No. 58. It is well known that installation of a coastal revetment and wave-dissipating breakwaters at a site updrift of littoral drift simply causes downcoast erosion, requiring further preventive measures
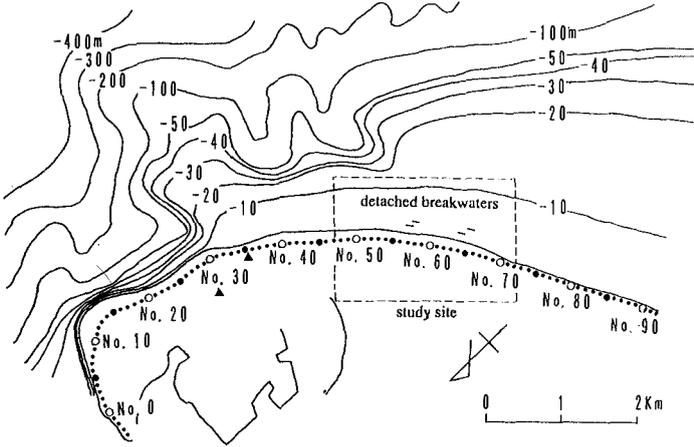
Figure 11. Bottom contours and alignment of survey lines at the tip of the sand spit.
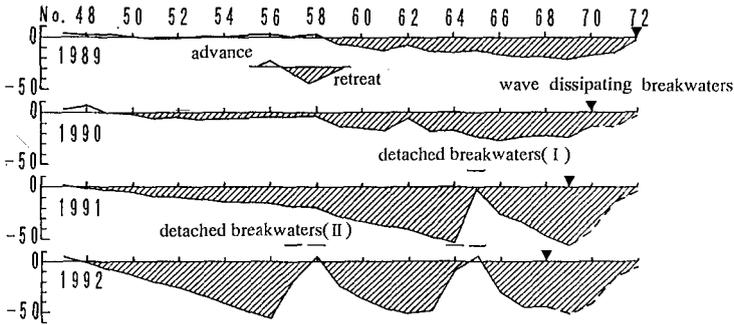
Figure 12. Change in shoreline position between No. 47 and No. 72.

against beach erosion. Recurrence of this process reduces the sandy coastline to an artificial coastline protected by various coastal structures, and the disappearance of natural sandy beaches. On the Shimizu coast, therefore, a method of stabilizing the coastline, in which a set of detached breakwaters is installed in a leap-frog manner at wide intervals, was employed. In 1991 a detached breakwater was installed at No. 65 as part of this plan. Since the detached breakwater blocked northward littoral drift, a step-type shoreline was formed at that location. As expected, downcoast, the shoreline between No. 64 and No. 48 retreated to become triangular. The area of erosion extended eastward about 900m in two years, resulting in the expansion rate of erosion of 0.45 km/yr. This propagation velocity is very close to the value of 0.5 km/yr obtained for the Shizuoka coast between 1983 and 1988, as mentioned earlier. In 1992 two sets of

detached breakwaters with an opening width of 500m were installed. Due to the installation of these detached breakwaters the shoreline between the two sets of detached breakwaters retreated a maximum of about 36m relative to the initial position in 1988, but the recession rate clearly decreased. In contrast the downcoast shoreline retreated in the same manner as the shoreline change observed in 1991.

Here detailed topographic changes around detached breakwaters are investigated. Figure 13 shows the change in sea bottom contours before and after the installation of detached breakwaters. Every contour extended straight alongshore in 1988 before the installation, as shown in Fig. 13(a). The interval between the contours between the shoreline and 4m depth is very narrow, in strong contrast to the gentle slope beyond 5m depth. In 1992 the coastline which was almost straight in the past became step-type form as a result of the installation of detached breakwaters I and II, as shown in Fig. 5(b). Typical topographic features showing the dominance of northward littoral drift can be observed in the vicinity of detached breakwaters 1 and 11. For example, the western shoreline of these detached breakwaters extends straight toward the breakwater, whereas the eastern shoreline has an embayment shape with maximum shoreline retreat at the location beside the detached breakwater.

Mihono-Matsubara Sand Spit protrudes the furthest northeastward at No. 12, as shown in Fig. 11. At this site the sandy beach is very wide, but steep submarine canyons are developed very close to the shoreline. Figure 14 shows the beach profiles measured in 1988 and 1992 along No. 14 through No. 10 in the vicinity of the tip of the spit. At No. 14 sand is deposited up to a depth of 65m to form a steeper slope. A similar feature can be observed at No. 13, showing deposition up to a depth of 65m. The depth of the submarine canyon gradually decreases north of No. 14, and the offshore point of transition of the slope is located at 50m depth at No. 12. Sand is deposited again at No.
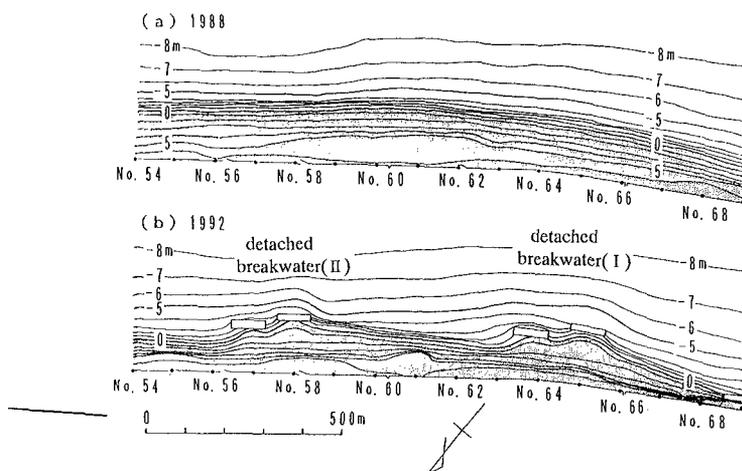

Figure 13. Topographic changes around two sets of detached breakwaters 1 and 11 between 1988 and 1992.
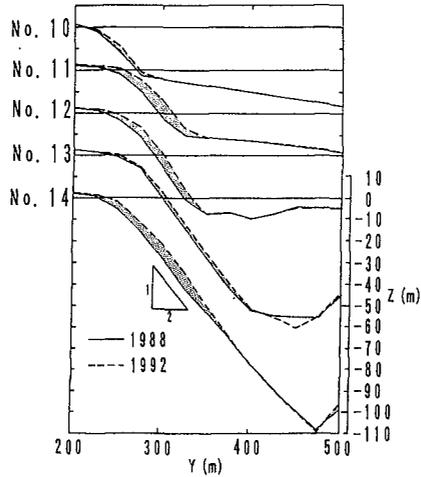
Figure 14. Change in longitudinal profile between 1988 and 1992.

12, while on upward convex profile is maintained. At No. 11 maximum advance of the shoreline position, 16m, is observed.

At No. 10 the point of transition of the slope becomes shallow, 22m depth, compared to the depth at survey lines located south of this line, and sand is deposited only on the steep slope in a zone shallower than 22m depth. It should be noted that sand is deposited up to 70m depth at maximum and 22m depth at minimum in the five beach profiles located in the vicinity of the tip of the sand spit. This is in marked contrast with the fact that the beach was eroded in a region shallower than 7m depth, as mentioned in section 3.2. In the case of beach erosion the shoreline retreats mainly due to the erosion concentrated in a zone shallower than the closure depth of around 7m on this coast, whereas sand discharges into the very deep region, where depth is one order of magnitude greater than the closure depth in the erosion zone, due to the topographic features of the sand spit. This is a very severe problem for this coast, because the total area of accretion becomes much smaller than the area of erosion in comparison to the areal change of the beach, causing net loss in the area of sandy beaches.

Here the change in sand volume of the beaches in accretion and erosion zones is shown in Fig. 15, taking 1988 as the reference year for comparison. As erosion and accretion zones, the area between No. 47 and No. 72 and the area north of No. 47 are selected on the basis of the recent shoreline changes, as shown in Fig. 12. In the erosion zone $5.4 \times 10^5 m^3$ of sand was eroded from 1988 to 1992, resulting in an annual decrease rate of sand volume of $1.35 \times 10^5 m^3/yr$. This is approximately equal to the rate of littoral drift through No. 47, because the coastline west of No. 72 is totally covered by sea walls with concrete armor units at the foot and detached breakwaters, and therefore sand supply from upcoast through No. 72 is assumed to be negligible. This transport rate is very close to the value obtained further upcoast of Shizuoka coast, as discussed in the
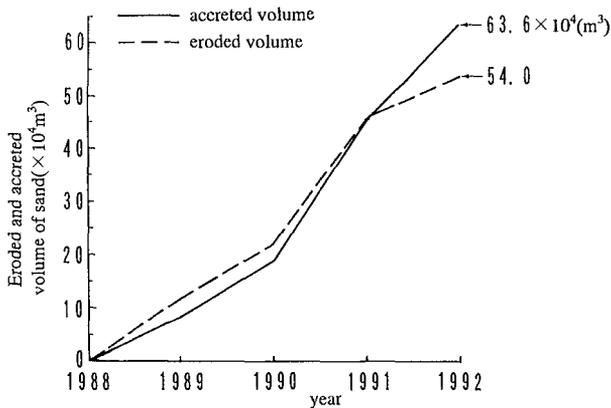
Figure 15. Time change in sand volume in accretion zone north of No. 46 and in erosion zone between No. 47 and No. 72.

previous section.

Total change in accreted sand volume up to 1992 reaches $6.36 \times 10^5 m^3$ which is about 18% greater than total eroded sand volume, $5.4 \times 10^5 m^3$. However, the correspondence between the two results is considered to be fairly good, taking into account that volumetric calculation in the accretion zone is apt to include large error because of the wide calculation zone and because the sand supply through No. 72 by northward littoral drift is a small but non-negligible value.

6. CONCLUSIONS

The principal results of the present study can be summarized as follows.

(1) On the Shizuoka and Shimizu coasts, erosion waves propagated northeastward at a velocity of about 0.8km/yr between 1975 and 1983, and 0.5km/yr between 1983 and 1988. These erosion waves were caused by spatial discontinuity in longshore transport as a result of the installation of various coastal structures. Inman's (1987) method was employed to estimate their propagation velocity as 0.47km/yr, which agrees fairly well with observed values.

(2) A comparison of beach profiles revealed that significant topographic changes occurred in a region shallower than −7m, and it was confirmed that this water depth is approximately equivalent to the closure depth for profile changes on this beach. On the other hand, at the tip of the spit, a large amount of sand transported toward the tip of the spit is discharged and deposited up to a depth of 70m, which is one order of magnitude greater than the closure depth of this coast obtained in the erosion zone, forming a very steep slope of 1/2 due to the topographic features of the sand spit. Thus the occurrence of a net loss of sand toward the deep sea is of vital importance for solving beach erosion problems around a sand spit.

(3) The littoral transport rate was evaluated to be $1.3 \times 10^5 \text{m}^3$/yr near No. 70 and No. 166 on the Shizuoka coast from the temporal change in sand volume of the coast. In a recent erosion zone at the tip of the sand spit $5.4 \times 10^5 \text{m}^3$/yr of sand was eroded between 1988 and 1992, resulting in an annual decrease rate of sand volume of $1.35 \times 10^5 \text{m}^3$/yr, which is close to the approximate rate of northward littoral drift through No. 47. Thus the two estimated values are in good agreement.

ACKNOWLEDGEMENT

REFERENCES

Inman, D.L. (1987): Accretion and erosion waves on beaches, Shore & Beach, Vol. 55, No. 3, 4, pp. 61-64.

Johnson, D.W. (1919): Shore Processes and Shoreline Development, Wiley, New York, 584p. [Facsimile edition: Hafner, New York (1965)].

Toyoshima, O., W. Takahashi and 1. Suzuki (1981): Characteristics of the beach erosion on Shizuoka coast, Proc. 28th Japan. Coastal Eng. Conf., JSCE, pp. 261-265. (in Japanese)

Toyoshima, O.(1984): Beach erosion prevention works with new blocks, Proc. 31st Japan. Coastal Eng. Conf., JSCE, pp. 330-334. (in Japanese)

Uda, T. and K. Yamamoto (1986): Spit formation in lake and bay, Trans., Japan. Geomorpho. Union, Vol.7, pp. 1-22. (in Japanese)

Uda, T. and K. Yamamoto (1988): Formation process of a sand spit: Comparison of the field data with the model test, Trans., Japan. Geomorpho. Union, Vol. 9, pp. 295-307. (in Japanese)

Uda, T. and K. Yamamoto (1989): Topographic changes of Oyazawa-bana Spit on the north shore of Lake Hinuma: 1983 to 1988, Trans., Japan. Geomrpho. Union, Vol. 10, pp. 209-217. (in Japanese)

Uda, T. and K. Yamamoto (1991): Spit formation in lake and bay, Coastal Sediments '91, Vol. 2, pp. 1651-1665.

Uda, T. and K. Yamamoto (1992): Beach changes around a sand spit - The example of Mihono-Matsubara, Coastal Eng. in Japan, Vol. 35, No.1, pp. 111-128.

Zenkovich, V.P. (1967) : Processes of Coastal Development, Oliver & Broyd, Edinburgh, 738p.