The development of sand waves and the maintenance of navigation channels in the Bisanseto Sea

Kazumasa KATOH[1], Hidetoshi KUME[2],
Keiji KUROKI[3] and Junzo HASEGAWA[3]

Abstract

An Inosakinotsugai is a shoal located in the Bisanseto navigation channel, on which are formed sand waves of 100m wavelength. The heights of sand waves develop to be about 5 meters, which makes the water depth shallower than that required for navigation. Authors have analyzed the process of sand wave development by utilizing the sounding data obtained during a period from 1984 to 1996. As a result, it is shown that 1) the sand waves developed faster in the area where the speed of sand accumulation is faster, 2) the sand waves migrated from the both sides of the shoal toward the shoal ridge, and 3) the speed of migration is proportional to the horizontal distance from the ridge. In the maintenance dredging, the developing speed of sand waves must be taken into consideration.

1. Introduction

The Bisanseto navigation channel is the only trunk channel connecting the eastern and the western parts of the Seto Inland Sea and branches off to the southern and the northern channels in the offshore area of Kagawa Prefecture. The connection channel joins the southern and the northern channels near the juncture (Figure 1). As shown in Figure 2, a shoal (called Inosakinotsugai) extends from Mitsugo Island to the northwesterly direction at the depth of less than 20 m, and caldrons greater than the maximum depth of 85m are on the eastern and the western sides. In other words, the seabottom topography from the connecting channel to

1)Port & Harbour Res. Inst., Nagase 3-1-1, Yokosuka, Kanagawa, 239-0826, JAPAN
2)The Overseas Coastal Area Development Institute of Japan (OCDI),
Kazan Bldg., 3-2-4 Kasumigaseki, Chiyoda, Tokyo, 100-0013, JAPAN
3)ECOH co., Kitaueno 2-6-4, Taitou, Tokyo, 110-0014,JAPAN
E-mail:jhasegawa@ecoh.co.jp

the north channel resembles horseback. At the saddle are formed sand waves of about 5 m wave height and 100 m wavelength (Ozasa, 1975). There are several areas in Bisanseto where sand waves are formed at the saddle of the shoal. The problem here is that they are located inside the channel and the sand wave crests develop to the height which decreases the water depth below the required depth for a navigation channel (the northern channel; 19 m, the connection channel; 13 m).

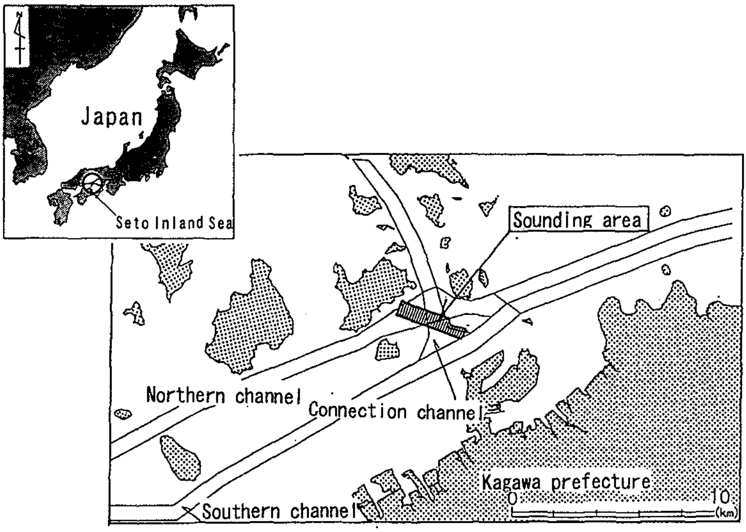

Figure 1. Study Area

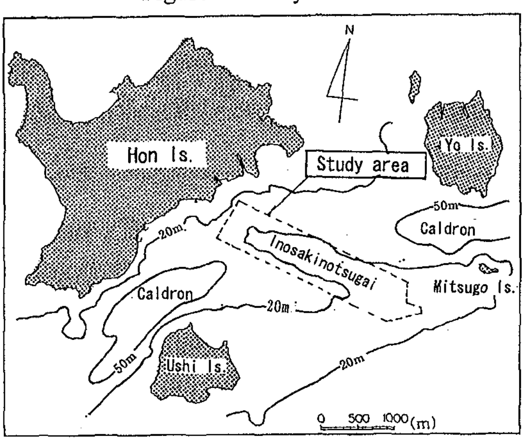

Figure 2. Seabottom Configuration near Inosakinotsugai

During the period between 1981 to 83, about 2.2 million m^3 dredging was performed to remove sand waves. Dredging to 22 m water depth in the north channel and 15 m in the connection channel was conducted by removing the convex portions of the sand waves. During 10 years following this period, sand waves were again formed and have developed to reduce the depth to less than the water depth that should be maintained.

Ozasa (1975) studied in detail the shapes and the mechanism of formation of sand waves at Inosakinotsugai. So, this paper discusses the maintenance of the navigation channels (water depth) in Inosakinotsugai area (Figure 2) and the future needs of maintenance dredging. We utilized the data obtained from the sounding surveys conducted once a year between 1984 (immediately following the dredging) and 1996, and conducted the analysis by converting the data to digital values in 10 m grids.

2. Outline of Sand Waves

Figure 3 shows deviations in the geological features of the seabottom observed in November, 1996 using the average profile of the entire study period as the standard, and shows the sand wave crests with deviations of +1 m and more than +2m. According to the figure, the crests occur successively in the direction from NNW to SSE. The reference lines of A to H are set in the direction perpendicular to the crests. The sand wave cross profiles along these lines are analyzed in Chapter 4.

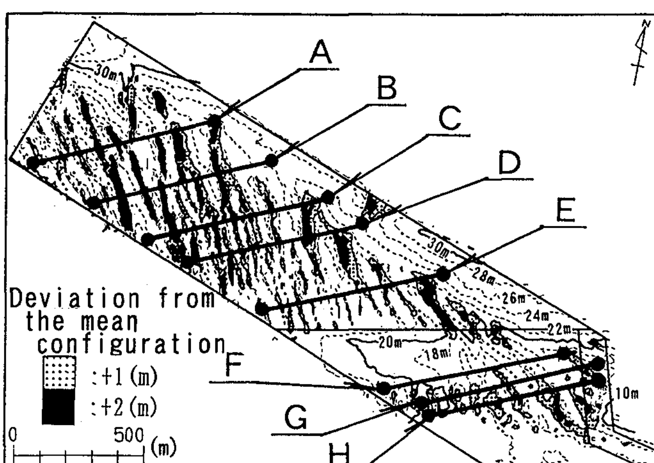

Figure 3. Sand Wave Formation

Ozasa (1975) conducted the sediment surveys, tidal current observations, and diving surveys in the area surrounding Inosakinotsugai. According to his surveys, the median grain size of sediments forming Inosakinotsugai falls within the range of 0.5 to 2.0 mm and tends to become smaller toward the tip (NNE direction) of Inosakinotsugai. The sorting coefficient was more than 2 at the base of Inosakinotsugai and becomes smaller toward the tip (or sorting becomes efficient). These results suggest that the net sand transportation occurs at "Mitsugo Island (the base of the shoal), passes over the shoal, and heads towards the tip of the shoal (see Figure 2)."

The currents are basically in the east-west directions. However, the velocity is different at the time of flood tide and the ebb tide; the flood current (the westerly current) predominates to the north of the shoal, and the ebb current (the easterly current) predominates to the south. Therefore, the crest line of sand waves is essentially normal to the direction of the predominant current.

According to the diver's visual observation, there are many ripples of a scale not sufficiently measurable by the sounding survey (the wavelength 50 to 100 cm, the wave height several cm).

3. Changes in the Depth of Navigation Channels

3.1 Definition of the Minimum Water Depth

Inosakinotsugai area was divided into eight segments as shown in Figure 4. The segments ① through ⑥ in the north channel are set by crossing the crest line of the sand waves at right angle. The areas of the

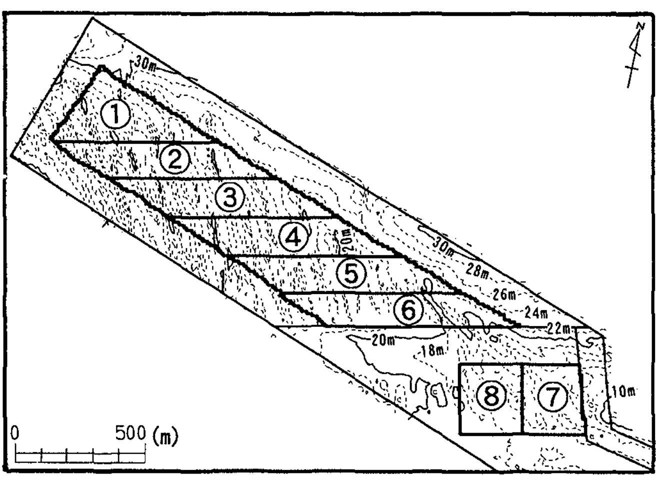

Figure 4. Segments for Water Depth Calculation

segments ① through ⑥ are substantially the same, but those of the segments ⑦ and ⑧ in the connecting channel are about 66% of the former.

The average depth in the segments is calculated for each sounding survey. The water depth above the sand wave crests (the minimum water depth) is important for maintaining the channel depth.

The segment ⑦ became shallower than the maintenance depth earlier than any other segments. The Maritime Safety Agency imposed navigation control in this area in December, 1992. Therefore the minimum water depth was defined based on of the conditions of the segment ⑦ prevailing at the time the control was initiated. Figure 5 shows the grid scores for each year of the water depth data in the segment ⑦ where the water depth is shallower than the maintenance depth of 13 meters. Increases in the grid scores can be approximated by parabolas shown by the dotted line in the figure, which is determined by the method of least squares of the data after 1988. Based on the approximated curve, the grid score of 8.89 for the month immediately preceding the month when the navigation control was imposed, November 1992, was obtained. Thus, the mean of the water depths for the top 9 grids from the shallower depth in the segment was defined as the minimum water depth. Since the area of segments ① through ⑥ is larger than that of ⑦, the number of grids to calculate the minimum water depth must be increased accordingly. However, the number of grids was set at 9 for all the segment in this paper.

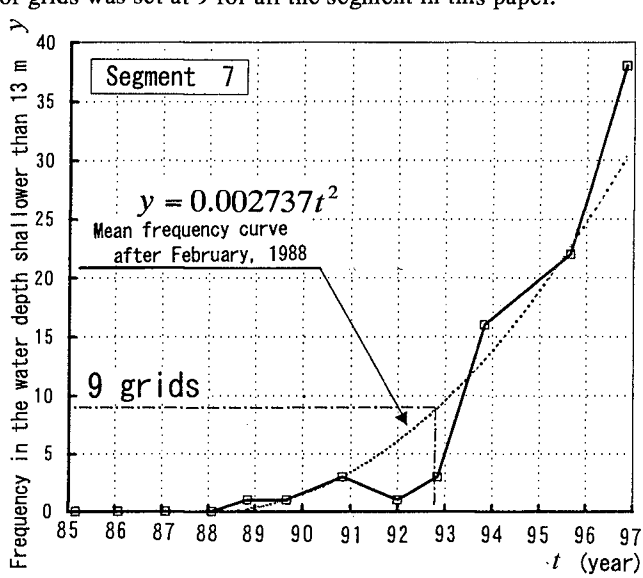

Figure 5. Grid Scores in the Water Shallower than 13 m

3.2 Chronological Changes in Mean and Minimum Water Depths

Figures 6-(1) and 6-(2) show chronological changes in the mean water depth, open circles, and the minimum water depth, solid circles, in the segment ④ on the side of the north channel and the segment ⑦ on the connecting channel side, respectively.

As the mean water depth becomes shallower at a substantially constant rate, the equation (1) is approximated;

$$h = a + bt \qquad (1)$$

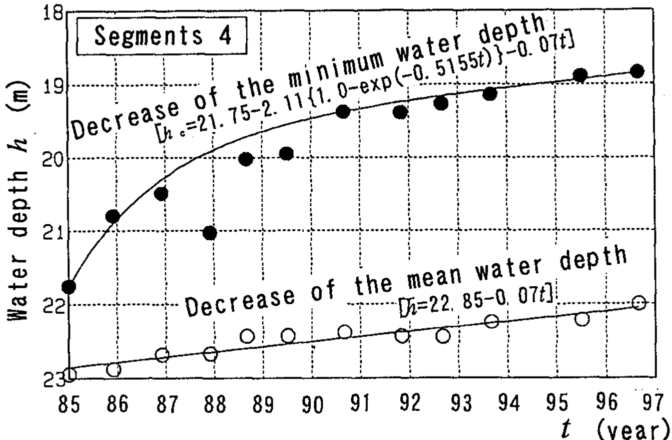

Figure 6(1). Chronological Changes in Mean and Minimum Water Depths (Segment 4)

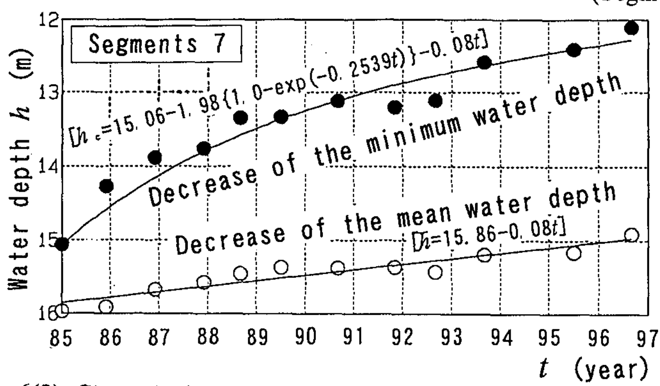

Figure 6(2). Chronological Changes in Mean and Minimum Water Depths (Segment 7) where h is the mean water depth, t is the years after dredging, and a and b coefficients.

On the other hand, variations for the minimum water depth were large in the initial period and the amount of variation tended to decrease with time. This change can be interpreted that the sand waves were formed again after the artificial impact of dredging and developed toward equilibrium. This change can be approximated by exponential function. Provided, however, the change in the minimum water depth included that of the mean water depth, inflow of sand into the segment, the equation (2) is approximated;

$$hc = \alpha\{1 - \exp(\beta x)\} + \gamma + bt \qquad (2)$$

where hc is the minimum water depth, t is the elapsed years after dredging, α, β, γ are constants, α is corresponding to the half wave height of the sand wave which has reached the equilibrium, β is the speed with which the equilibrium is reached, and γ is the initial value of the minimum water depth.

Coefficients for the equations (1) and (2) are obtained by the method of least square. That is to say, the coefficient b in the equation (1) is obtained first, and the value b is substituted in the equation (2) to obtain remaining coefficients. Figure 6 shows the approximate straight line and curve using thus determined coefficients.

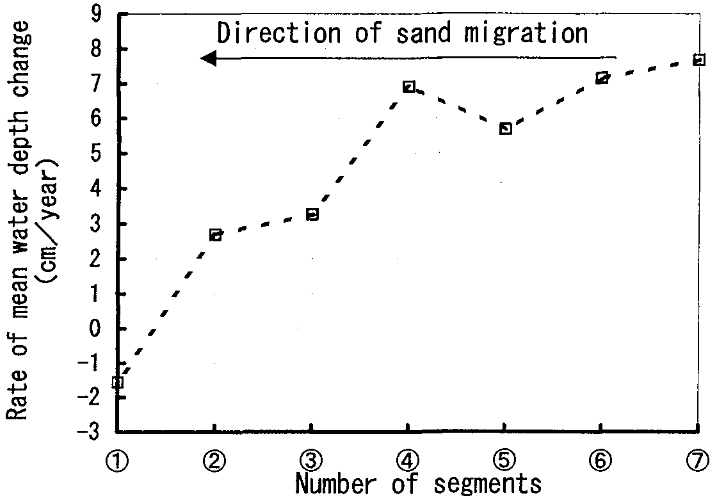

Figure 7. Changes in Mean Water Depth in Segments

Figure 7 shows the speed, the coefficient b in the equation (1), of changes in the mean water depth of the segments ① thorough ⑦. The rate of the mean water depth becoming shallower is faster in the segment ⑦ and becomes gradually slower towards the segment ①. In other words, the rate of accumulation heading from Mitsugo Island toward the tip of Inosakinotsugai decreases and the water depth toward the same direction tends to become larger, indicating that sands are being transported and accumulating in the same direction. This result coincides with the direction of sand transportation inferred by Ozasa (1975) from the plane distribution of the mean grain size and sorting coefficient of sediments. From the rate of accumulation (3 cm/year) in the segment ⑧ (not shown), it is presumed that the sand is being transported from the segment ⑦ toward the segment ⑧ even the quantity is small. Ozasa (1975) assumed similarly in respect of this brunch.

A relation between the rate of accumulation in each segment and the years of sand wave development is plotted in Figure 8. The years of development as used herein is the number of years required to reach 90% of the equilibrium value and is calculated using the coefficient β in the equation ②. The figure shows that the greater the amount of sand flowing into the segment is, the faster the sand waves develop.

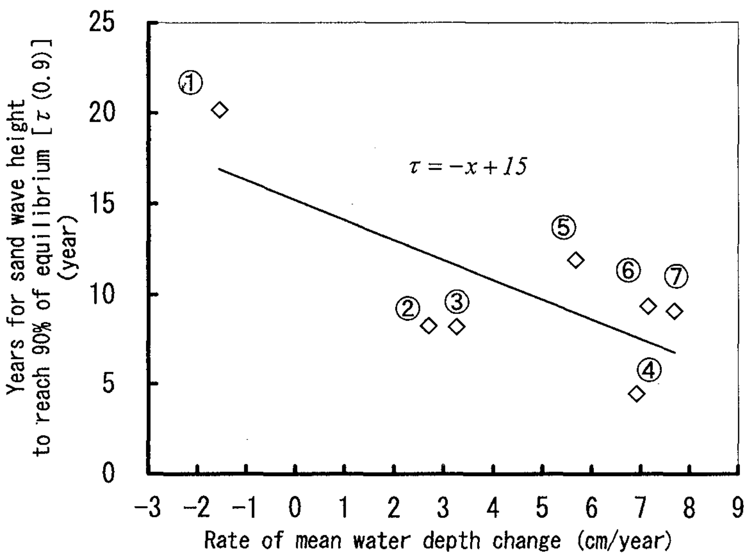

Figure 8. Relation between Accumulation Speed and Sand Wave Development Speed

4. Sand Wave Migration

Figures 9(1) and 9(2) show the transverse profiles of the reference lines A and F in the order of the years measured from the top to the bottom. Provided, however, the profiles are shown as deviations from the average profile during the period shown at the top.

Features of Figure 9 are also observed in respect of other reference lines not shown. The sand wave of 2 to 6 meters wave height and 80 to 180 meters wavelength exist, and when their crest positions, solid circles in the figure, are traced time-wise, they shift toward the top of the shoal as compared with the average profile at the top. The crest migration is approximated as in the solid lines and the rate of migration is calculated.

The migration rates for all the reference lines are plotted in Figure 10, where the horizontal axis is the crest position of sand waves in the median period during analysis as represented by distance from the shoal ridge with the positive direction toward east (to the right in Figure 9). According to this figure, the speed with which the sand wave approaches the shoal ridge is proportional to the horizontal distance, and holds the relation

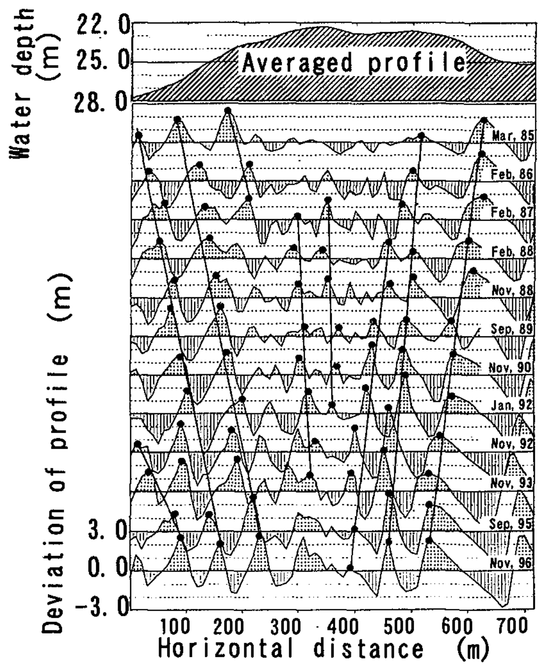

Figure 9(1). Changes in Average Profile and Sand Wave Forms
(Measurement Line A)

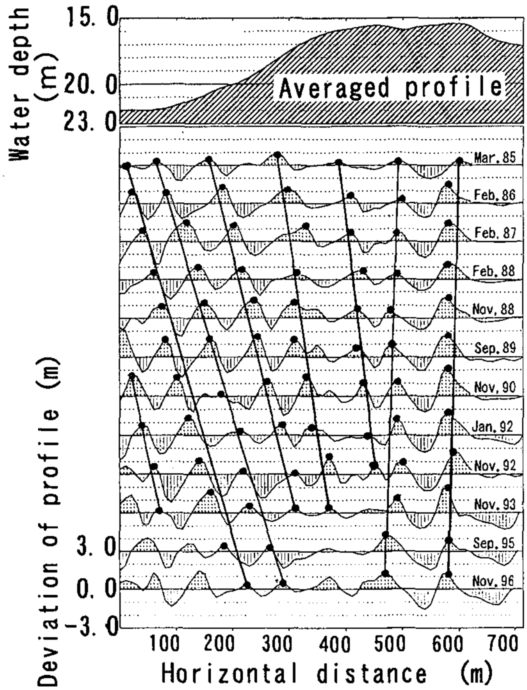

Figure 9(2). Changes in Average Profile and Sand Wave Forms (Measurement Line F)

of v = -0.04·x(m/year) up to 500 m on the horizontal axis. Here, x is in the relative position to the ridge. The data shown by solid circles where the horizontal distance is more than 500 meters are all inside the connection channel and are at the constant speed of 15 m/year.

There are many reports about sand waves migration (such as Harris, 1989). Mogi (1971) reported that the sand waves shift in the direction same as permanent current in long term. As, the westerly current prevails in the north side of Inosakinotsugai and the easterly current prevails in the south side, (Ozasa,1975) suggests that Mogi is correct also in respect of this point. The forms of sand wave observed by Harris (1989) are asymmetrical and sharp in gradient on its migrating side. Based on the above going, Figure 9 is re-examined and the forms of sand wave are recognized to have sloped sharply toward the direction of it's migration.

It is more reasonable to consider that the sand wave migration is not a mere phase shift but accompanies the sand transport in the same direction. The segment analyzed is therefore divided in the cross sectional direction to

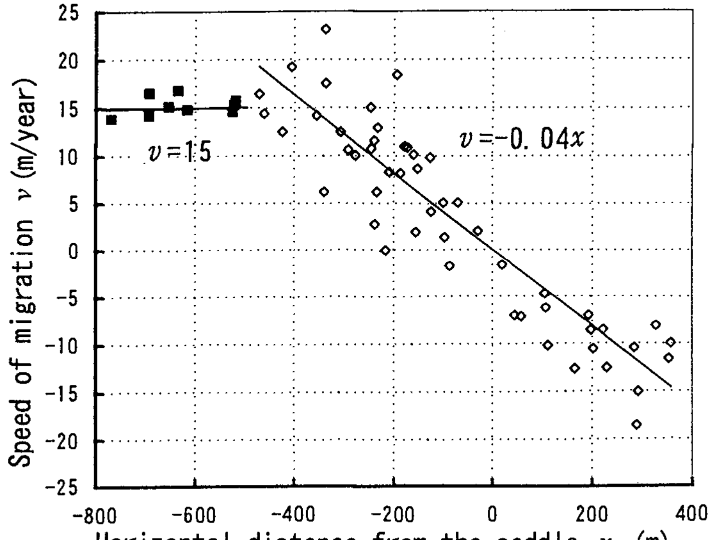

Figure 10. Speed of Migration to the Shoal Ridge

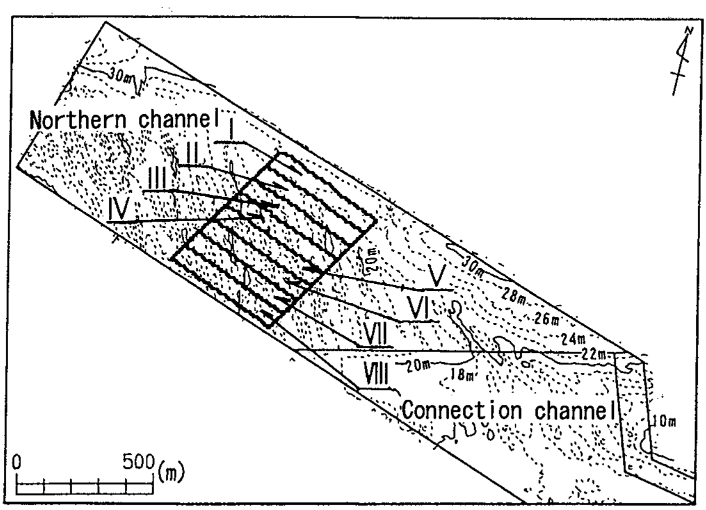

Figure 11. Segments for Calculation

extend the vertical direction of Inosakinotsugai (as shown in Figure 11). The volumes of sand accumulation during the analysis period in each segment are shown in Figure 12. Figure 12 also shows the average profile in the south-north directions at the center of the segment, similarly to the average profile shown in the top of Figure 9. It is apparent that accumulations are greater toward the shoal ridge and decrease toward both sides. The result does not contradict the inference that sands are transported in the process of sand wave migration toward the shoal ridge.

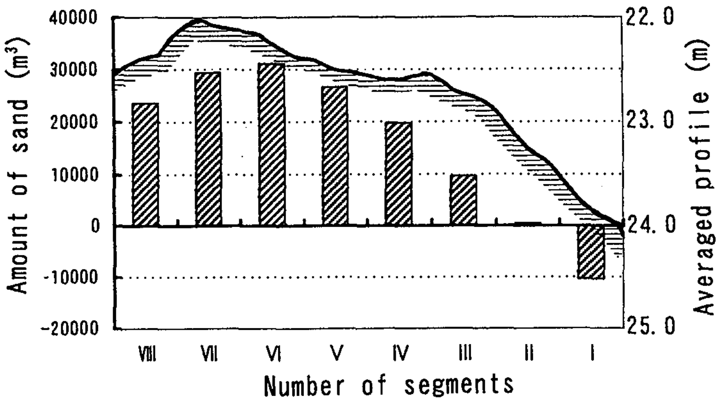

Figure 12. Sand Accumulation in Segments
(Transverse Direction of the Shoal)

5. Discussion of Maintenance Dredging

It is observed that two different factors are overlapped, which basically make the navigation channel shallow. They are the decrease in the mean water depth caused by accumulation of sands which are transported from the direction of Mitsugo Island and development of sand waves. These two factors act in combination to decrease the minimum water depth. The next dredging project must take them into consideration.

Dredging performed during the period from 1981 to 1983 anticipated that the sand waves would reach equilibrium after dredging and removed the convex portions (Onodera, 1981), thereby addressing one of the two factors. In order to deal with another factor of the decrease in the mean water depth, overall dredging of the further depth or pocket dredging on the upstream side where the sands flow into the channel may be conducted to capture the sands. The former is considered to accompany great difficulties since the last dredging was performed up to 22 m, a substantially critical depth for dredging. The latter method entails hardly any problems in dredging as it is performed at a shallower depth.

Pocket dredging is expected not only to control the inflow of sands into the channel but also to achieve secondly effects. As shown in Figure 8, the years required for sand wave development is shorter if the accumulation speed is faster. By referring to Figure 8, it is assumed that the time required for the sand waves to reach 90% equilibrium increases from 9 to 15 years if the rate of accumulation becomes 0 cm/year from 6 cm/year, thus delaying the decrease in the minimum water depth.

6. Conclusions

Following conclusions are obtained.

(1) Basically, two factors are overlapped for decrease of the navigation channel depth in Inosakinotsugai area; they are the decrease of the mean water depth due to accumulation of sand inflowing from the direction of Mitsugo Island, and development of sand waves.

(2) Sand waves develop faster in the segments where the rate of sand accumulation is faster.

(3) Sand waves formed after dredging migrated from both sides of the shoal toward the shoal ridge. The speed of migration is proportional to the horizontal distance from the ridge, and is 4 m/year if the distance is 100 meters. The direction of migration is the same as that of the permanent current.

(4) Maintenance dredging should be performed by considering development of sand waves and changes in the mean water depth. The former can be addressed by dredging in anticipation of sand waves developing to equilibrium as in the previous dredging project. The latter can be dealt with pocket dredging in the upstream side of the sand migration to decrease the sand inflow into the channel. This method may be effective to delay the sand wave development.

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