

REASON FOR FIXATION OF MOUTH OF SMALL RIVER BEHIND NATURAL REEF

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The mechanism by which the mouth of a small river is stably fixed in the wave-shelter zone behind an offshore reef composed of natural rocks was studied, taking a small river flowing into the Moriya coast together with two other small rivers as examples. The beach topography around the river mouth and the shape of the stream behind the reef were measured on this coast, and the wave height distribution around the reef was calculated using the angular spreading method, and the reason why the river mouth is stably fixed at this location was considered. Furthermore, the numerical simulation of beach changes using the BG model when an offshore breakwater was installed as a model of a natural reef was carried out to study the longshore change in the berm height. The primary cause for the fixation of a river mouth behind a reef was found to be the decrease in wave height behind the reef, which in turn decreases in the berm height.

Keywords: river mouth; deposition of sand; berm height; angular spreading method; BG model; beach changes

INTRODUCTION

The mouth of a small river flowing into a pocket beach, which is exposed to the open ocean, is often fixed in the vicinity of one of the headlands at the ends of the pocket beach, where the wave-sheltering effect of the headland can be expected, and the natural headland plays the role of a training jetty. When considering the wave conditions at such a location, the wave height in the vicinity of the headlands is reduced owing to the wave-sheltering effect of the headlands, resulting in a decrease in the berm height of the beach. The river flowing into the sea is therefore assumed to easily cross the sandy beach with a lower berm height. Normally the discharge of a small river is minimal, meaning that its ability to remove sand from the berm is weak. The small river, therefore, preferentially flows through the location with the lowest berm height. The quantitative evaluation of such an effect in stabilizing the river mouth in the wave-shelter zone has not yet been fully studied, although a qualitative explanation was given by Uda et al. (1997). This study aims to investigate this mechanism. First, taking the Shiota River flowing into the Pacific Ocean, the Ochiai River flowing into Wakasa Bay, and a small river on the Moriya coast, located in the south part of Boso Peninsula, as examples, the reason why the mouth of each river is stably fixed at a location behind a reef composed of rocks was investigated. Then, the beach topography around the river mouth and the shape of the stream behind the reef were measured on the Moriya coast, and the wave height distribution around the reef was calculated using the angular spreading method (Sakai et al. 2006). Moreover, the numerical simulation of beach changes was carried out using the BG model (a model for predicting three-dimensional beach changes based on Bagnold's concept) (Serizawa et al. 2006).

EXAMPLES OF FIXATION OF RIVER MOUTH BEHIND OFFSHORE REEF

Mouth of Shiota River in Kita-ibaraki City

The Shiota River is a small river with 4.0 km length and a catchment area of 10.6 km² flowing into the Pacific Ocean. Figure 1 shows the satellite images of the mouth of the Shiota River taken in 2012 and 2014. The river meandered northward from the mouth in both years, the shoreline around the river mouth smoothly protruded offshore, forming a cusped foreland owing to the wave-sheltering effect of the offshore reef, and the opening of the river mouth was located at the tip of the cusped foreland. In 2012, the stream directly meandered to the north from the river mouth, leaving a stream of 100 m length north of the river mouth. The tip of the stream was completely buried with sand and a new stream was formed 44 m south of the tip of the previous stream. The tip of the new stream was located behind the offshore reef. Similarly, the stream of the river meandered northward, and the tip of the stream was located behind the offshore reef in 2014. Figure 2 shows a photograph of the Shiota River mouth taken on February 28, 2012. The stream flowed into the Pacific Ocean behind the offshore reef with many scattered rocks, where incident waves lost their energy owing to wave breaking and wave diffraction.

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Figure 1. Satellite image of Shiota River flowing into Pacific Ocean in Kita-ibaraki City.



Figure 2. Opening of Shiota River mouth (February 28, 2012).

Mouth of Ochiai River in Mihama Town in Fukui Prefecture

The Ochiai River is a small river of 2.45 km length that flows into Wakasa Bay in Mihama Town in Fukui Prefecture. The beach material around the river mouth is composed of decomposed granite and is



Figure 3. Satellite image of Ochiai River.

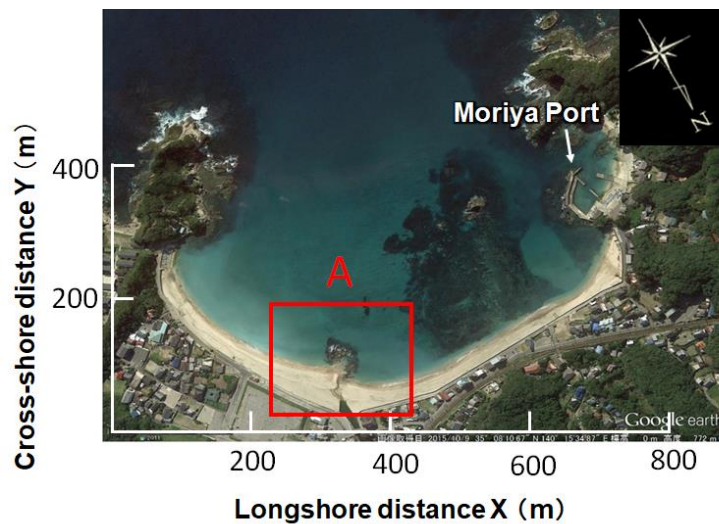


Figure 4. Satellite image of Moriya coast.

mostly medium-size and fine sand. Figure 3 shows a satellite image of this river mouth taken in 2015. The stream of the Ochiai River flows down between two offshore reefs, and the many rocks scattered around the river mouth also seem to be effective for fixing the river mouth.

Mouth of a Small River Flowing into Moriya Coast

The Moriya coast is located in the south part of Boso Peninsula in Chiba Prefecture, and is a pocket beach of 610 m length bounded by natural headlands at both ends of the beach with a small river flowing into the bay at the central part of the coast. Figure 4 shows a satellite image of the Moriya coast taken on October 9, 2015. The coast faces the Pacific Ocean in the SW direction. Small rocks are scattered near the center of the pocket beach to form a reef, and a small river with 800 m length, a catchment area of $1.3 \times 10^5 \text{ m}^2$, and a mean width of 5 m flows down to the sea behind the reef. These examples of the mouth of three small rivers clearly demonstrate that the mouth is fixed behind the offshore reef composed of rocks, implying that the wave-sheltering effect of the offshore reef is important for fixing the river mouth. Therefore, a field observation was planned to measure the topography around the river mouth, taking the small river flowing into the Moriya coast as the example.

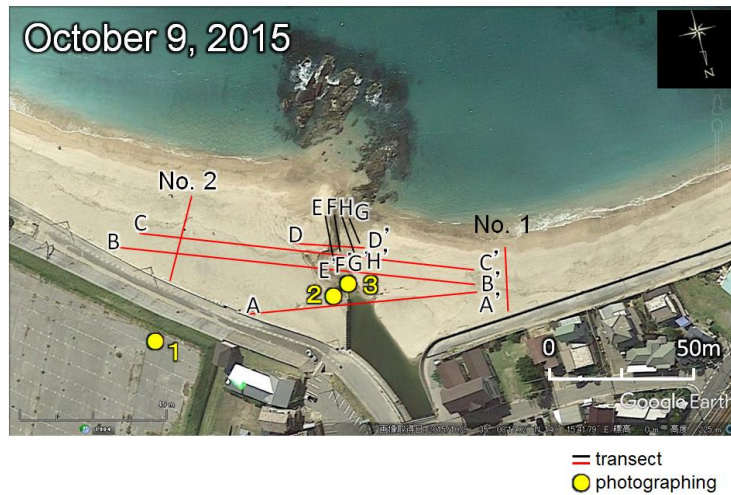


Figure 5. Enlarged satellite image of rectangular area in Fig. 4 and arrangement of transects behind reef.

METHOD OF FIELD OBSERVATION

On July 10 and September 30, 2016, field observations were carried out at the Moriya coast, and the field conditions in rectangular area A, as shown in Fig. 4, were investigated. An enlarged satellite image of the rectangular area is shown in Fig. 5. There is a well-developed sandy beach behind the reef, and immediately behind the reef a small river flows into the sea. Site photographs of the river mouth were taken at points 1, 2, and 3. The beach topography around this river was measured using an RTK-GPS, and the elevation of the rocks and profiles along eight transects between A-A' and H-H' across the stream were also measured. Furthermore, beach profiles were measured along transects Nos. 1 and 2, and the sampling of beach material was carried out. The shoreline variation of the pocket beach and the change in the river mouth were investigated using aerial photographs taken in 1990, 2000, and 2015.

RESULTS OF FIELD OBSERVATION

Field Conditions of the River Mouth

Figure 6 shows a photograph of the rocks composing the reef and a small river flowing down behind the reef, taken from St. 1 on a hill behind the coast, as shown in Fig. 5, on July 10, 2016. There are four rocks, Nos. 1-4 (R1-R4), with some intervals between them, and the interval between R3 and R4 was large. Sand was deposited behind the rock, and a cusped foreland was formed. The small river flows into the sea behind R4 while slightly meandering westward. In addition, a photograph of the river mouth taken on September 30, 2016 from St. 2 in Fig. 5 while looking the SW is shown in Fig. 7. The

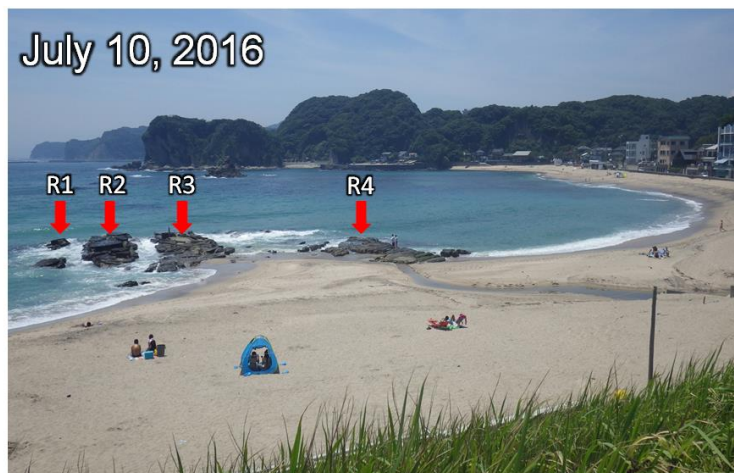


Figure 6. View of rocks and a small river, taken from a hill.



Figure 7. Stream flowing down to sea behind reef.



Figure 8. Raised water level owing to backwater effect caused by river mouth closure.

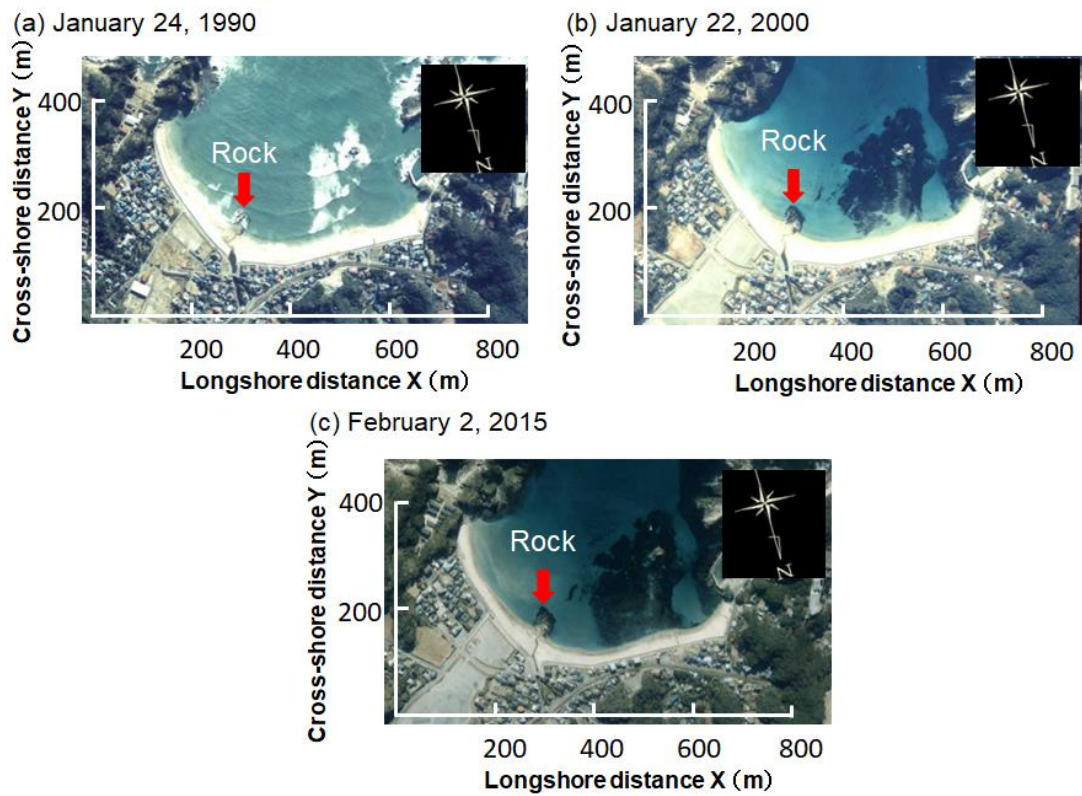


Figure 9. Aerial photographs of Moriya coast.

stream again flowed into the sea behind the reef, similarly to on July 10, 2016, despite the increased meandering of the stream. In the area upstream of the river mouth, the water level was raised, as shown in Fig. 8, owing to the backwater effect of the stream triggered by the river mouth closure.

Long-term Changes in Shoreline Position around River Mouth

Using the aerial photographs taken in 1990, 2000, and 2015, long-term shoreline changes around this small river were investigated (Fig. 9). No changes were observed in the shoreline configuration of the pocket beach, implying that this pocket beach has a stable form. The shoreline changes its direction behind the reef, as shown in Fig. 9, and runs in the E-W direction west of the rock. In addition, a wide exposed rocky bed extended offshore of the shoreline approximately 100 m west of the rock, forming a gradually protruding cusped foreland. The mouth of the small river flows down to the sea toward the lee of this rock, and the mouth was fixed immediately behind the rock. The lack of variation in the shoreline position suggests that the river mouth has been stably fixed behind the reef.

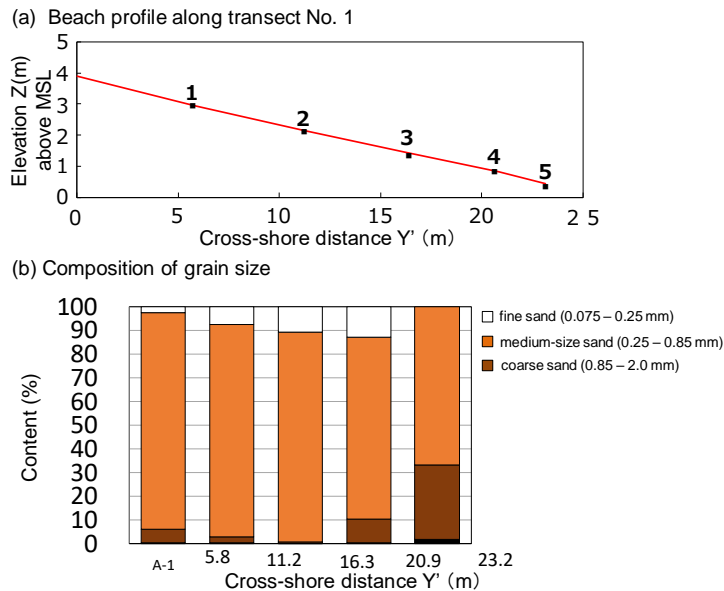


Figure 10. Longitudinal profile and grain size composition along transect No. 1.

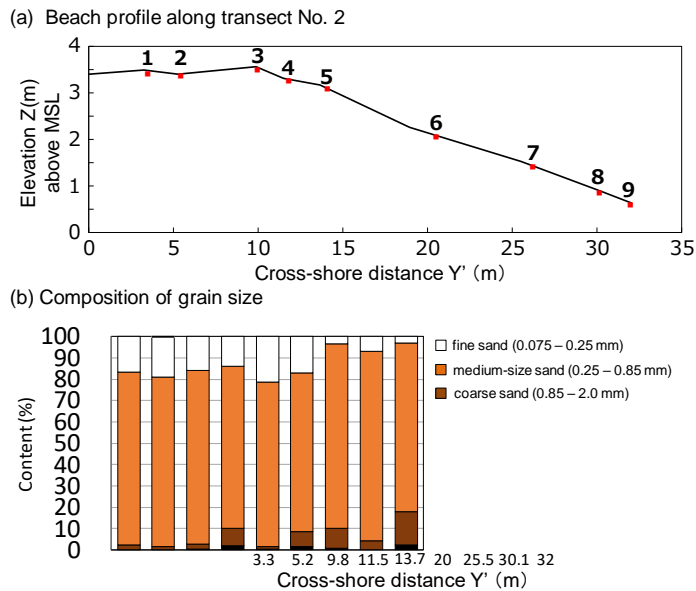


Figure 11. Longitudinal profile and grain size composition along transect No. 2.

Longitudinal Profile along Transect Nos. 1 and 2 and Grain Size Distribution

Figure 10 shows the longitudinal profile and cross-shore distribution of the grain size of the beach material along transect No. 1. Most of the beach material is composed of medium-size sand, followed by coarse and fine sand, with increasing content of coarse sand toward the shoreline. Similarly, Fig. 11 shows the longitudinal profile and cross-shore distribution of the grain size of the beach material along transect No. 2. The content of medium-size sand was dominant at all sampling points along the transect. Thus, the beach material was mainly composed of medium-size and fine sand with a low content of coarse sand, meaning that the flow did not infiltrate into the sandy beach and flowed down to the shoreline while forming a surface flow.

Beach Topography Surrounding the River Mouth

Figure 12 shows the beach topography around the mouth behind the reef. A channel had been formed behind the reef, and the opening was located immediately behind the reef. The maximum elevation of the reef was 0.6 m above MSL, and the beach elevation varied between 0.78 m immediately behind the reef and 3.6 m at a location far from the reef. Although the shoreline protruded behind the reef because of the wave-sheltering effect of the reef, immediately behind the reef a V-shaped valley was maintained and the small river flowed down to the sea through this gap. Furthermore, on the upstream side of this gap, the water depth increased upstream and the lowest riverbed elevation increased toward the opening behind the reef.

Longitudinal Profiles across the Channel

Figure 13 shows the profiles along transects A-A', B-B', C-C', and D-D', as shown in Fig. 5, with the water level of the channel along each transect. The maximum riverbed elevation at A-A' was +0.015 m above MSL and the water depth was 0.5 m. In contrast, the maximum riverbed elevation along transects B-B', C-C', and D-D' was almost constant at 0.4 m. Furthermore, the riverbed was flat along transects C-C' and D-D' behind the rocks, and the river flowed into the sea as a very shallow stream with a high velocity. Since the water level at the river mouth of the small river was approximately 0.4 m, the height of the river mouth bar should be lower than this height for the stream to stably flow into the sea. Figure 14 shows the profiles along transects E-E', F-F', G-G', and H-H', where river water flows down to the sea with a high velocity immediately upstream of the opening located on the sandy beach, as shown in Fig. 5. The lowest elevation of the riverbed was +0.29 m above MSL along E-E', +0.20 m along F-F', +0.15 m along G-G', and +0.13 m along H-H'; the riverbed elevation significantly

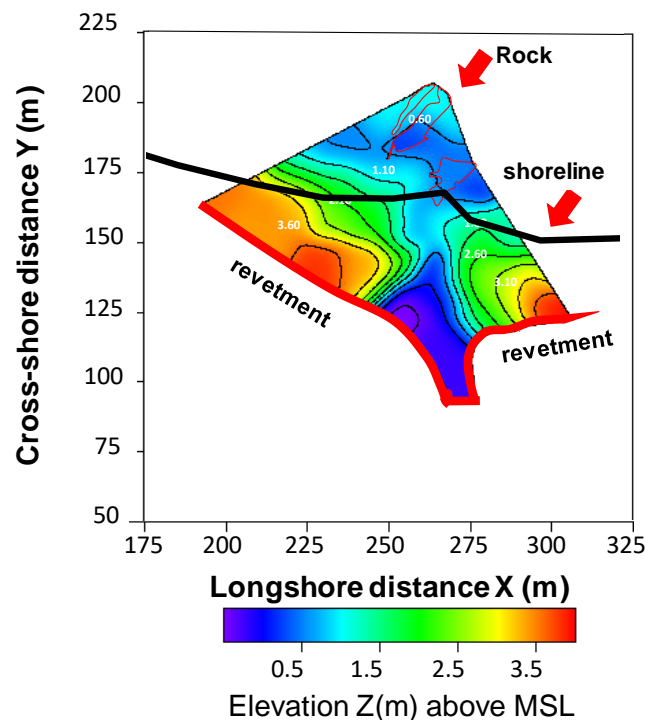


Figure 12. Beach topography behind reef.

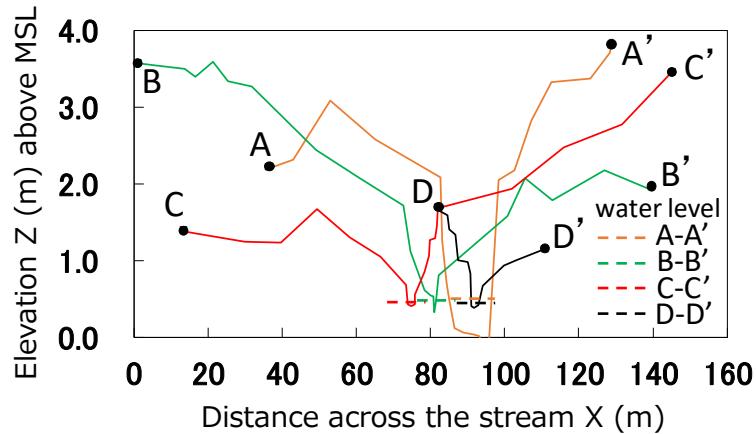


Figure 13. Profile along transects A-A', B-B', C-C', and D-D'.

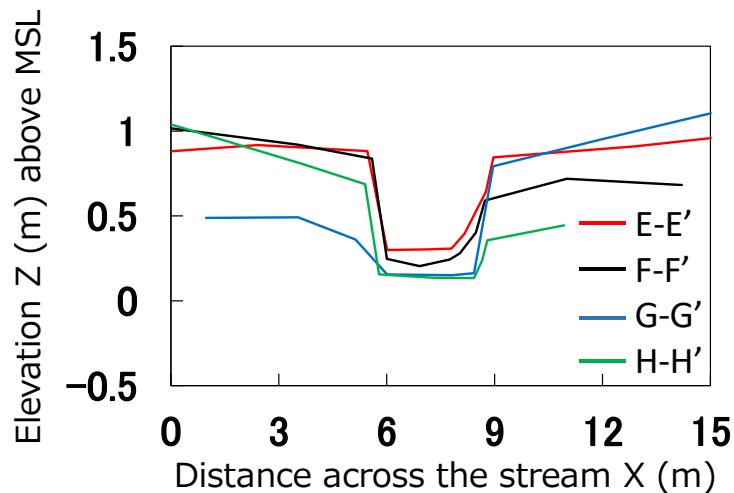


Figure 14. Profiles along transects E-E', F-F', G-G', and H-H' across the stream.

decreased from the water level of +0.4 m at the mouth of the river. It is seen from these results that the riverbed elevation gradually decreases to the sea before the river flows into the sea.

WAVE DIRECTION AND K_d VALUE BEHIND REEF

The stream of a small river near its mouth is assumed to be fixed behind the offshore reef because of the decrease in berm height owing to the wave-sheltering effect. Thus, we evaluated the distribution of the wave direction and the K_d value by the angular spreading method for irregular waves (Sakai et al. 2006), assuming that waves were obliquely incident to the shoreline at angles of 0° , 5° , 15° , and 25° relative to the direction normal to the shoreline, given the seabed topography in the rectangular area shown in Fig. 4.

Figure 15(a) shows the distribution of the wave direction when waves are incident to the reef at an angle of 0° . In the calculation, the effects of rocks Nos. 2 and 4 were considered except rock No. 3. The red and blue colors in Fig. 15 correspond to the wave propagation in the counterclockwise and clockwise directions, respectively. Waves propagate behind the reef owing to the wave diffraction. Figures 15(b), 15(c), and 15(d) also show the results when waves are incident at angles of 5° , 15° , and 25° , respectively. It is clear that when waves are incident counterclockwise at an angle of 25° , more wave energy arrives behind the rocks than when waves are incident at angles of 0° , 5° , and 15° .

Figure 16 shows the K_d value around the rocks corresponding to the wave directions shown in Fig. 15. It is clear that the relative wave height decreased behind the rocks in each case, whereas it increased shoreward, and the lowest ratio of the relative wave height was 0.2 behind the rocks. However, the K_d value far from the rocks increased up to 0.7.

When waves are incident from the Pacific Ocean on the Moriya coast, the wave diffraction effect of the reef is determined by the K_d value, and the wave height decreases behind the reef. Although the Moriya coast faces the Pacific Ocean, it is a well-sheltered pocket beach, resulting in a low mean wave height of 1 m. Since the berm height is of the same order as the wave height, the berm height becomes 0.2 m above MSL. This value has the same order of magnitude as the riverbed elevation behind the rocks, and the wave height behind the rocks decreases, regardless of the wave direction, and the stream was considered to be fixed at this location. These natural rocks were randomly distributed in the area. Therefore, the location of the stream is assumed to be stably maintained, even though the wave-sheltering effect alters in response to the changes in the wave direction or wave height or the change in the flow of the small river.

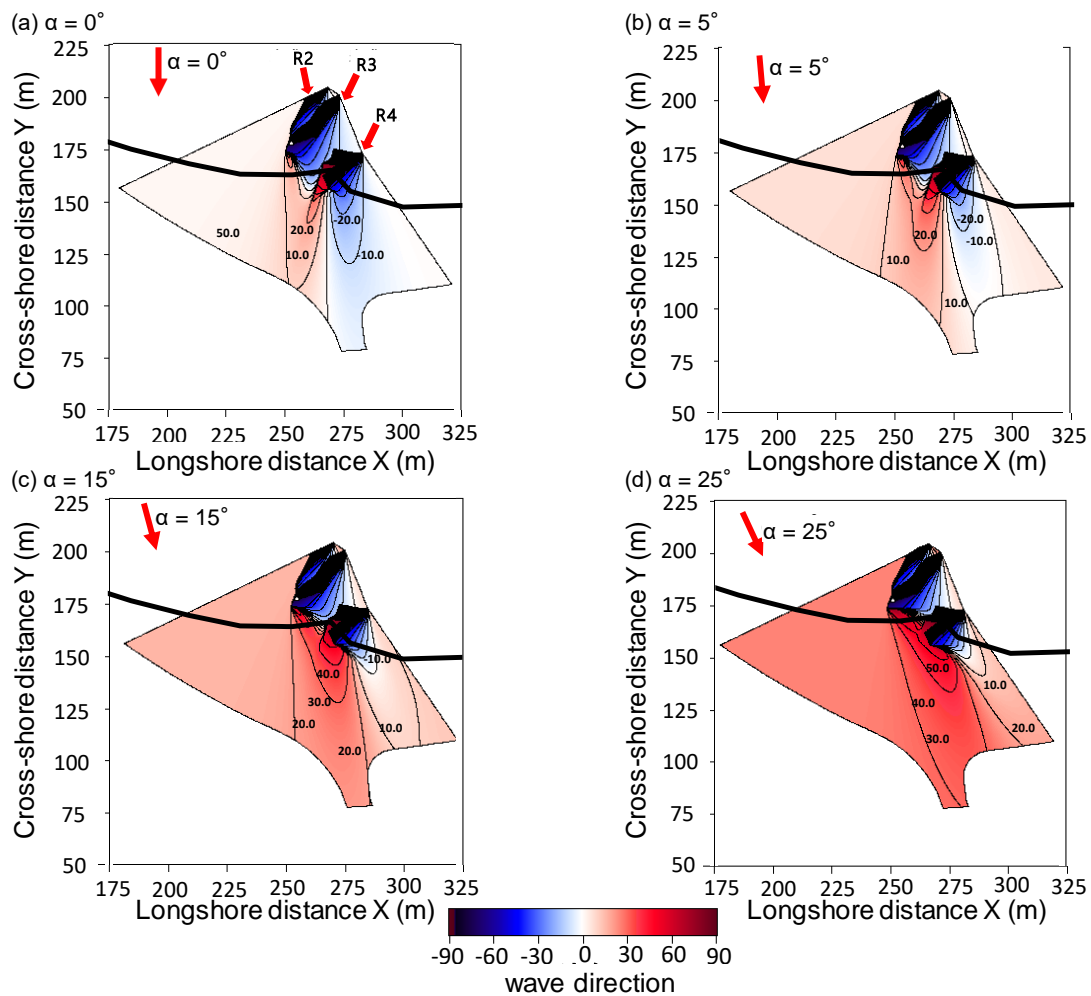


Figure 15. Distribution of wave direction.

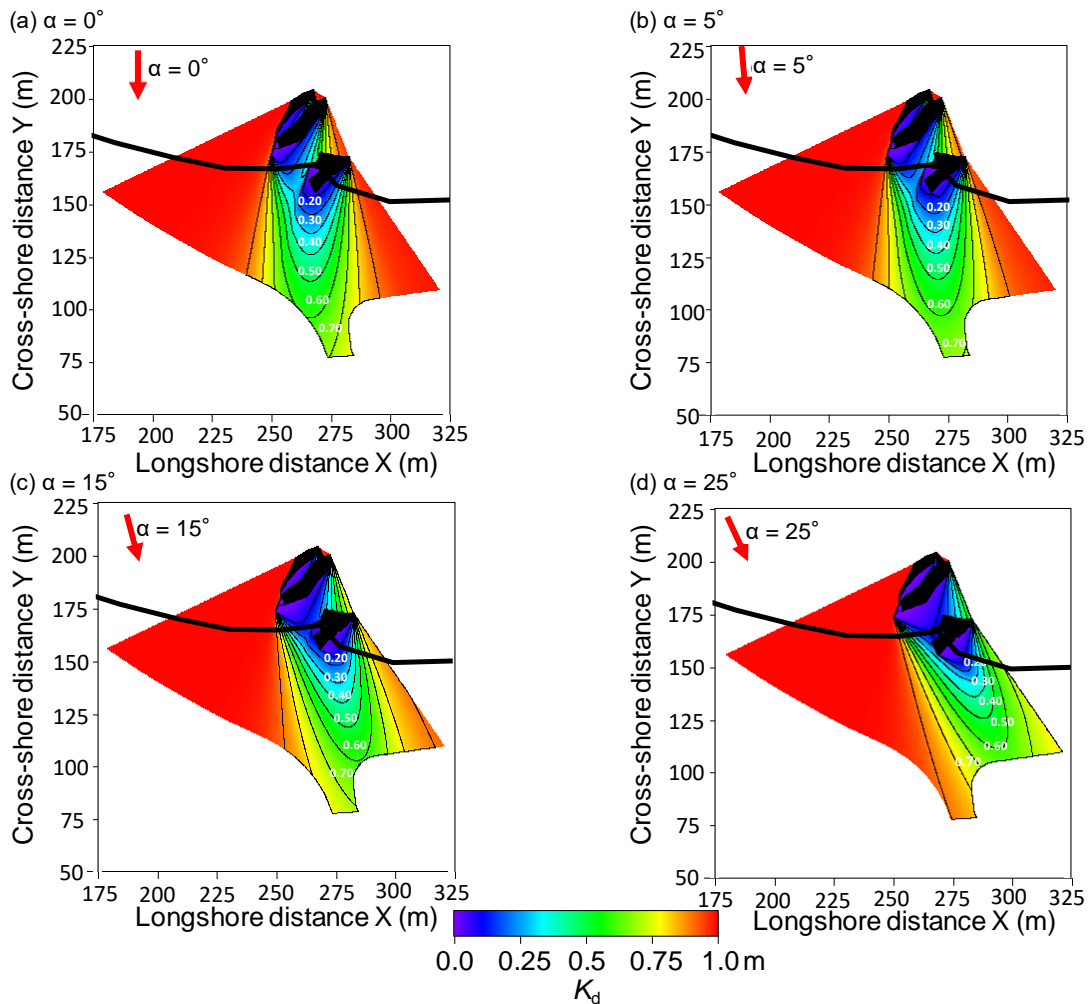


Figure 16. Distribution of K_d value.

PREDICTION OF TOPOGRAPHY BEHIND A DETACHED BREAKWATER

To investigate the decrease in the beach elevation behind an offshore reef, an offshore breakwater was considered as a model of the offshore reef, and the numerical simulation of beach changes was carried out using the BG model (Serizawa et al. 2006). An impermeable breakwater of 120 m length at an offshore distance of 200 m was assumed to have been constructed on a coast with parallel contours with an initial beach slope of 1/20 along with an equilibrium slope of sand of 1/20 (Fig. 17(a)). The wave-sheltering effect of the breakwater was evaluated using the angular spreading method for irregular waves, and the berm height h_R was altered in response to the longshore distribution of the wave height, given $\Delta t = 0.1$ s, $\Delta x = 20$ m, $\Delta y = 10$ m, and the depth of closure, h_c , of 8 m. Figure 17(b) shows the results of the calculation up to 10^6 steps. A cusped foreland was formed behind an impermeable detached breakwater. Figure 18 shows the profiles across transects at $X = 0$, 700, and 740 m, as shown in Fig. 17(b). The berm height at the locations shown by arrows decreases from 3.0 m along the transect at $X = 0$ m to 1.79 m along the transect at $X = 700$ m and 1.06 m along the transect at $X = 740$ m. Figure 19 shows the longshore change in the berm height, which was markedly reduced behind the offshore breakwater. Thus, it is concluded that a small river can flow down to the sea behind the offshore breakwater owing to the reduction of the berm height.

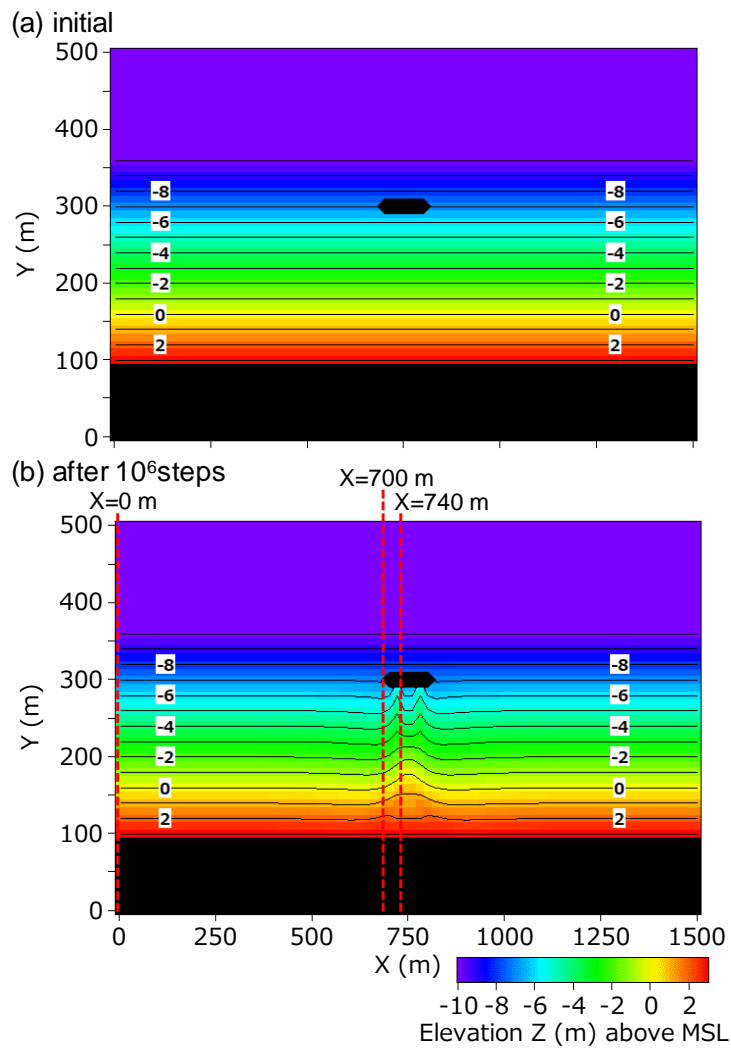


Figure 17. Initial topography and predicted topography behind an offshore breakwater.

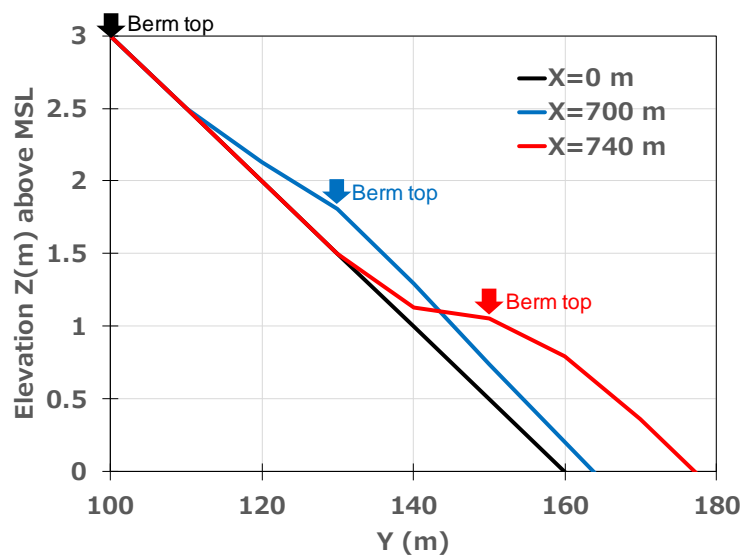


Figure 18. Initial topography and predicted topography behind an offshore breakwater.

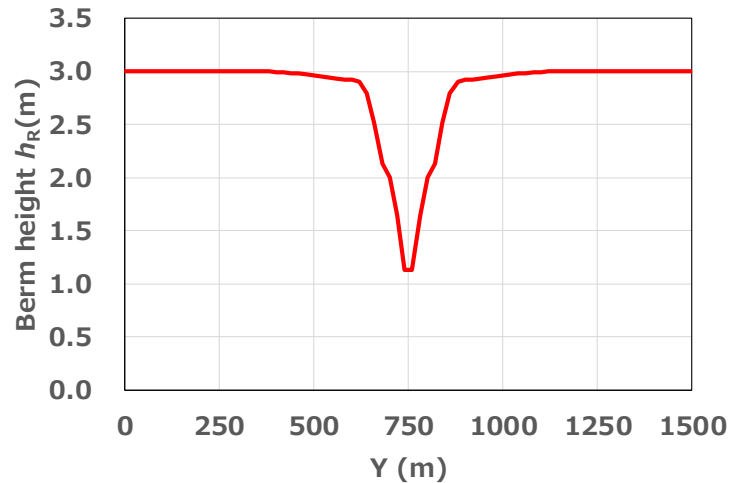


Figure 19. Initial topography and predicted topography behind an offshore breakwater.

CONCLUSIONS

At the mouth of a small river flowing into the sea at the central part of the Moriya coast, the stream has been stably maintained at a location behind a reef composed of several rocks. The primary cause for the fixation of the river mouth behind the reef was found to be the wave-sheltering effect of the reef, by which the height of the sandy beach is locally reduced. The results of this study suggest that the mouth of a small river can be stabilized by the installation of rocks in front of the river mouth, which can be used as a method of river mouth improvement instead of the ordinary method of using training jetties. It is not necessary for these natural rocks to have a fixed shape and they may have randomly scattered. When several rocks are randomly scattered in an offshore area near the shoreline, the stream can be stably maintained, even though the incident wave direction and wave height change or the stream meanders, reducing the necessity of river mouth excavation to maintain the channel. This method, therefore, has high flexibility compared with the construction of a river mouth jetty to forcibly maintain the river channel.

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