FIELD OBSERVATION AND NUMERICAL SIMULATION OF BARRIER ISLAND FORMATION AS RESULT OF ELONGATION OF SAND SPIT AND ITS ATTACHMENT TO OPPOSITE SHORE

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An artificial mound was produced from dredged materials containing sand and gravel in the Nakatsu tidal flat facing the Suo-nada Sea, and this artificial mound served as a supply source of sediment for the development of a barrier island. A sand spit extended from this mound in an extremely shallow sea and attached to the opposite shore, resulting in the formation of a barrier island. The planar changes in the sand spit were investigated using aerial photographs. Observations were compared with the results of a numerical simulation regarding the formation of a barrier island on a sloping bed with a 1/40 slope using the BG model (a model for predicting three-dimensional beach changes based on Bagnold's concept). The observed change in the barrier island and the calculated results were in good agreement.

Keywords: barrier island; Nakatsu tidal flat; BG model; aerial photographs; longshore sand transport

INTRODUCTION

Barrier islands develop along the marginal coast of a flat shallow sea. Various explanations have been given for the cause of the development of barrier islands: the elongation of a sand spit, the emergence of a longshore bar during a decrease in sea level, and the submergence of a beach ridge during an increase in sea level (Schwarz 1971). However, the theoretical explanation for the growth of barrier islands is still inadequate. Nummedal (1983) studied the physical process of the formation of a barrier island (henceforth, 'a barrier') and concluded that it is closely related to four factors: the increase in sea level over the past several thousand years, the longshore distribution of the sand source and the loss of sand, the exchange of sea water across inlets, and the wave energy level. Most studies regarding barrier islands have focused on the development and deformation of a barrier in terms of the stratification of sand layers in the sand bar and the change in longitudinal profiles. Moreover, studies on the three-dimensional development of a barrier considering the depth of water in which the barrier develops and wave intensity are inadequate. Uda and Serizawa (2011) studied the relationship between wave energy and the depth of water in which a barrier develops regarding a bay barrier extending deep into a bay (Bird 2001), using the BG model (a model for predicting three-dimensional beach changes based on Bagnold's concept). The predicted results were in good agreement with the formation of a bay barrier in a movable-bed experiment. It was confirmed that a bay barrier is mainly formed by the occurrence of wave dissipation associated with wave breaking on the flat shallow bottom, from which a bay barrier extends. A barrier was formed under the condition that the ratio of the water depth of the flat shallow bottom to the wave height (γ) was smaller than 1.0, but no barriers were formed when γ was larger than 2.3. The marginal coast of a tidal flat satisfies these conditions, and a barrier can develop.

In the Nabeshima area in the Nakatsu tidal flat facing the Suo-nada Sea, an artificial mound was constructed using dredged materials containing gravel, and this artificial mound served as a supply source of sediment for the development of a barrier. Although numerical simulation of the development of a barrier is possible, as shown by Uda and Serizawa (2011), there are few studies in which the development of a barrier is really demonstrated in an extremely shallow sea. In this area, a sand spit extended first, and then it connected to the opposite shore, forming a barrier. In this study, the planform changes of this barrier were investigated using aerial photographs, and the deformation was studied. Then, observations were compared with the results of a numerical simulation of the formation of a barrier on a sloping bed with a 1/40 slope, which was carried out by San-nami et al. (2014) using the BG model.

GENERAL CONDITIONS OF BARRIER IN NABESHIMA AREA

The study site is the vicinity of the Inumaru River mouth flowing into the Suo-nada Sea east of Nakatsu Port, as shown in Fig. 1. The Imazu fishing port is located on the right bank of this river, and the reclaimed land of the Nabeshima area is located east of this fishing port, together with a rectangular reclaimed land on the north side. Furthermore, east of this reclaimed land, an artificial mound (denoted by AM in Fig. 1) of 60 m width and 200 m length in the south-north direction is surrounded by a tidal flat. Because this artificial mound is composed of sand and gravel, wave abrasion occurred, material

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was transported in both directions while forming a sandy beach, and a barrier enclosing a lagoon was formed on the east side.

(a) Satellite image around Nakatsu Port

(b) Satellite image around Imazu Fishing Port

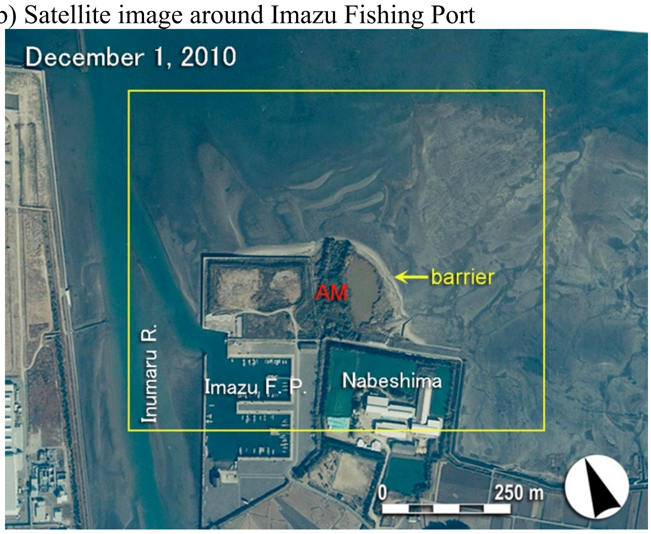

Figure 1. Location of study area near Nakatsu Port.

FIELD OBSERVATION

The artificial mound and its surroundings were observed on May 31, 2012 and October 18, 2013. This artificial mound significantly protruded northward in the past. Then, the north end was eroded by wave abrasion, and the eroded material was moved to form a sand spit on the east side. Figure 2 shows an overview of the artificial mound and the barrier enclosing a lagoon by the southward extension of a sand spit. The barrier was very narrow at the connecting point with the artificial mound, and gradually increased southward. Figure 3 shows the training jetty, which prevents sand from depositing at the mouth of the drainage channel with an opening facing the east.

The artificial mound had two ridges. Figure 4 shows the cliff formed on the west ridge. Although the crown of the mound was covered with vegetation, a cliff of 2 m height was formed and a shingle beach extended in front of the cliff. In contrast, a sandy beach was formed in front of the reclaimed land immediately north of the Imazu fishing port, as shown in Fig. 5, and the gravel bed in front of the artificial mound well contrasted to the sandy beach in front of the reclaimed land. Figure 6 shows the gravel bed offshore of the cliff, which is assumed to be stable against wave action. From these observations, it is concluded that sand was selectively transported to the area in front of the reclaimed land from the artificial mound, whereas gravel with a large grain size remained offshore of the artificial mound, while forming an armor coat.

Figures 7 and 8 show the cliff formed at the north end of the eastern ridge and the enlarged picture of the exposed cliff surface indicated by a circle in Fig. 7, respectively. Taking into account that not only the large amount of gravel but also many shell debris (white area in Fig. 8) were contained in the layer, it is clear that this artificial mound was produced from the dredged material. Thus, in the Nabeshima area, the artificial mound was eroded by waves, and the material from this mound was transported in both directions, with an effect of sorting grain sizes, and a barrier was formed east of the artificial mound. For the development of a barrier, it is necessary that a sufficient volume of sand is supplied under the oblique wave incidence to the shoreline in the extremely shallow sea. This area satisfied these conditions.

Figure 9 shows the beach condition southeast of the artificial mound. The shoreline was fully covered with large gravel of size ranging from 10 to 20 cm, and an armor coat was formed on the shoreline, suggesting that the rate of sand transport is small, even when waves were incident to the shoreline with a large incidence angle. The size of the gravel, however, decreased toward the berm top, and it is possible for such a material to be transported under storm wave conditions. Figure 10 shows the condition of the barrier shoreline, taken from on top of the training jetty, and the foreshore slope in this area was approximately 1/6. Waves were obliquely incident to the shoreline, permitting the predominance of southward longshore sand transport. Here, when referring to the tide level at Nakatsu Port, the high water level (HWL) was the datum level (DL) +3.45 m, the mean sea level (MSL) was DL +1.95 m, and the low water level (LWL) was DL +0.80 m with an average elevation of the tidal flat of DL +2.0 m.

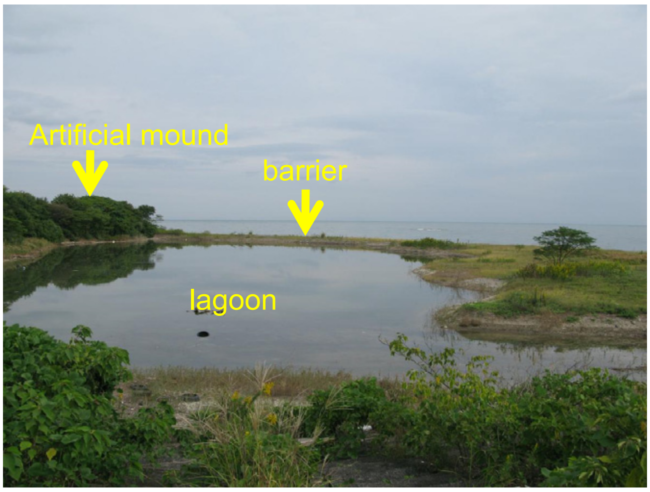

Figure 2. Barrier and lagoon formed offshore of Nabeshima area (October 18, 2013).

Figure 3. Training jetty extended near south end of the barrier (October 18, 2013).

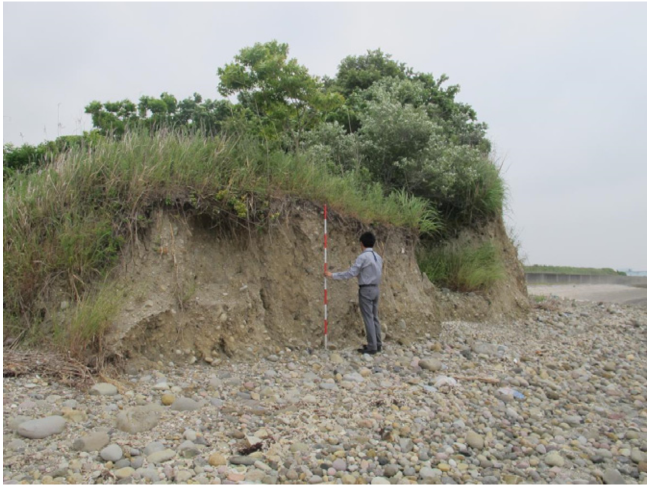

Figure 4. Scarp formed at north end of west part of artificial mound and gravel bed (May 31, 2012).

Figure 5. Sandy beach formed in front of seawall surrounding reclaimed land (May 31. 2012).

Figure 6. Wide armor coat covered by gravel offshore of artificial mound (May 31, 2012).

Figure 7. Scarp formed at north end of east part of artificial mound (October 18, 2013).

Figure 8. Exposure of gravel and shell contained in artificial mound (October 18, 2013).

Figure 9. Upcoast covered with large gravel (October 18, 2013).

Figure 10. Oblique wave incidence immediately north of jetty (October 19, 2013).

ELONGATION OF SAND SPIT

By selecting a rectangular area, as shown in Fig. 1(b), the deformation of the artificial mound was investigated using aerial photographs. Figure 11 shows an aerial photograph taken on October 12, 1981 of the artificial mound composed of sand and gravel, which were dredged from a nearby tidal flat. The Imazu fishing port breakwater and the seawall in the Nabeshima area had already been constructed by 1981, and the artificial mound of 244 m length extended normal to the seawall as a slender isolated sand body on tidal flat. The width of the mound was 152 m at the base and the width of the neck was 38 m at the central part of the mound.

Figures 12(a) – 12(j) show the planar deformation of the artificial mound between 1998 and 2010 in the same area as that shown in Fig. 11. Until December 1998, land reclamation was carried out along the west side of the artificial mound (denoted by AM), as shown in Fig. 12(a), and a slender sand spit of 74 m length extended straight from the east end of the artificial mound to point P, and the elongation direction of the sand spit changed there by 65° to the right. The sand spit further extended southward for 122 m from point P. In contrast, sand was deposited to form a sandy beach in front of the seawall west of the artificial mound. Also, a 20-m wide opening remained between the tip of the sand spit and the seawall, permitting the tidal exchange of the water of the lagoon behind the sand spit through this opening. In February 2000, although the overall configuration of the sand spit did not change from that in 1998, the opening width between the tip of the sand spit and the seawall decreased by 15 m, as shown in Fig. 12(b). Furthermore, the shoreline protruded at point Q in the middle of the sand spit, and the shoreline direction changed by 41° at point Q, implying that part of the sand spit south of point Q was subject to a large wave-sheltering effect due to the sand spit itself.

By November 23, 2000, the opening width decreased by 6 m owing to the successive elongation of the sand spit, and the width of the sand spit near point Q increased from 38 m on February 4, 2000 to 42 m, as shown in Fig. 12(c). Then, sand transported from the tip of the sand body was deposited to form a triangular sandy beach west of the artificial mound, as shown in Fig. 12(d). Also, the width of the sand spit increased to 52 m near point Q, 10 m wider than that in November 23, 2000, and the opening width between the tip of the sand spit and the seawall decreased to 4.5 m. A drainage channel extended at point R located 58 m east of the tip of the sand spit, and the tip of this drainage channel was 51 m apart from the seawall. By December 1, 2002, the sand spit further extended to connect to the opposite shore (Fig. 12(e)). The width of the sand spit further increased owing to the successive deposition of sand south of point Q. On December 10, 2004, another sand spit elongated near the tip of the previous sand spit, causing the almost complete closure of the channel, as shown in Fig. 12(f). During this period, the shape of the previous sand spit was maintained on the lagoon side, because the new sand spit covered the shoreline of the previous sand spit. By December 28, 2005, the tip of the sand spit further extended southward and the tip of the drainage channel was completely buried with sand (Fig. 12(g)). During this period, part of the sand was transported southward, while passing through the tip of the drainage channel. By December 19, 2006, the sand spit completely connected to the opposite shore, filling the drainage channel, and the sandy beach extended east of the drainage channel (Fig. 12(h)).

By December 2007, the sand spit fully connected to the opposite shore (Fig. 12(i)). Comparison between Figs. 12(i) and 12(a) shows that the offshore length of the artificial mound was reduced by 26 m, i.e., from 218 m in 1998 to 192 m in 2007. The gravel bed offshore of the artificial mound, as shown in Fig. 6, was considered to be exposed to waves because of this erosion. A large amount of sand was deposited near the tip of the sand spit, and the sand spit became approximately semicircular. By December 1, 2010, a barrier with a lagoon inside fully developed (Fig. 12(j)). During this period, the drainage channel had to be extended eastward by 19 m because of the closure of the channel mouth by sand deposition.

By setting transects a-a' and b-b', as shown in Fig. 12, the change in the width of the sand spit was investigated, as shown in Fig. 13. The width along transect a–a' was almost constant at 26 m, whereas the width across transect b–b' increased between 2002 and 2003, and then it approached a constant value of 62 m. Because the width of the sand spit along transect b–b' increased between 1998 and 2002, the shoreline configurations of the sand spit in 1998, 2002 and 2010 were compared, as shown in Fig. 14. The cliff line at the north end of the artificial mound in 1998 is also shown in Fig. 14. In front of the seawall of the reclaimed land, sand supplied from the erosion of the artificial mound was deposited, and the triangular foreshore expanded over time. When selecting point S at the location without shoreline changes near the north end of the artificial mound, the direction normal to the shoreline in 2010 becomes N17°E. This direction is assumed to be approximately equal to the predominant direction of waves incident to the north end of the artificial mound, and this direction is close to the direction of PQ, implying that the sand spit extended to the direction of wave propagation.

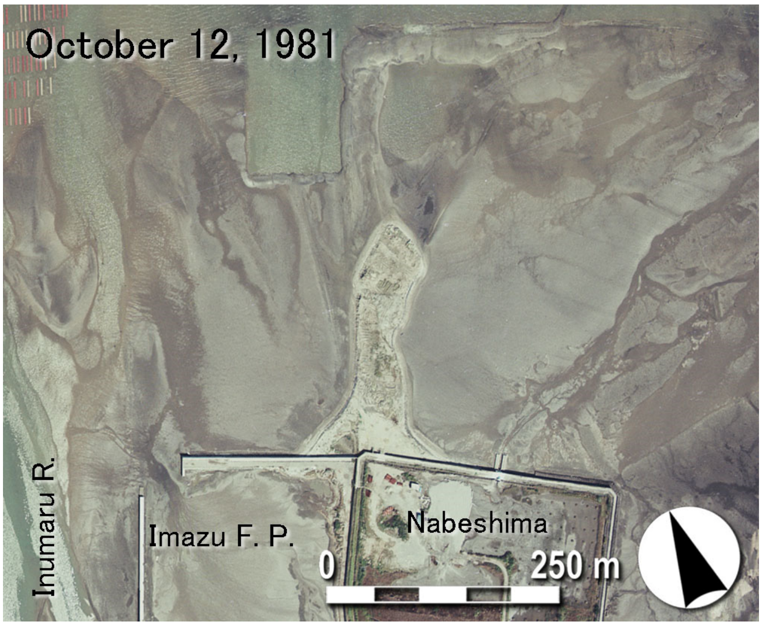

Figure 11. Aerial photograph offshore of Nabeshima area taken on October 12, 1981 before the extension of a barrier.

NUMERICAL SIMULATION OF FORMATION OF BARRIER

In the Nabeshima area, a slender sand spit elongated and its tip attached to the opposite shore to form a barrier. Then, a sandy beach was newly formed in front of the seawall beyond the training jetty because of successive southward sand transport. Before the attachment of the tip of the sand spit to the opposite shore, sand transport was considered to be negligibly small because of the discontinuity of the shoreline. To analyze the process near the tip of the sand spit, results of numerical simulation by San-nami et al. (2014) and Miyahara et al. (2015) were evaluated, in which similar topographic changes as those in the Nabeshima area were predicted using the BG model. Here, results from both research groups were compared in terms of the topographic changes around the tip of the sand spit.

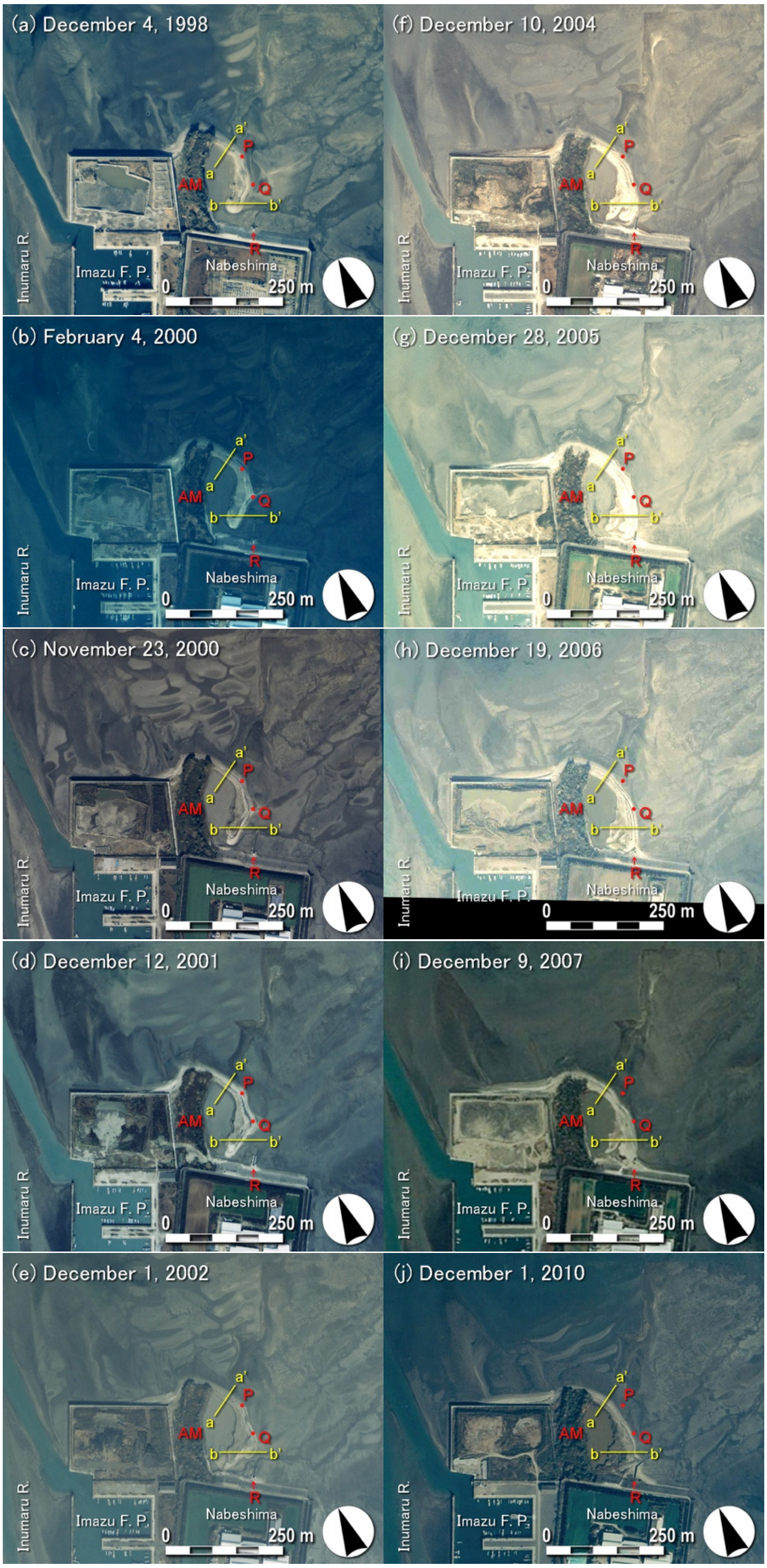

Figure 12. Succesive development of a barrier between December 1988 and December 1, 2010.

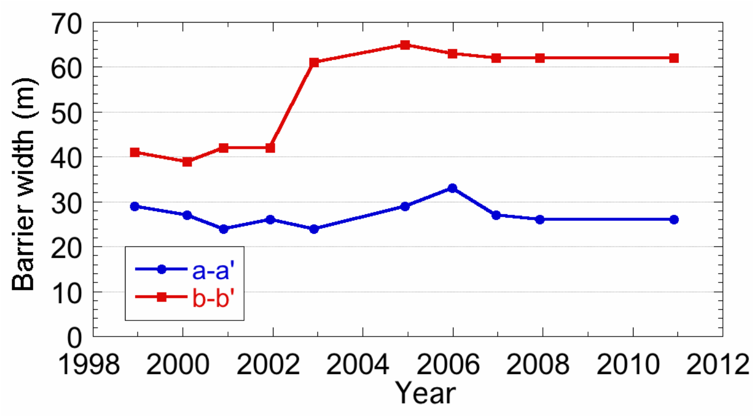

Figure 13. Change in width of sand spit.

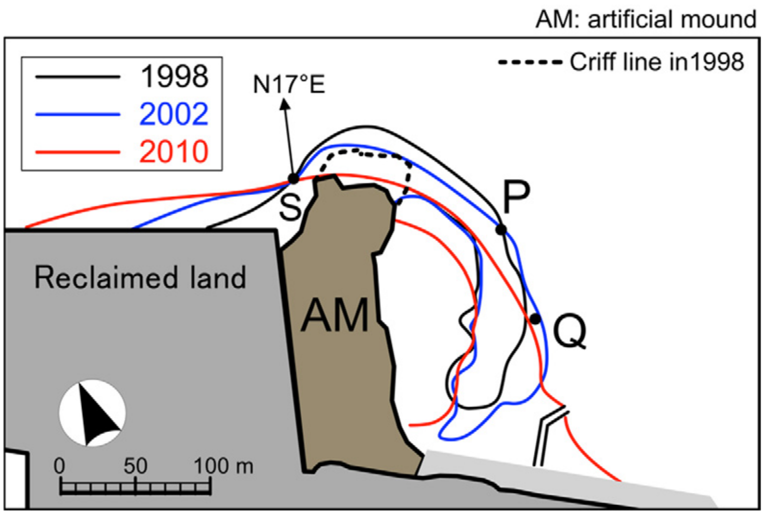

Figure 14. Shoreline configurations of sand spit.

San-nami et al. (2014) calculated the elongation of a sand spit on the seabed with different water depths and slopes using the BG model proposed by Uda and Serizawa (2011) to understand the fundamental features of the development of a sand spit with a model scale of 1/100. In the calculation of the elongation of the sand spit, the water depths of the shallow seabed where the sand spit elongates were changed to 5, 10, 15, and 20 cm in Cases 1-4, respectively. The seabed slopes of the sand deposition zone were also changed to 1/50, 1/40, 1/30, and 1/20 in Cases 5-8, respectively. The incident wave height H_i was 4.6 cm and the wave period T was 1.27 s. Waves were obliquely incident with an angle of 20° normal to the initial shoreline. The depth of closure was given as $h_c = 2.5H$, where H is the wave height at a given point. The berm height and equilibrium slope of sand were assumed as 5 cm and 1/5, respectively, on the basis of the experimental results, along with the repose slope of sand of 1/2. The calculation domain was discretized by meshes of 20 cm, and 8 hr of calculation (8×10^4 steps) was carried out using the time intervals of $\Delta t = 10^{-4}$ hr.

In the Nabeshima area, the sand spit elongated rightward (southeastward), which is opposite to the direction in the study by San-nami et al. (2014), that is, the sand spit elongated leftward. Therefore, the reversed coordinate system with respect to the x-axis was taken, in which the x-axis is positive rightward. A sandy beach model with an elevation of 10 cm was set as the source of the longshore sand transport in the left half of the calculation domain (Fig. 15(a)). Waves with a height H_i of 4.6 cm were assumed to be incident from the direction normal to the x-axis, causing the predominance of rightward longshore sand transport. To form a sand spit, a break in the coastline direction was set on $x = 0$ m, and on the right side of the corner of the coastline, a seabed was inclined rightward with a 1/40 slope.

Figure 15(b) shows the topography of the elongating sand spit after 1.0 hr. Sand was transported rightward from the sand source, and deposited near the break in the coastline direction on the sloping shallow seabed and a sand spit elongated. Moreover, a slender sand spit of 54 cm width extended after 1.0 hr. With the elongation of the sand spit, the tip of the sand spit gradually entered into the zone with a large water depth. This situation can be clearly seen in Fig. 16, in which the topographies in the rectangular area indicated by the dotted line in Fig. 15(b) between t =1.0 and 3.8 hr are shown at 0.2 hr intervals.

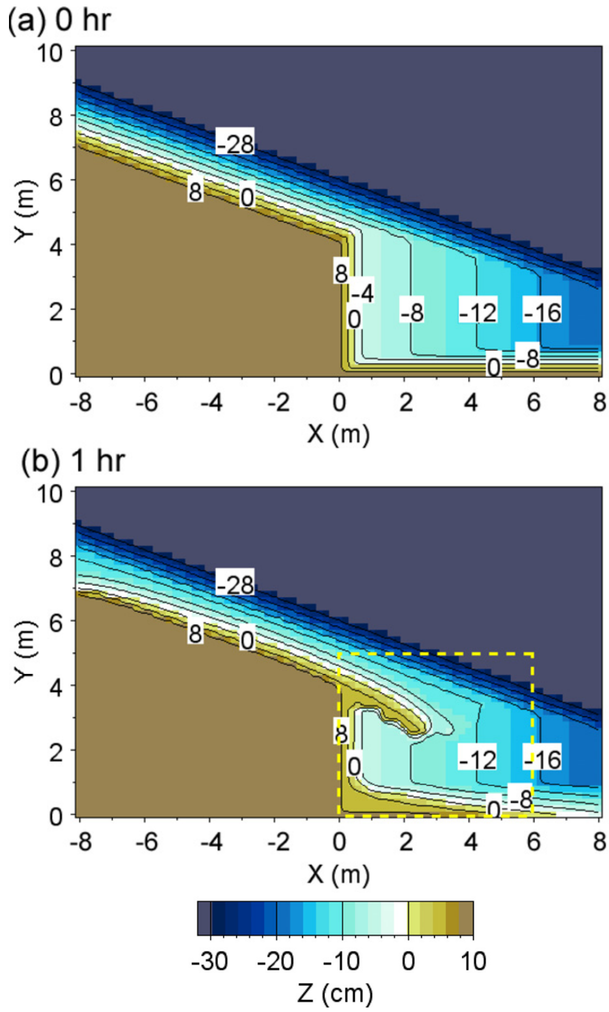

Figure 15. Calculation domain and topography elongationg spit after 1.0 hr.

During t = 1.0 and 2.0 hr, the sand spit elongated rightward and the tip of the sand spit gradually entered into a zone with a large water depth, and the width of the tip increased. Regarding the elongation of the sand spit in the Nabeshima area, the opposite shore was covered with the seawall, so that no beach changes corresponding to the elongation of the sand spit were observed. In the calculation, the wave-sheltering effect of the sand spit itself reached the opposite shore, resulting in the formation of a cuspate foreland. After t = 2.2 hr, the water depth in front of the sand spit decreased and the sand spit almost connected to the opposite shore. After t = 2.8 hr, the sand spit connected to the opposite shore. After the attachment of the tip of the sand spit to the opposite shore, longshore sand transport along the shoreline was possible and a large amount of sand was transported and a smooth, continuous shoreline was formed. The same topographic changes were observed in the aerial photograph taken on December 10, 2004 (Fig. 12(f)) and that taken on December 19, 2006 (Fig. 12(h)). Also, the same phenomena were observed downcoast of the Pengambengan fishing port in the western part of Bali Island, Indonesia (Uda et al. 2015).

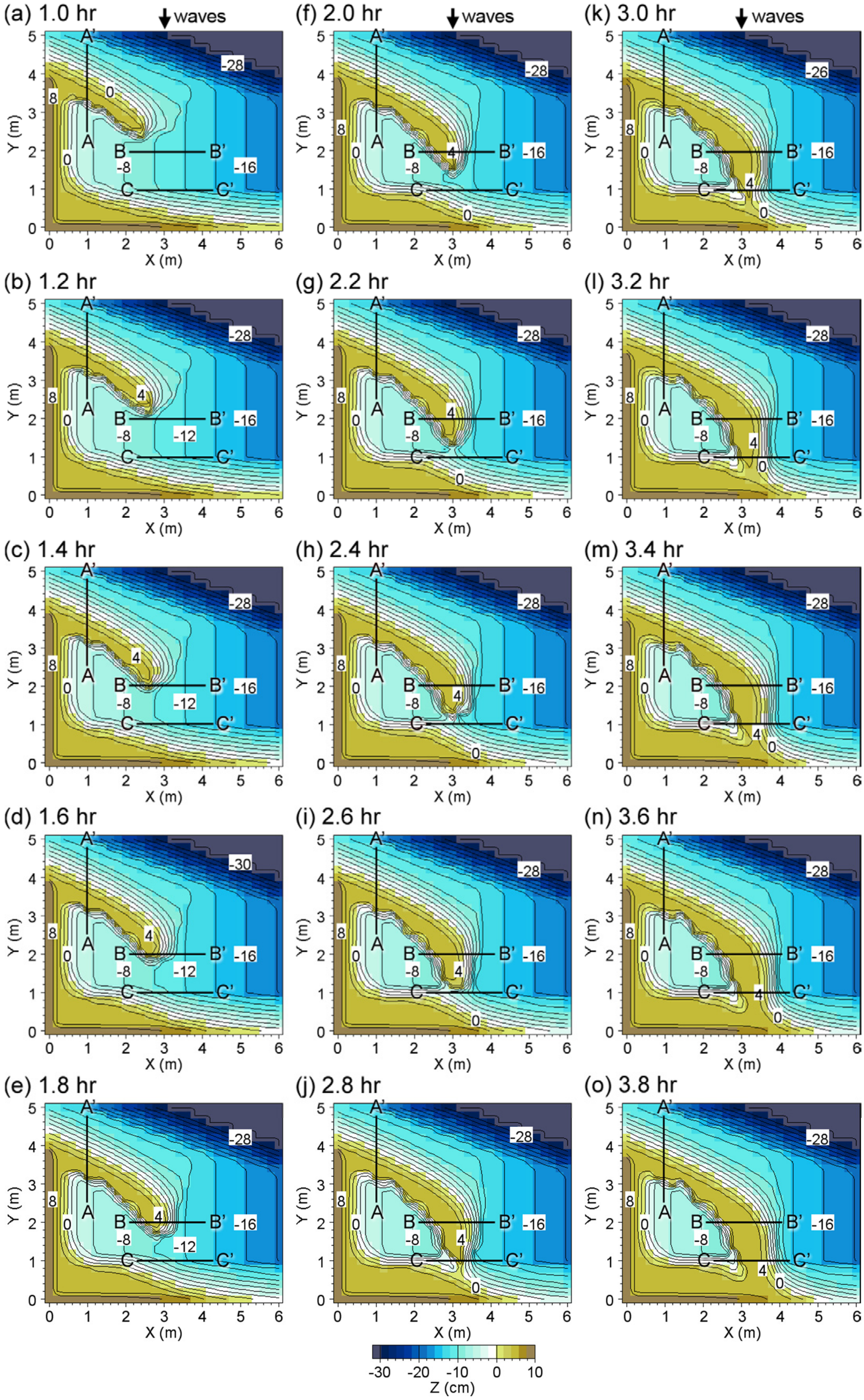

Figure 16. Formation of a barrier in a rectangular zone indicated by dotted line in Fig. 15.

CHANGE IN LONGITUDINAL PROFILE

To investigate the topographic changes associated with the elongation of the sand spit, the changes in longitudinal profile along three transects (A-A': $X = 1$ m, B-B': $Y = 2$ m, C-C': $Y = 1$ m, as shown in Fig. 16) are shown in Fig. 17. Along transect A–A' located near the break point in the coastline, although the seaward slope of the beach was gradually eroded, resulting in the shoreline recession, the barrier shifted landward as a whole at the same time, as a result of the sand deposition on the lagoon side of the barrier owing to the cross-shore sand transport over the barrier. However, after $t = 1.6$ hr when the tip of sand spit extended sufficiently long, the change in beach profile became small compared with those along transects B–B' and C-C', as mentioned later. Along transect B–B' with a uniform slope of 1/40 at the initial stage, the barrier rapidly developed between $t = 1.2$ and 1.8 hr, and then the width of the barrier increased with time owing to the further deposition of sand along the seaward slope of the barrier.

Along transect C-C' with a uniform initial slope of 1/40, a gentle slope was formed with the development of a cuspate foreland on the opposite shore of the sand spit by $t = 2.6$ hr, and then a barrier rapidly developed near the offshore end of the gentle slope. The rapid development of the barrier occurred between $t = 2.6$ and 3.2 hr, with a time lag compared with the time between $t = 1.2$ and 1.8 hr along transect A-A'. This means that longshore sand was successively transported to the tip of the sand spit, resulting in the development of the barrier.

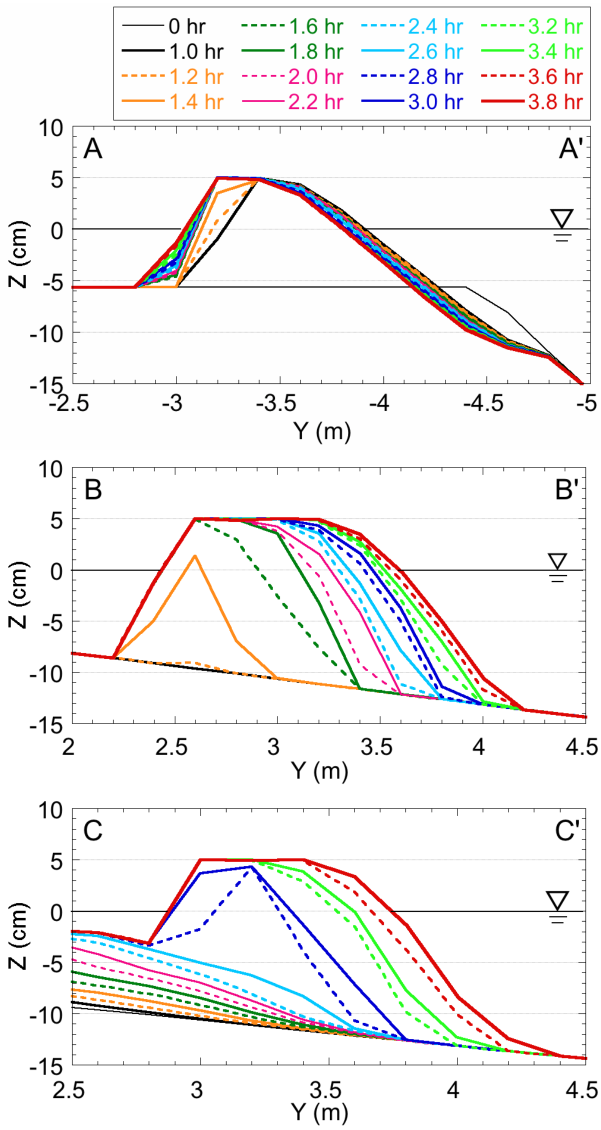

Figure 17. Changes in cross section along transects A–A', B–B' and C–C'.

DISCUSSION

The topographic changes of a barrier in the Nabeshima area were investigated from the stage that the sand spit has significantly elongated, whereas the numerical simulation of elongation of a sand spit was carried out from the initial stage without a sand spit. Therefore, when comparing both results, the same stage of the development of the sand spit must be selected: in this study, the beach changes after t =1.6 hr when the sand spit monotonically extended were selected, similarly to the formation of a barrier in the Nabeshima area. The beach width across transects A-A' and B-B' located at the base and the head of the sand spit, respectively, was obtained from Fig. 17 and is shown in Fig. 18. This result can be compared with the same result shown in Fig. 13, and it is found that a constant volume of sand is continuously transported to the tip of the sand spit alongshore, while maintaining a constant width at the base of the sand spit, whereas near the tip of the sand spit, the width of the sand spit increases over time, because sand is successively supplied from upcoast.

Uda et al. (2008) investigated the deformation of a barrier in the Sanbyakken area located west of Nakatsu Port, as shown in Fig. 1, and concluded that the height of the sand bar and the elevation of the tidal flat are +5 and +2 m above DL, respectively, together with the characteristic height of beach changes (average thickness of sand layer) of 2.8 m. The Nabeshima and Sanbyakken areas both face the Nakatsu tidal flat and are only 6 km apart; therefore, in the Nabeshima area, the same characteristic height of beach changes as that in Sanbyakken area could be employed. When the planar area of the barrier, as shown in Fig. 12, is multiplied by the height of 2.8 m, the volume of the barrier becomes 26,320 m^3. On the other hand, Seino et al. (2007) found that the longshore sand transport ranges between 589 and 2,518 m^3/yr on the basis of the deformation of a sand bar in the Sanbyakken area. Because the development of a barrier in the Nabeshima area started at least since 1981, 32 years have passed until 2013. By dividing the volume change by this period, the average longshore sand transport is estimated to be 823 m^3/yr, which drops in the range of the measured transport rate. Thus, in the Nabeshima area, a rather small-scale barrier was considered to have developed over a period of 32 years, depending on the available volume of sand and rather calm wave conditions in the tidal flat. In the Nabeshima area, artificial alteration forcibly carried out in the tidal flat was the cause of the development of the barrier.

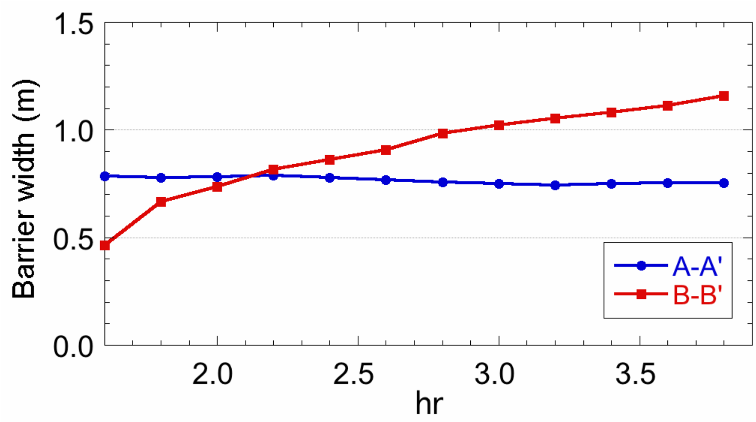

Figure 18. Changes in barrier width along transects A–A' and B–B'.

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