FIELD INVESTIGATION OF TOPOGRAPHIC RESPONSE TO FLOODS AND WAVES AROUND TENRYU RIVER MOUTH

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Bathymetric changes around the mouth of the Tenryu River, one of the largest rivers in Japan and flowing into the Pacific Ocean, were analyzed using the narrow-multibeam survey data taken between 2006 and 2011. The formation/deformation of the river mouth terrace triggered by floods, the formation of bar and trough topography associated with the incidence of storm waves, and the gradual erosion by the imbalance of longshore sand transport were investigated. The sand volume in the study area decreased by 1.66×10^6 m^3 between 2006 and 2011 at a rate of 3.1×10^5 m^3/yr. Because fluvial sand is assumed to have been supplied at a rate of 1.5×10^5 m^3/yr, the rate of decrease in sand volume transported away from the river mouth area by longshore sand transport reached 4.6×10^5 m^3/yr. Urgent measures to mitigate beach erosion are required.

Keywords: River mouth; Tenryu River; Narrow-multibeam survey; bathymetric changes; river mouth terrace

INTRODUCTION

The Enshu-nada coast facing the Pacific Ocean has developed as a marginal coast of the Tenryu River delta, which was formed by the abundant supply of fluvial sand from the Tenryu River, as shown in Fig. 1. This river mouth delta was formed over a long period as a result of the gradual shoreline advance, while the sand supply from the river and longshore sand transport away from the river mouth are almost kept in dynamic equilibrium. However, large dams including the Sakuma Dam have been constructed and extensive riverbed mining has been carried out to obtain construction materials since the 1950s, and sand supply to the river mouth has markedly decreased while losing the balance between sand supply from the river and longshore sand transport, resulting in the shoreline recession around the river mouth (Nagashima et al., 2005). To mitigate the shoreline recession around the river mouth by increasing sand discharge of the river, the bypassing of sand deposited in the reservoir upstream of the Sakuma Dam has been investigated, and its effect has already been predicted by using the contour-line-change model (Miyahara et al., 2010; 2011). In the realization of the plan, the investigation of the topographic changes around the river mouth in recent years after the fluvial sand supply had markedly decreased is important. In this study, the results of the narrow-multibeam survey carried out along the Enshu-nada coast including the Tenryu River mouth by the Hamamatsu River and Road Office of the Ministry of Land, Traffic and Infrastructure were analyzed to investigate the topographic changes in an extensive area. In particular, the responses of the river mouth topography to the floods of the Tenryu River and storm waves were investigated in detail along with the estimation of the recent decrease in sand volume offshore of the river mouth.

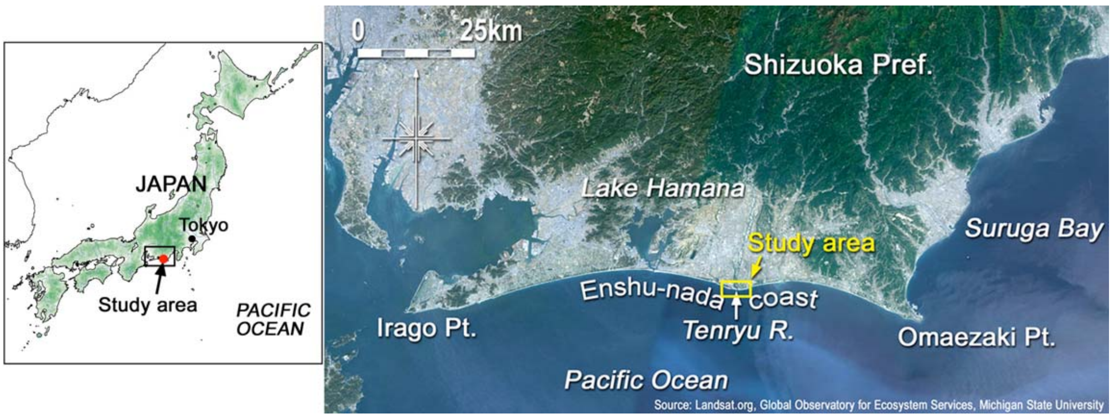

Figure 1. Location of Tenryu River delta facing the Pacific Ocean.

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COMPARISON OF AERIAL PHOTOGRAPHS

In recent years, the shoreline around the Tenryu River mouth rapidly receded because of the decrease in sand supply from the river. Figures 2(a) and 2(b) show the aerial photographs taken in January 2006 and January 2012, respectively. The Hamamatsu-goto coast, west of the river mouth, has been protected by six detached breakwaters, and a river mouth bar extended eastward from the foot of these detached breakwaters with an opening very close to the east bank of the river. On the Ryuyo coast, east of the river mouth, a sandy beach of 100 m width extended continuously between the left bank of the river and five detached breakwaters. By January 2012, the right river mouth bar was eroded, and the beach width of the right river mouth bar was significantly reduced. The beach width in front of the seawall of the Hamamatsu-goto coast is very narrow, so that the wave overtopping is feared at present.

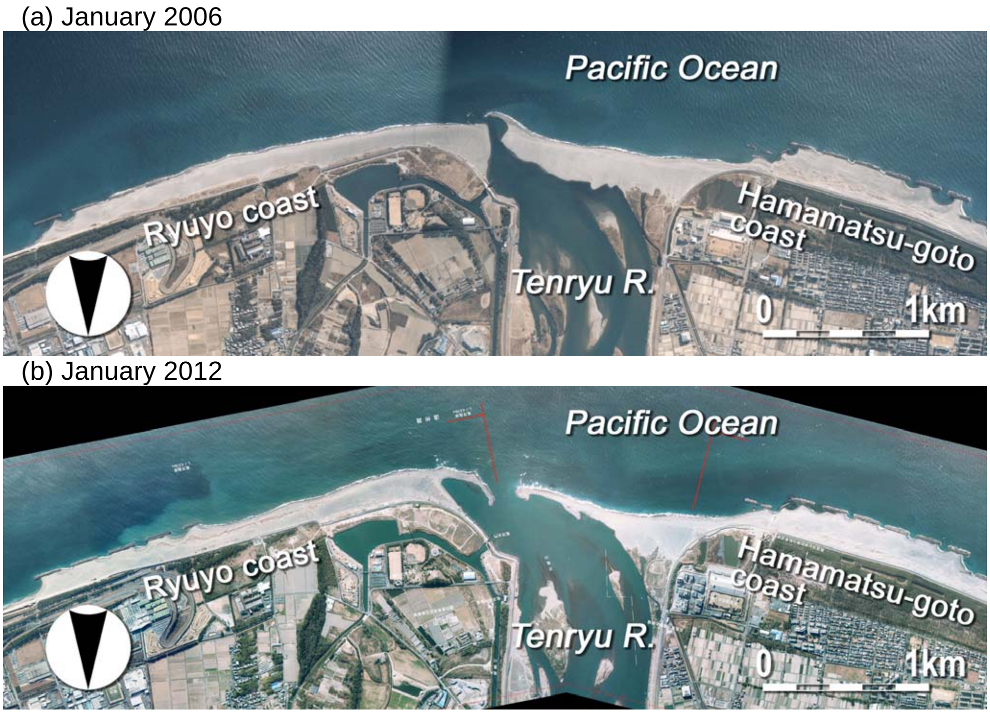

Figure 2. Aerial photographs of Tenryu River mouth taken in 2006 and 2012.

FLOOD AND WAVE CONDITIONS DURING OBSERVATION PERIOD

The bathymetric changes offshore of the river mouth were investigated using the narrow-multibeam survey data obtained since July 2006. In particular, the responses of the river mouth topography to floods and waves were investigated in detail between January 2008 and December 2011. During the observation period, the records of the river discharge and waves were available between 2008 and 2010, and between 2008 and 2011, respectively. Figure 3 shows the daily mean discharge of the Tenryu River between January 2008 and December 2010 measured at Kashima observatory 25 km upstream of the river mouth along with the number of narrow-multibeam surveys. In the observation period of the responses of the river mouth topography to floods and waves, floods with a relatively large discharge occurred June 2008, the end of July 2009, April and June 2010 and July 2010. In particular, the flood in July 2010 was caused by the heavy rainfall associated with a low pressure and the daily discharge reached a maximum of 3640 m^3/s.

Figure 4 shows the change in significant wave height $H_{1/3}$ and wave period during the observation period obtained at the Ryuyo wave observatory located offshore of the Tenryu River mouth. During the observation period of the responses of the river mouth topography to floods and waves, storm waves with the significant wave height $H_{1/3}$ larger than 5 m occurred two times: $H_{1/3}$ = 5.06 m on March 14, 2009 and $H_{1/3}$ = 10.75 m on October 8, 2009 owing to Typhoon 0918. The energy mean wave height and wave direction in each observation period are summarized in Table 1.

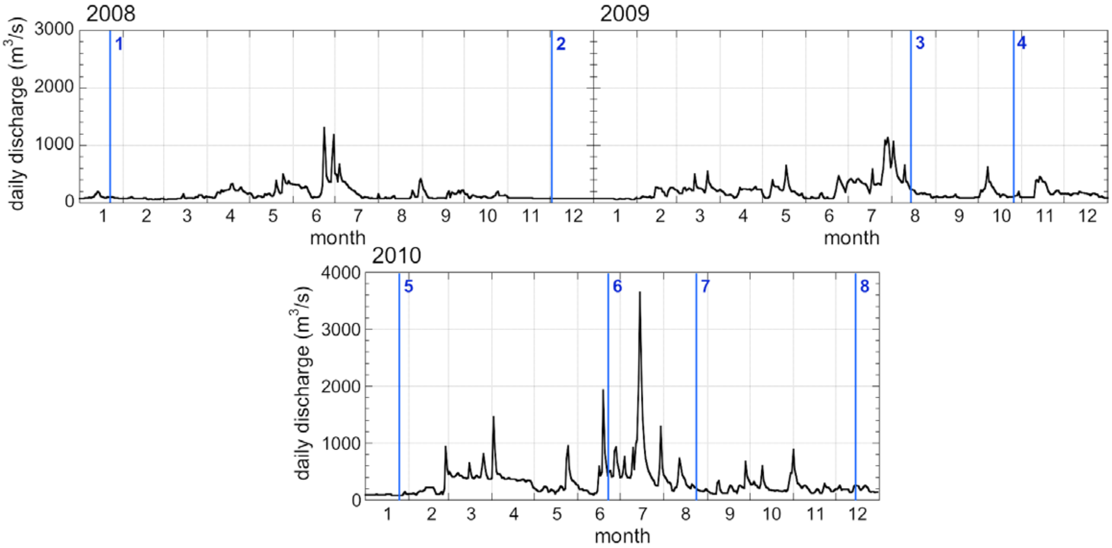

Figure 3. Discharge of Tenryu River between 2008 and 2010.

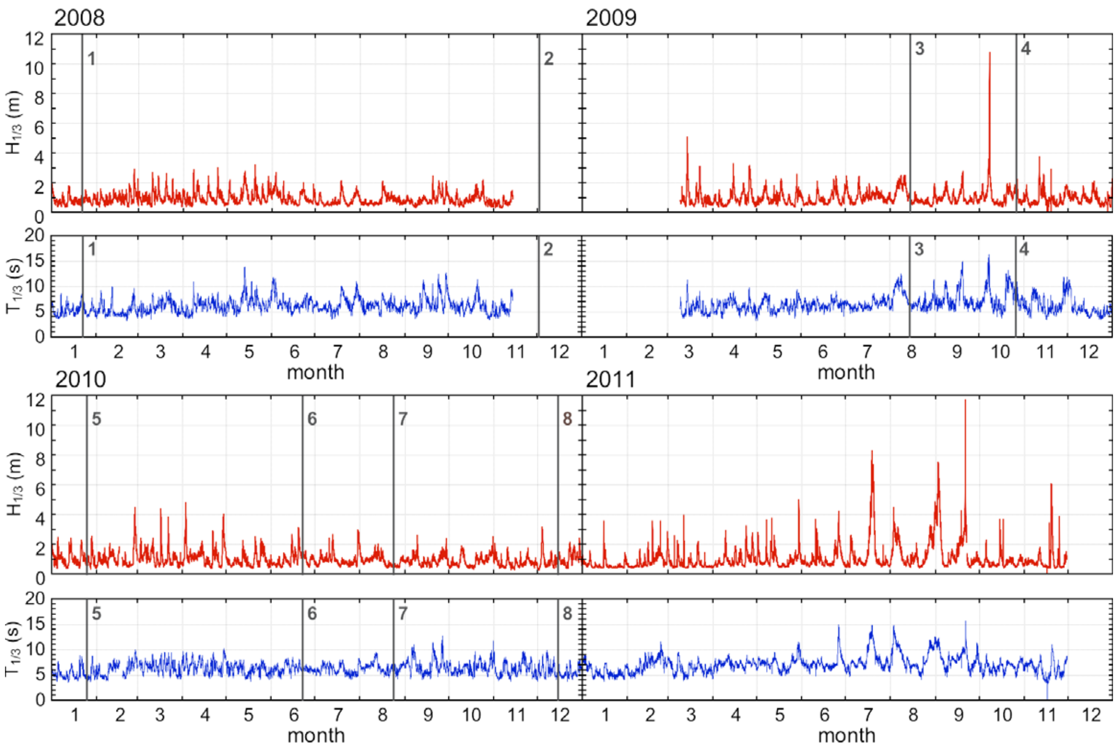

Figure 4. Wave climate between 2008 and 2011.

Table 1. Wave conditions during field observation.

Observation No.	1-2	2-3	3-4	4-5	5-6	6-7	7-8
Energy-mean significant wave height (m)	1.06	1.20	1.40	1.10	1.27	1.05	1.20
Wave period (s)	6.3	6.4	7.4	5.9	6.4	6.3	6.4
Wave direction (NX°E)	171	190	166	208	186	198	190
Maximum wave height (m)	3.2	5.1	10.8	3.1	4.8	2.9	3.1

LONG-TERM CHANGES IN RIVER MOUTH TOPOGRAPHY

Using the narrow-multibeam survey data taken between July 2006 and December 2011, the overall bathymetric changes around the river mouth were first investigated. Figure 5 shows the bathymetries in July 2006, August 2009 and December 2011. In July 2006, a 1.3-km-long river mouth bar extended from the right bank with an opening close to the left bank. A river mouth terrace was formed with protruding contours up to -10 m along with the formation of the foreset slope offshore of the terrace. On the Hamamatsu-goto coast, a deep trough with a maximum depth of 9 m developed offshore of the detached breakwaters, as well as the formation of a bar in the depth zone between -6 and -10 m.

On the Ryuyo coast, east of the river mouth, bar and trough topography was also formed. Beyond these bars and troughs, the offshore contours smoothly extended alongshore. The depth by which the significant longshore changes in the nearshore contours ceases is approximately 10 m, suggesting that the depth of closure of the coast is 10 m.

By August 2009, although the river mouth bar maintained its form, the width of the river mouth terrace expanded alongshore, and in this case, the offshore limit of the protruding contours of the terrace was again located at a depth of 10 m. On the other hand, the troughs formed offshore of the Hamamatsu-goto and Ryuyo coasts were reduced in scale because of the incidence of calm waves before the observation, as shown in Fig. 4.

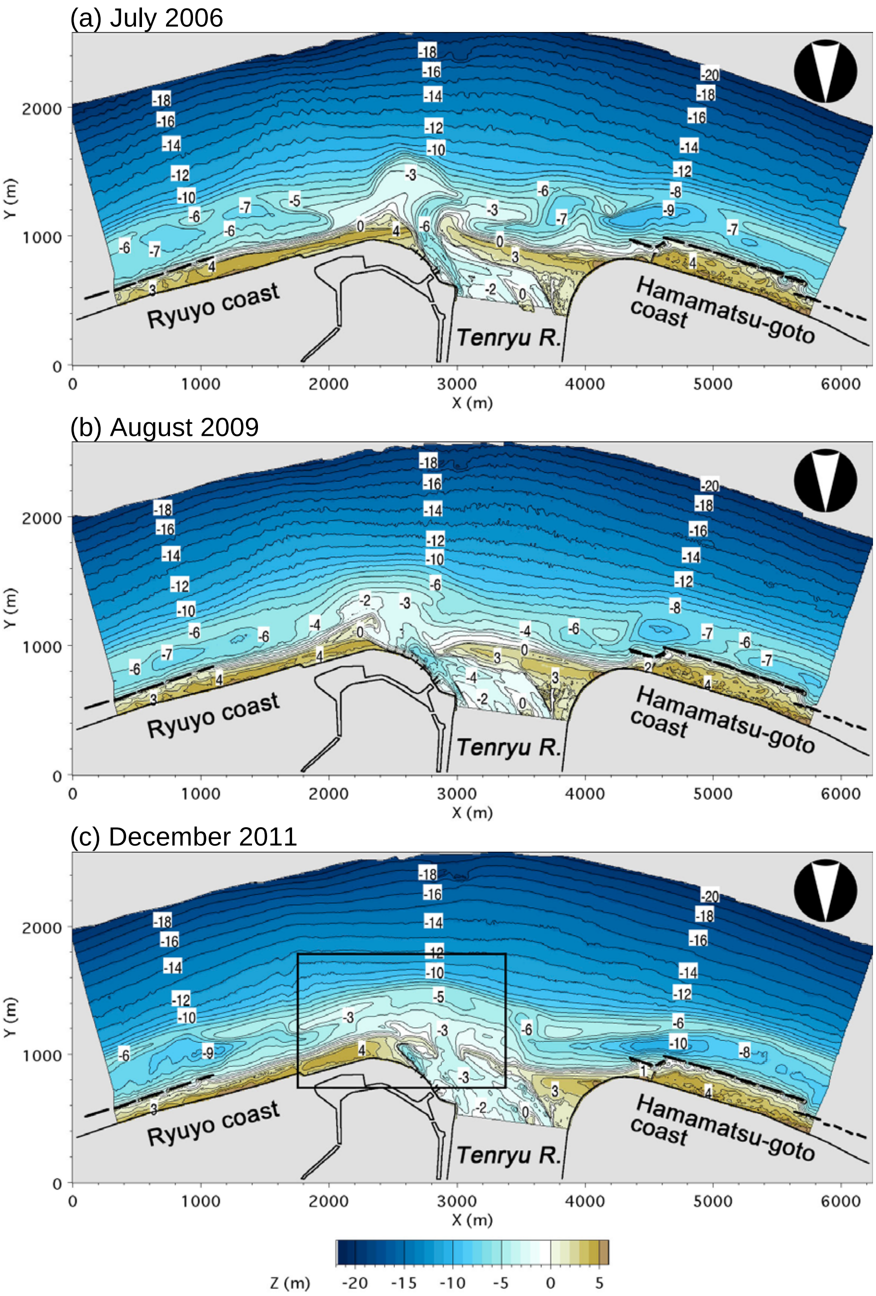

Figure 5. Bathymetries around Tenryu River mouth measured in July 2006, August 2009 and December 2011.

By December 2011, smooth contours were formed offshore of the opening of the river mouth, and the troughs further developed on both sides of the river mouth because of the incidence of storm waves before the observation, as shown in Fig. 4. Furthermore, the river mouth bar extending from the right bank markedly reduced in scale.

Figure 6 shows the bathymetric changes around the Tenryu River mouth between July 2006 and December 2011 together with the bathymetry in December 2011. The bathymetric changes occurred in the depth zone shallower than 10 m, by which it is confirmed that the depth of closure of the coast is 10 m. Sand was also deposited along the bars with the formation of bar and trough topography due to storm waves. A severely eroded zone expanded from the area immediately offshore of the detached breakwaters on the Hamamatsu-goto coast to the river mouth bar as a result of the successive erosion, which was supposed to be caused by the westward longshore sand transport. Thus, the study area is characterized by the formation/deformation of the river mouth terrace triggered by floods and wave action, the formation of bar and trough topography associated with storm waves, and the gradual erosion by the imbalance of longshore sand transport.

The volume changes in a zone shallower than -12 m in the entire area shown in Fig. 6 were calculated with reference to the bathymetry in July 2006. Figure 7 shows the results with the evaluation of the volume changes in the areas east and west of the opening of the river mouth at X = 2800 m. Although the sand volume in the area between X = 0 and 2800 m east of the river mouth was almost kept constant until 2010, it markedly decreased in 2011 when several storm waves with high energy hit the coast. The sand volume in the area between X = 2800 and 6200 m west of the river mouth markedly decreased in 2007 and 2011. In particular, the decrease in sand volume in 2011 was very large. In five years and five months, the sand volume in the study area decreased by 1.66×10^6 m^3 at a rate of 3.1×10^5 m^3/yr.

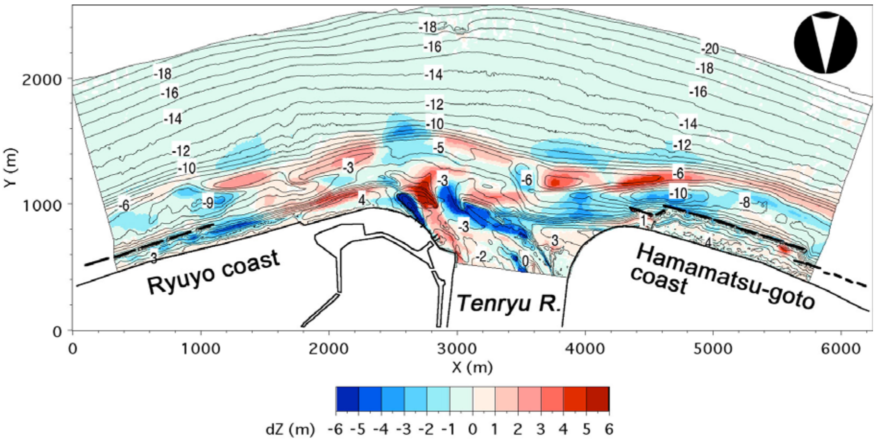

Figure 6. Bathymetric changes around Tenryu River mouth between July 2006 and December 2011 along with bathymetry in December 2011.

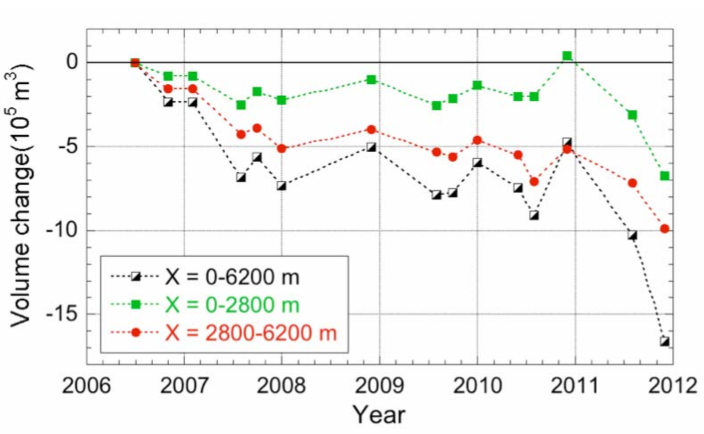

Figure 7. Volume change in depth zone shallower than -12 m in offshore area of Tenryu River mouth.

SHORT-TERM VARIATION OF RIVER MOUTH TOPOGRAPHY DUE TO FLOODS AND WAVES

The short-term topographic changes of the river mouth due to the floods and waves were investigated in a rectangular area, as shown in Fig. 5(c), using the bathymetric data obtained by the narrow-multibeam surveys. The observation was carried out eight times with the 1st observation in January 2008 and the 8th observation in December 2010.

1st observation (January 2008) to 2nd observation (December 2008)

Figures 8(a) and 8(b) show the bathymetries in January and December 2008, respectively. In January 2008, the contours offshore of the river mouth smoothly extended alongshore. However, in December 2008, the channel of the opening moved eastward by 220 m, and simultaneously, the east bank of the mouth was eroded, forming an offshore river mouth terrace with marked deposition of sand up to 3 m depth. During the observation period, two floods with daily mean discharges of 1314 and 1192 m^3/s occurred on June 23 and 30, 2008, respectively, owing to the rainfall associated with the low pressure, although a calm wave condition continued, as shown in Fig. 4.

Figure 8(c) shows the bathymetric changes between the two periods. The left bank of the river mouth was severely eroded, and eroded sand was transported offshore to form a river mouth terrace. In addition, the tip of the right river mouth bar was eroded and the sand was transported landward so that the right river mouth bar was forced to move landward. Thus, the topographic changes during this period were characterized by the discharge of the left river bank due to floods and the landward movement of the right river mouth bar by waves.

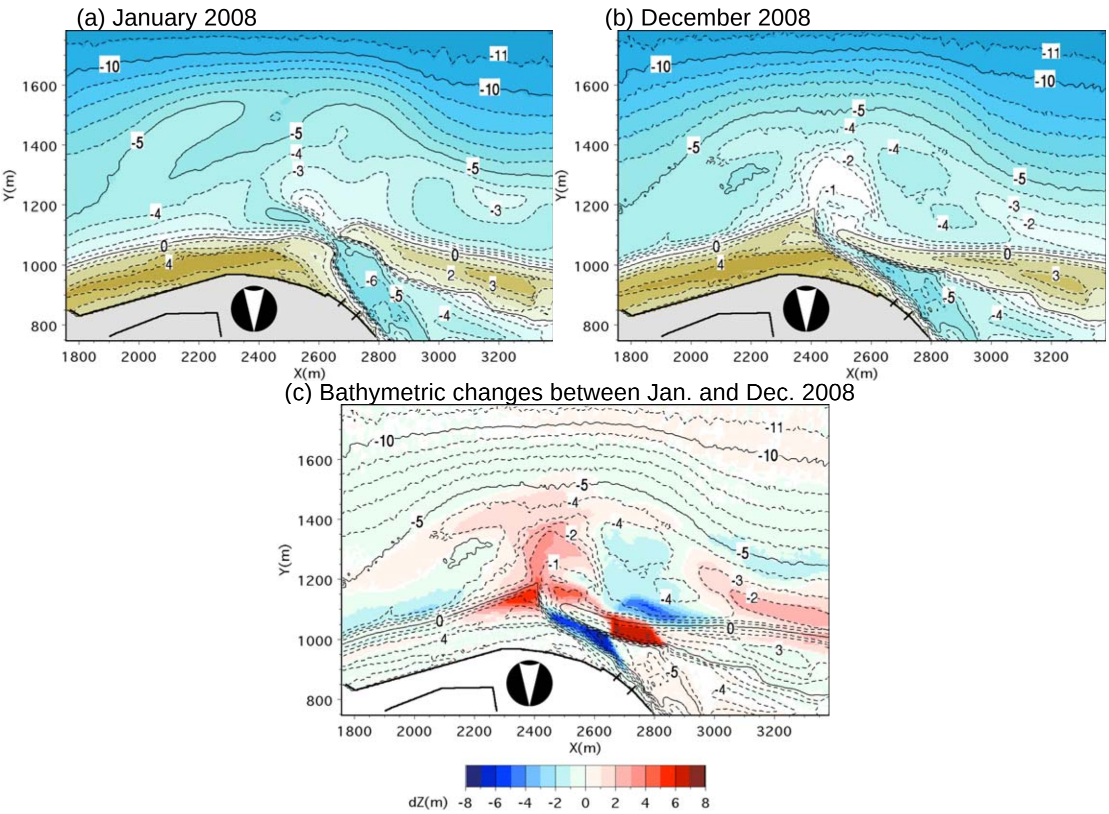

Figure 8. Bathymetries in January and December 2008, and bathymetric changes between these periods.

2nd observation (December 2008) to 3rd observation (August 2009)

Figures 9(a) and 9(b) show the bathymetries in December 2008 and August 2009, respectively. During this observation period, a flood with a daily mean discharge of 1140 m^3/s occurred with a long duration of 5 days owing to the precipitation associated with a low pressure between July 29 and August 2, 2009. As a result, a slender right river mouth bar extending eastward was truncated and disappeared over a distance of 380 m, resulting in the formation of a wider terrace and the opening width as wide as 500 m. Although the shoreline east of the river mouth extended straight in December 2008, the shoreline rotated counterclockwise by 5° near the river mouth by August 2009, and a sand spit was formed at the west end. The development of the sand spit with the form shown in Fig. 9(b) suggests that waves were incident from the southeast on the east side of the river mouth, as shown by an arrow.

Figure 9(c) shows the bathymetric changes between December 2008 and August 2009. Marked erosion concentrated in the channel along the left bank together with the erosion of the right river mouth bar, and eroded sand was mainly deposited in the area shallower than -3 m offshore of the left bank. The bathymetric changes in this period are characterized by the scouring at the river mouth owing to the flood currents and the resultant formation of a wide river mouth terrace, in which dominant topographic changes were observed in a zone shallower than -5 m.

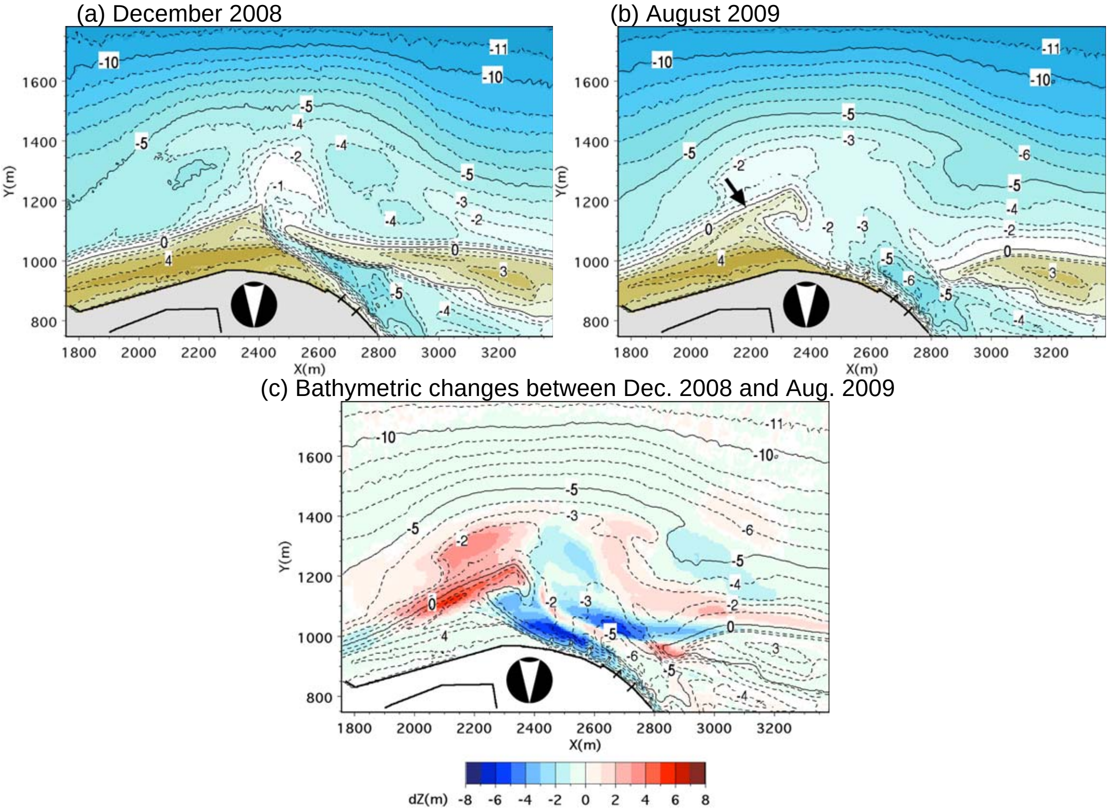

Figure 9. Bathymetries in December 2008 and August 2009, and bathymetric changes between these periods.

3rd observation (August 2009) to 4th observation (October 2009)

Typhoon 0918 hit the coast on October 8, 2009 with storm waves that recorded the significant wave height $H_{1/3}$ = 10.8 m and wave period T = 13.9 s, as shown in Fig. 4, and a flood with a mean daily discharge of 630 m^3/s occurred, as shown in Fig. 3. Figures 10(a) and 10(b) show the bathymetries in August and October 2009, respectively. The sand spit formed at the left bank of the river mouth significantly deformed and connected to the shoreline leaving a lagoon inside. Also, the tip of the channel extending offshore was buried by the movement of the sand spit. At the same time, the nearshore bar shown by the contour line with -2 m depth enclosed this deep channel. The opening was narrowed from 500 m in August 2009 to 225 m in October 2009, because of the action of storm waves.

Figure 10(c) shows the bathymetric changes between August and October 2009. On the left bank, sand was transported into the channel with the movement of the sand spit leaving the erosion zone along the shoreline on the left bank. Similarly, the right river bank was formed again while burying the outer marginal part of the channel by sand supplied from the depth zone shallower than -4 m immediately offshore of the right river mouth bar. Regarding this movement of the right river mouth bar, Takagawa et al. (2010) showed on the basis of the investigation of the X-band radar image that the deformation of the bar occurred within 3 hours during Typhoon 1018 because of high tide and storm waves with a significant wave height larger than 10 m. In this period, the action of storm waves, by which the sand deposition in the nearshore zone was significant, was mostly dominated compared with that due to floods.

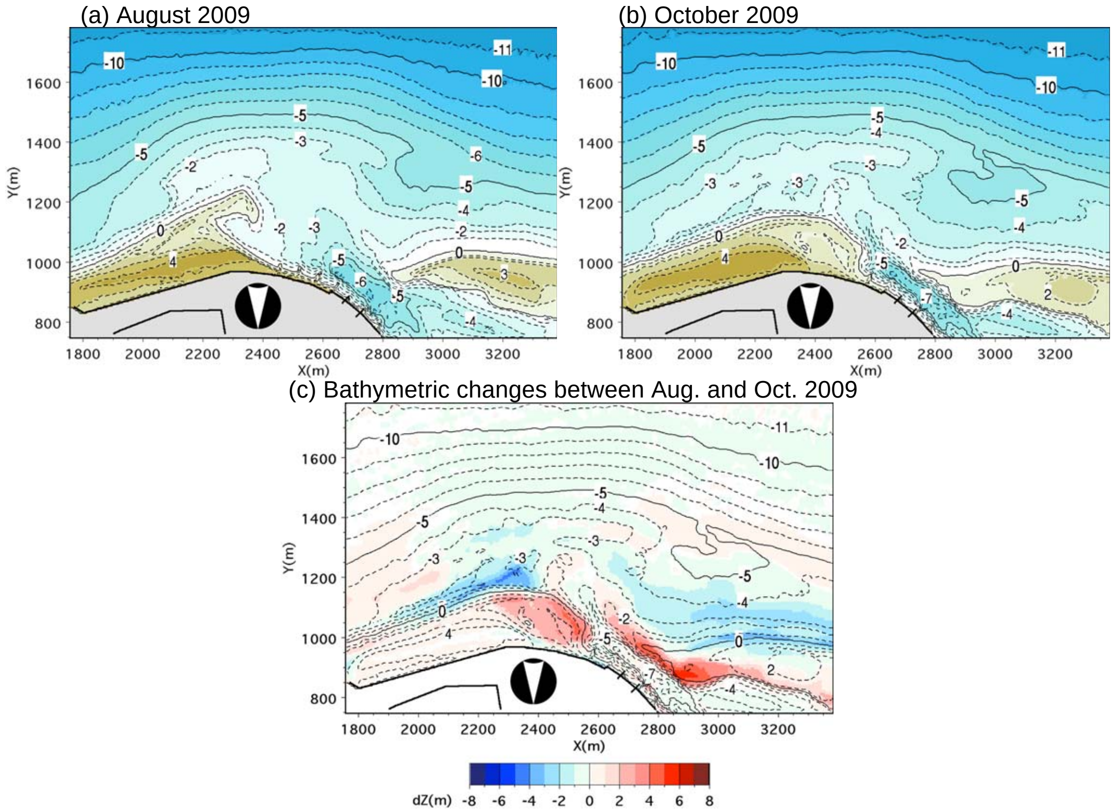

Figure 10. Bathymetries in August and October 2009, and bathymetric changes between these periods.

5th observation (January 2010) to 6th observation (June 2010)

Figures 11(a) and 11(b) show the bathymetry in January and June 2010, respectively. In January 2010, a terrace was formed offshore of the river mouth with an opening directing southeast and narrowed up to 50 m owing to the elongation of the right river mouth bar. However, because three floods with Q = 950 m^3/s on February 27, Q = 1470 m^3/s on April 2 and Q = 950 m^3/s on May 25 occurred by June 2010, a deep channel extending in the direction normal to the shoreline was formed at the river mouth, and the opening width was enlarged up to 100 m, resulting in the further development of the terrace owing to the deposition of sand. At the same time, a slender, submerged bar extended west of the opening.

Figure 11(c) shows the bathymetric changes between January and June 2010. The channel was deepened due to floods causing the scouring of the channel up to a maximum of 9 m depth. Although sand was deposited in an extensive area offshore of the river mouth due to the three large floods, dominant sand deposition occurred at the tip of the right river mouth bar and along the shoreline east of the mouth.

6th observation (June 2010) to 7th observation (August 2010)

Figures 12(a) and 12(b) show the bathymetry in June and August 2010, respectively. Although there was a flat terrace of 2 m depth offshore of the river mouth in June 2010, the right river mouth bar was eroded and the opening was enlarged up to 300 m in width along with the erosion of the east bank of the river because two floods with Q = 1930 m^3/s on June 19 and Q = 3640 m^3/s on July 16 occurred by August 2010. Sand transported by flood currents was deposited offshore of the river mouth, and a slender bar of 330 m length emerged. Simultaneously, the offshore contours up to the depth of 9 m markedly protruded due to offshore sand transport.

Figure 12(c) shows the bathymetric changes between June and August 2010. The right river mouth bar was severely eroded and the sand was transported offshore. Also, sand was transported offshore for a slender offshore bar to emerge immediately offshore of the previous channel. Thus, the disintegration of the river mouth bar was dominant due to the floods during this period.

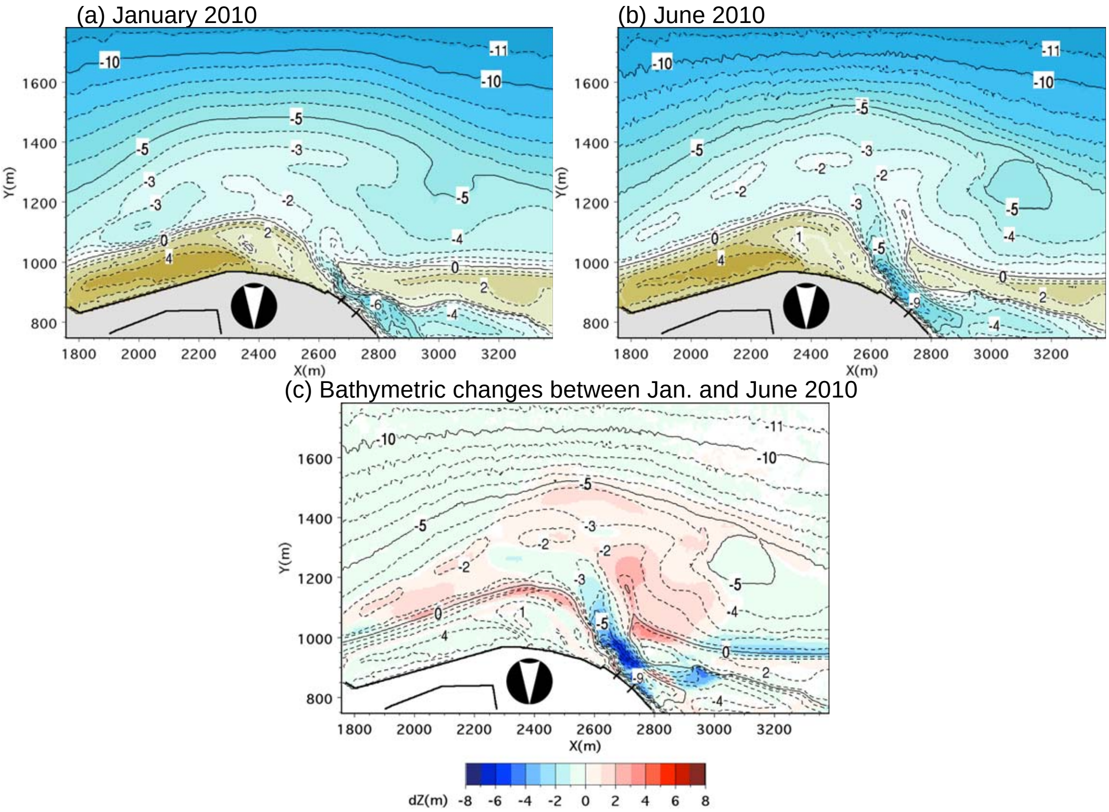

Figure 11. Bathymetries in January and June 2010, and bathymetric changes between these periods.

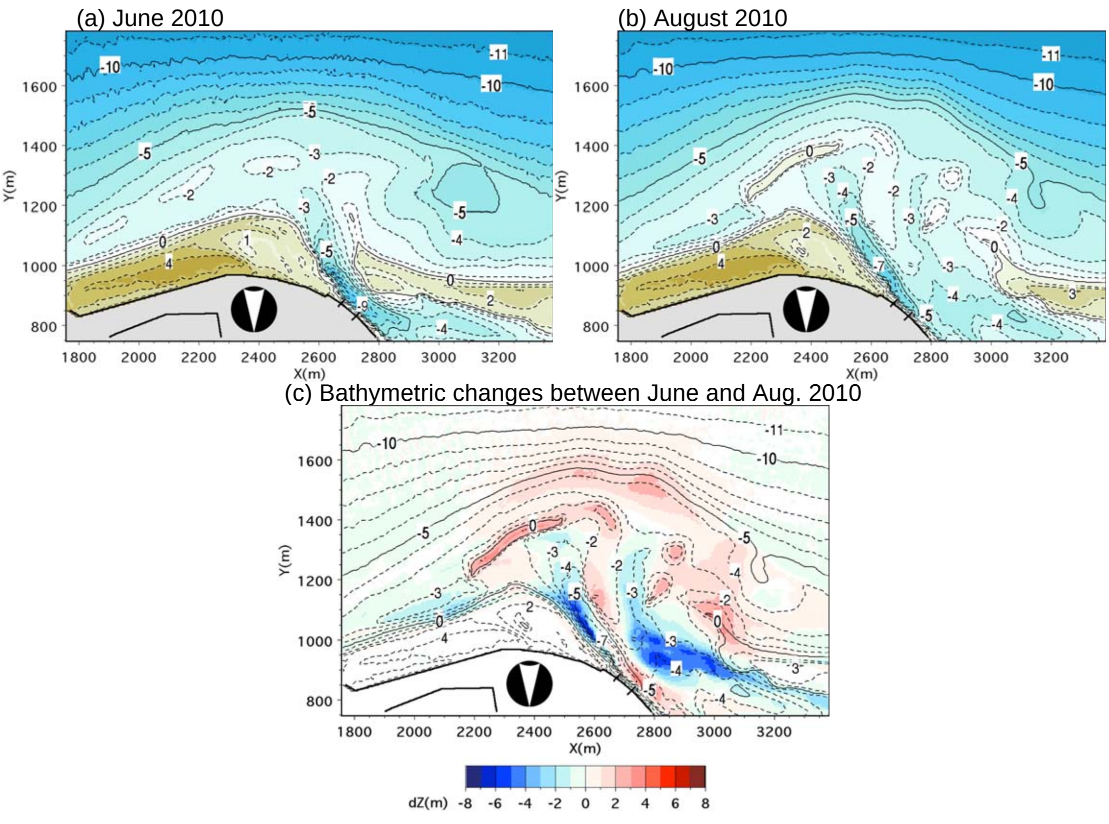

Figure 12. Bathymetries in June and August 2010, and bathymetric changes between these periods.

7th observation (August 2010) to 8th observation (December 2010)

Figures 13(a) and 13(b) show the bathymetry in August and December 2010, respectively. Because a calm wave condition continued in this period, as shown in Fig. 4, shoreward sand transport was predominant, resulting in the elongation of the right river mouth bar along with the development of a sand spit at the tip of the sand bar of the left bank toward the opening. Although the shape of the sand spit is similar to that in August 2009, the location of the sand spit further shifted upstream. On the other hand, a slender sand bar formed offshore of the river mouth in August 2010 was eroded to form a flat seabed.

Figure 13(c) shows the bathymetric changes between these periods. Sand accumulated at the tip of the right river mouth bar and a sand spit was formed on the east river bank. A calm wave condition and lack of floods caused shoreward sand transport around the river mouth.

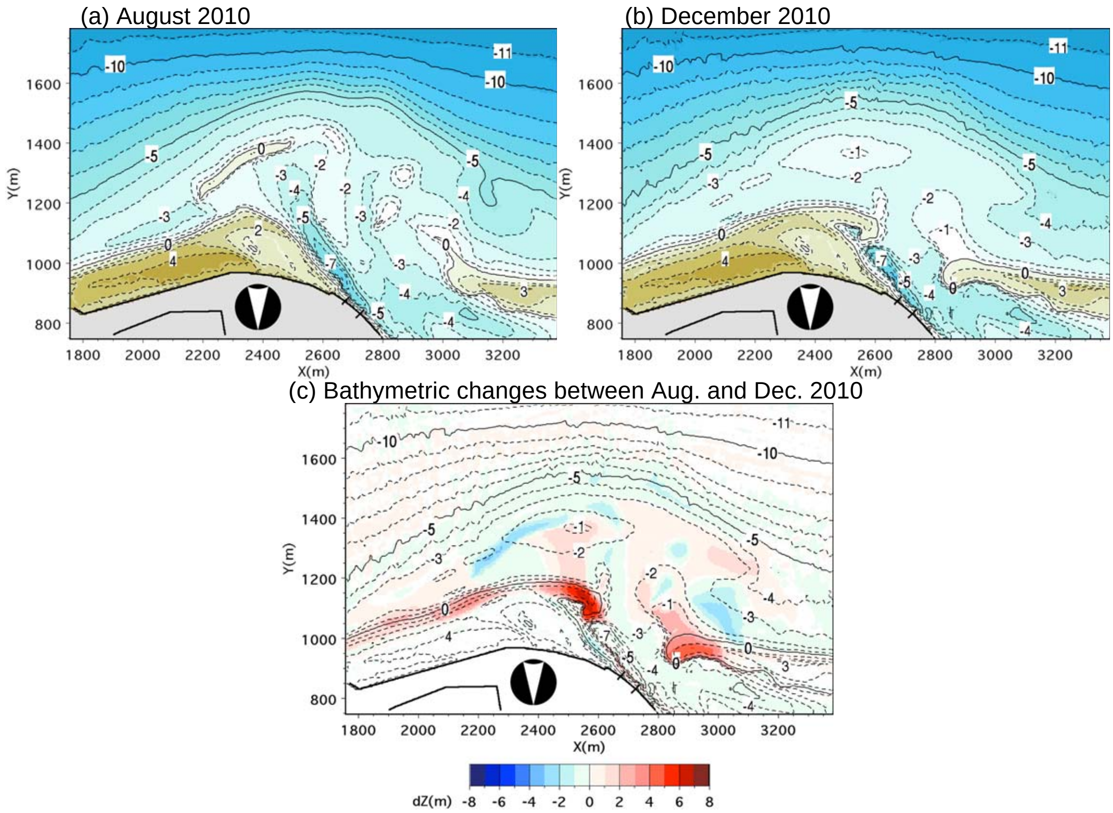

Figure 13. Bathymetries in August and December 2010, and bathymetric changes between these periods.

CLOSURE OF ARTIFICIAL OPENING OF RIVER MOUTH BAR DUE TO WAVE ACTION

On July 15, 2007, a flood with a maximum discharge of 5532 m^3/s occurred, and the flood currents flowed out through an artificial opening excavated on the foreshore of the right river mouth bar, and a channel of 2 m depth was formed, and then this opening was buried by sand between August and October 2007.

Figure 14 shows the enlarged figure showing the contours around the opening. Immediately after the flood, a deep channel of 2 m depth was formed and the contours surrounding the tip of the right river mouth bar protruded offshore. The opening, however, was entirely buried by sand and a straight shoreline was formed by October 2007 owing to the depositional action of waves. These beach changes were successfully predicted using the BG model by Serizawa et al. (2009).

Figure 15 shows the changes in the longitudinal profiles along transects A-A′, B-B′ and C-C′. Although a sand bar with a berm height of 3.5 m developed in February 2007 along transect A-A′, sand was transported offshore by flood currents and deposited in a zone shallower than the depth of 10 m by August 2007. In particular, the sand deposited above mean sea level was eroded and a flat seabed was formed on the mean sea level. The beach profile was quickly restored and a berm of 2.6 m height was formed again by October 2007. Along transects B-B′ and C-C′, the beach profiles were well maintained between February and August 2007.

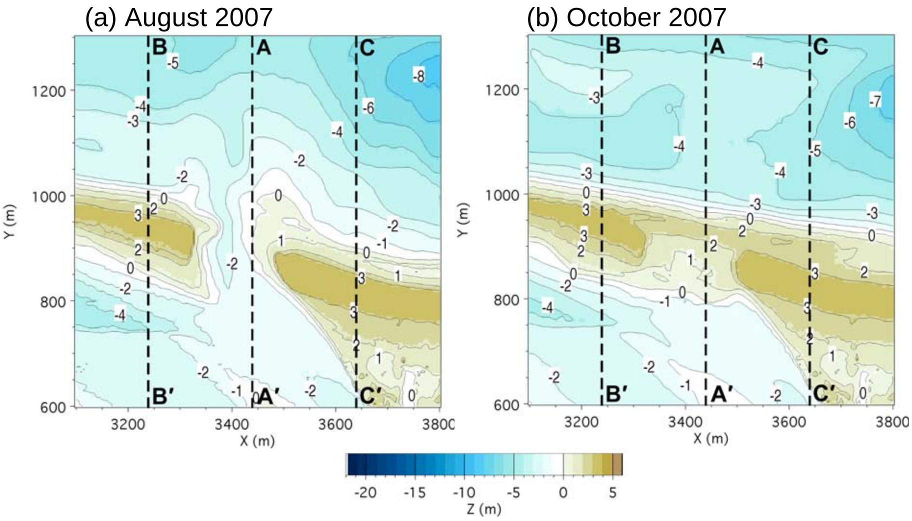

Figure 14. Formation of opening across right river mouth bar and closure of opening due to wave action between August and October 2007.

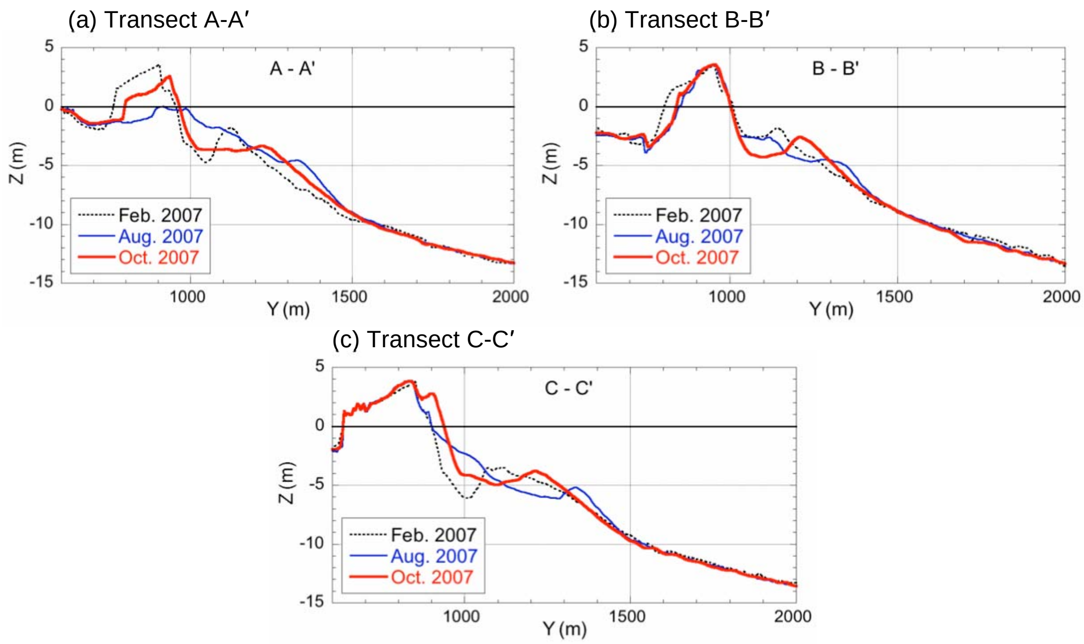

Figure 15. Change in longitudinal profiles along transects A-A', B-B' and C-C'.

DISCUSSION

The sediment budget around this river mouth can be schematically drawn as shown in Fig. 16 and Eq. (1).

$$\Delta V = (Q_0 - Q_1 - Q_2)\,\Delta t \quad (1)$$

The increase in sand volume is due to the fluvial sand supply (Q_0) from the Tenryu River, whereas the decrease in sand volume is due to the westward and eastward longshore sand transport, Q_1 and Q_2, respectively. The net volume change ΔV in the study area decreased by 1.66×10^6 m^3 in five years and five months (Δt) at a rate of 3.1×10^5 m^3/yr, as shown in Fig. 7.

Miyahara et al. (2010) estimated that the fluvial sediment supply from this river was 6.0×10^5 m^3/yr under the natural condition before the construction of dams and extensive riverbed mining, and the amount of sand supplied from the river was divided into two, 3.0×10^5 m^3/yr, which constituted westward and eastward longshore sand transport. Thus, the decrease rate of sand volume in the examination area is comparable to the eastward and westward longshore sand transport rate estimated from the long-term evolution of the shoreline. They also estimated that the sediment yield after the construction of dams was reduced to 1.5×10^5 m^3/yr, assuming that 25.5% of the sediment yield between the watershed areas downstream and upstream of the dams was maintained. Assuming that the same rate of sand supply of 1.5×10^5 m^3/yr is expected during the observation period, and that Q_1 is equal to Q_2, then we obtain $Q_1 = Q_2 = 2.3\times10^5$ m^3/yr, which corresponds to 77% of the longshore sand transport under the natural condition.

The sand volume in the study area decreased by 1.66×10^6 m^3 between 2006 and 2011 at a rate of 3.1×10^5 m^3/yr. Because the fluvial sand is assumed to have been supplied at a rate of 1.5×10^5 m^3/yr, the rate of decrease in sand volume transported away from the river mouth area by longshore sand transport reached 4.6×10^5 m^3/yr.

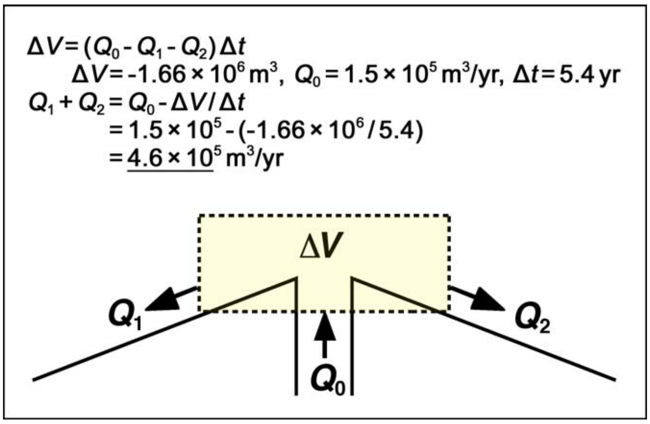

Figure 16. Schematic diagram of sand budget around river mouth.

CONCLUSIONS

The study area around the Tenryu River mouth is characterized by the formation/deformation of the river mouth terrace triggered by floods, the formation of bar and trough topography associated with the incidence of storm waves, and gradual erosion by the imbalance of longshore sand transport. The sand volume in the study area decreased by 1.66×10^6 m^3 between 2006 and 2011 at a rate of 3.1×10^5 m^3/yr. Assuming that the same rate of sand supply of 1.5×10^5 m^3/yr is expected during the observation period, as described by Miyahara et al. (2010), the sand volume around the Tenryu River is decreasing at a rate of 4.6×10^5 m^3/yr by longshore sand transport in both directions, because fluvial sand is assumed to be supplied at a rate of 1.5×10^5 m^3/yr. Under this condition, beach erosion around the Tenryu River mouth will be intensified in the near future. Urgent measures are needed to mitigate the beach erosion in the area around the Tenryu River mouth.

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