THE DEVELOPMENTAL PROCESS OF FLOOD SHOALS BASED ON OBSERVATIONS IN TOUFUTSU LAKE, JAPAN

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ABSTRACT: Recently, the flood tidal sand bars have been developed at the entrance channel of Toufutsu Lake located along Okhotsk Sea in Hokkaido, and they affect flood control, inland water fisheries in lake, and so forth. In this study, we aimed to reveal the developmental process of sand bars by observations, which are velocity observation, water level observation, bed material investigation and video monitoring. Followings were major accomplishments of this study. (1) The maximum magnitude of reverse velocity at St.400 in the entrance channel during the periods of flood-tide was faster than that of normal velocity during the periods of ebb-tide. (2) The relationship between velocity at SP400 and friction velocity at SP400 during the periods of flood-tide is different from that during the periods of ebb-tide. (3) The flood tidal sand bars at the entrance channel of Toufutsu Lake were developed by not only sea waves, but also adverse tidal current in the spring-tide.

Keywords: Flood tidal shoals, tidal current, wind wave, video monitoring

INTRODUCTION

Toufutsu Lake and Urashibetsu River are located along the Okhotsk Sea in Hokkaido, Japan as shown in Figure 1. The surface area and the average depth of Toufutsu Lake are 9.3 km^2 and approximately 4.0 m, respectively. The catchment area and the length of main channel of Urashibetsu River are 187.5 km^2 and 36.9 km, respectively. Urashibetsu River is originates at Mt. Mokoto in Oozora town and pours into the Okhotsk Sea through Toufutsu Lake. The ordinary mean annual discharge of Urashibetsu River is lower than 10 m^3/s.

In Toufutsu Lake inland water fisheries, such as the cultivation of oysters, shrimp fishing and so forth, are conducted by local fishermen. In addition, we can see more than two hundreds thirty kinds of wild bird throughout the year and see the whooper swans which stay in Toufutsu Lake during winter. Therefore Toufutsu Lake was registered as a wetland under the Ramsar Convention in November, 2005. On the other hand, no sand bars at the outlet to the entrance channel from Toufutsu Lake before 1977 as shown in Figure 2(a). However, sand bars have been significantly developed

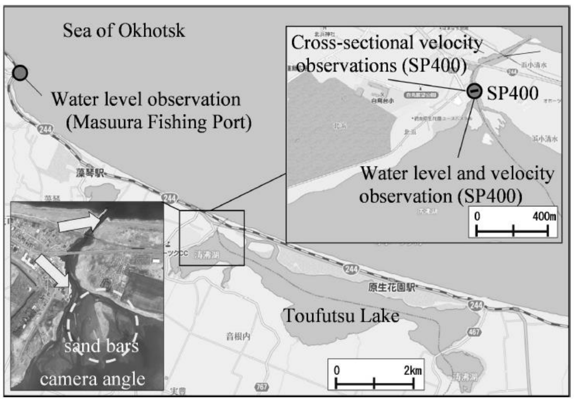

Fig. 1 Plan view of Toufutsu Lake and observation station (photo by Shin Engineering Consultants Co. Ltd.)

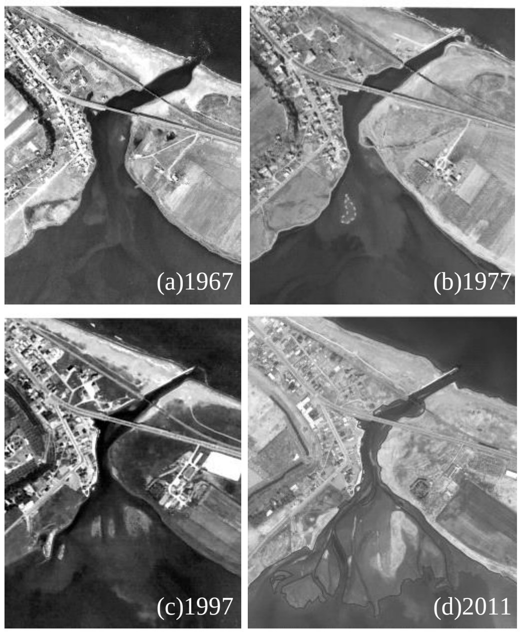

Fig. 2 Aerial photographs in Urashibetsu River estuary

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since 1977 as shown in Figure 2(b), (c) and (d). As the result, the depth at the entrance channel of Toufutsu Lake has been shallowing, and the problems, such as flood control, the decline of salinity and so forth, occur.

The river channel near the river mouth moved periodically or seasonally before 1977, accordingly, the position of the river mouth also moved as shown in Figure 2. Therefore there were frequent flood damages that were caused by the closure of the river mouth after storm attack. Urashibetsu River was excavated for flood control in 1976 and training jetties were constructed at both sides of the river mouth in 1977 to prevent the closure of a river mouth from littoral drift as shown in Figure 2(b). After the construction of training jetties, not only the number of the closure of a river mouth decrease, but also the number of flood damages decrease.

Watabe et al. (2009) evaluate the sequential sedimentation history of the sand bars by means of Multi-channel Analysis of Acoustic Surface Waves technology and indicate that the sedimentation stratigraphy under the sand bars were significantly different from muddy to sandy, even though the sand bars apparently consisted of the same sandy material. However, in order to prevent the developmental of the sand bars, we have to not only grasp the sedimentation history, but also understand the relationship between the sand bars and external force.

In this study, to explain the developmental process of sand bars we conducted wave observation, velocity measurements, bed material investigation and so forth in Urashibetsu river estuary. In additional, for the purpose of analyzing the morphological changes of the sand bars caused by the external force, such as wave height, tidal waves and so forth, we conducted video monitoring by using two network cameras.

FIELD OBSERVATIONS

Summary of the Field Observations

In order to grasp the mechanism that sand bars have been developing at the entrance channel of Toufutsu Lake we conducted some observations as shown in Table 1 and in Figure 1. The water level measurements were conducted at SP400 and Masuura fishing port for from September 18, 2010 to December 24, 2010 and for from November 22, 2011 to December 24, 2011. The waves and velocity measurement were conducted at SP400 for from September 19, 2010 to December 23, 2010 and for from November 23, 2011 to December 24, 2011. Bed material investigation was conducted at 8 points on September, 2010 and November, 2011 as shown in Figure 3. The video monitoring was conducted at 2 points (to the direction of the training jetties and to the direction of the lake) for from September 18, 2010 to December 24, 2010 as shown in Figure 1. We conduct analysis based on these observations data in this study.

Table 1 The items of field observation

Items of measurement	Observation Station	Duration of observation
Water level	SP400and Masuura fishing port	・9/18/2010-12/24/2010 ・11/22/2011-12/24/2011
Velocity, Wave height, Wave period and Wave direction	SP400	・9/19/2010-12/23/2010 ・11/23/2011-12/24/2011
Cross-sectional Velocity Profile	SP400	・Every hour on the hour in 12/8/2010 ・Every hour on the hour

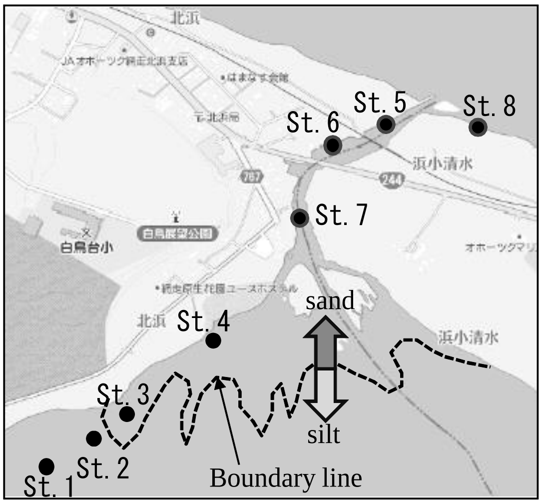

Fig. 3 Monitoring points of Bed Material. Dashed line shows the boundary line between silt nature and sand nature

Waves and Current Observations

There are several different kinds of currents including oceanic, tidal current, run off from rain, and wind-driven in Urashibetsu River estuary. Therefore field fixed point observations on waves and velocities at SP400 were carried out by using Wave and Current Meter (IO-Technique, WH-99) in order to grasp flow characteristics. This observation equipment is an automatic recording device that measures the x- and y-components of velocity and water level fluctuation by a pressure sensor. We installed it to the approximately 10m spot from the left bank and the sensor was fixed at 0.5 m above the river bed as shown in Figure 4. These respective data which are Waves and velocities obtained from it were stored for 20 minutes (sampling frequency was 2Hz) every 1 hour.

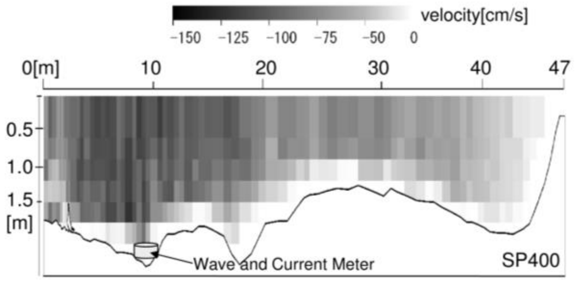

Fig. 4 Cross-sectional velocity profiles at around 8:00 of December 23, 2011 (flood-tide period) and the location of fixed observation station of Wave and Current Meter (IO-Technique, WH-99)

Water Level Observation

Field fixed point observations on water levels were carried out by using two pressure type water level sensors (Rigou Co.) in order to grasp flow characteristics between the sea and the river entrance channel. We installed one of two observation equipment at Masuura fishing port to grasp tidal waves in the coastal and installed the other at SP400 to grasp the river water level as shown in Figure 1. These respective data were stored for 1 minutes (sampling frequency was 1 Hz) every 1 hour.

Cross-Sectional Velocity Profile Measurement

Field observation on the cross-sectional velocity profile at SP400 was carried out by using an Acoustic Doppler Current Profilers (RD Instruments 1200kHz Workhorse, ADCP) with bottom tracking instrument. The river width at SP400 is approximately 60.0 m and the maximum depth is 2.5 m, with an averaged depth of approximately 1.6 m as shown in Figure 4. The ADCP was mounted on one side of the observation boat, and the boat was running across the river. The sampling frequency was 5.0 Hz, and the ADCP was set to transmit pings every 1 seconds. The size of the bins was set to 0.2 meters except the bottom and the top unmeasured zones.

Bed Material Investigation and Field Reconnaissance

The estuary sediment properties are important clue in the determining the mechanism of sediment movement in estuary due to external force. Therefore we conducted field reconnaissance and data collection of surface sediment in order to obtain the grain size and the particle density. Figure 3 shows the plan view of 8 monitoring points. The station for sampling of surface sediment was planned while considering the spatial variation of morphology in Urashibetsu estuary. The sampled sediments were dried and sieved to obtain the grain size distribution curve.

Network Camera Monitoring

Two network cameras (CANON, VB-C60) with small solar panels and a cell-phone unit were used to analyze the relationship between the morphological changes of the sand bars and the external forces such as wave height, tides and so forth. We installed one of two cameras in the river mouth and installed the other in the second floor of the Hakuchou Park Bird-Watching Building in Abashiri Semi-National Park as shown in Figure 1. Sampling frequency was 1 hour.

THE RESULTS OF OBSERVATIONS

The results of observations are as follows. Here, the results in 2011 are mainly described.

Observation Results of Water Level and Velocity

Figure 5(a) shows the variation of three water levels, namely, the sea water level at Urashibetsu fishing Port, river entrance channel water level at SP400 and the prediction tide at Abashiri Harbor. By the way, Abashiri Harbor is approximately 8 km northwest from Urashibetsu river mouth. Though water level observed at SP400 was basically synchronized with tidal waves observed at Masuura fishing port for the observation periods, the phase delay between two observation points was observed. Additionally the amplitude of tidal waves observed at SP400 was smaller than that at Masuura fishing port. The phase delay relates to energy loss, section of area, lake area, hydraulic mean depth and so forth (Kondo, 1972). Figure 5(b) shows the variation of two velocities, namely, velocity observed at 400 (normal and reverse flows) and velocity smoothed with the 25 hour moving average method. We define the direction of normal and reverse flows at SP400 as shown in Figure 6. Figure 5(c) and (d) show the variation of significant wave height $H_{1/3}$ and significant wave period $T_{1/3}$ at Monbestu Minami NOWPHAS observatory, Japan, respectively. By the way, the Monbestu minami observatory (located at 50m depth) is approximately 90 km northwest from Urashibetsu river mouth. Figure 5(e), (f) and (g) show the variation of sea level pressure, wind vector and the amount of the precipitation at Abashiri Meteorological observatory, respectively. By the way the Abashiri observatory is approximately 2 km northwest from Urashibetsu river mouth.

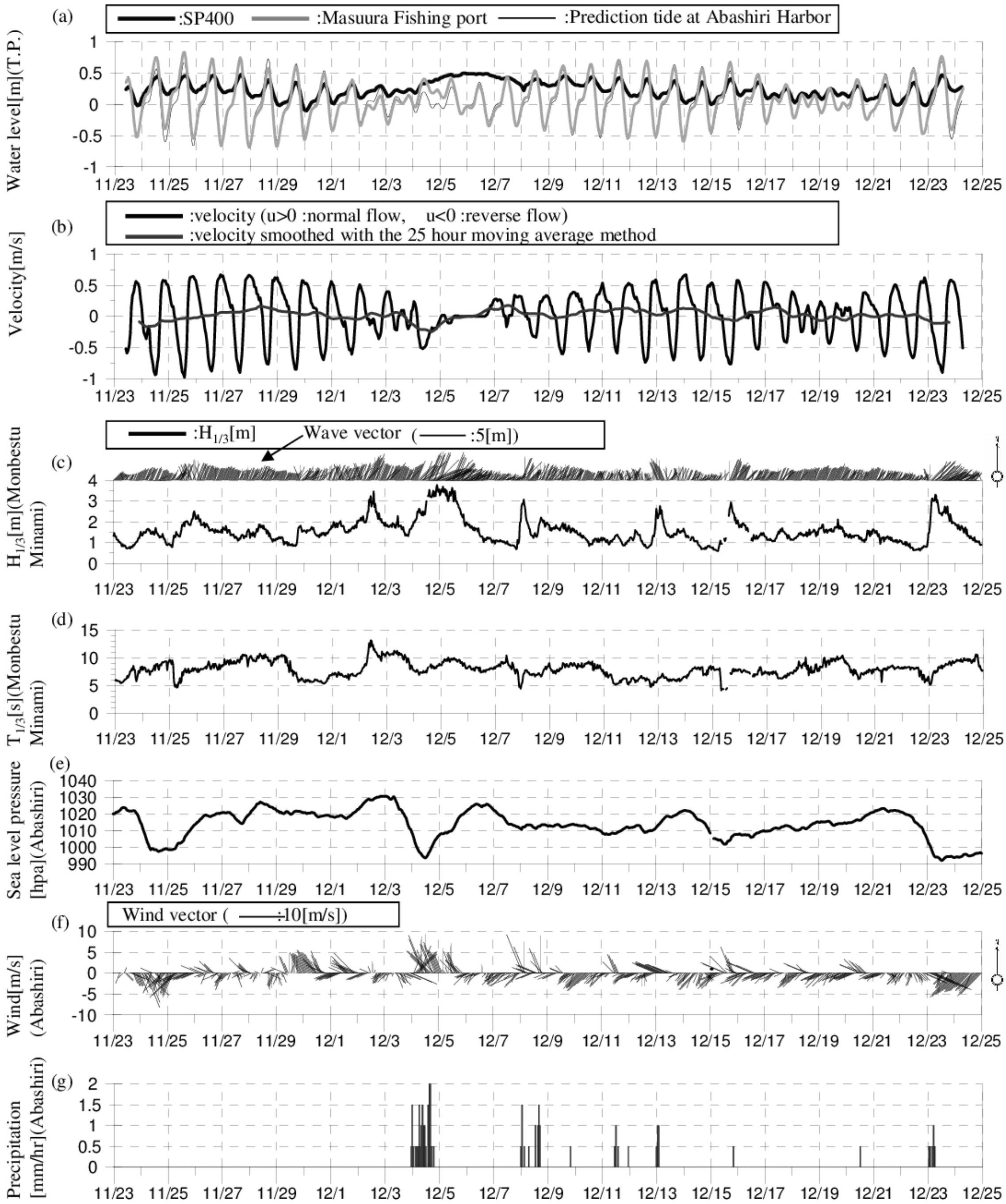

Fig. 5 Time series of (a)three water levels, namely, sea water level at Urashibetsu fishing Port, river entrance channel water level at SP400 and the prediction tide at Abashiri Harbor, (b)normal and reverse flow observed at SP400 and velocity smoothed with the 25 hour moving average method at SP400, (c)significant wave height ($H_{1/3}$) and vector of low-pass filtered wind waves at Monbestu minami station, (d)significant wave period ($T_{1/3}$) , (e) sea level pressure at Abashiri Meteorological observatory, (f)wind vector, (g) the amount of the precipitation

For from 4 to 7 on December, water level at SP400 gradually rose. During the same period of time, wave set-up caused by high waves ($H_{1/3}$), sea level pressure depression, wind that blew from over the sea to Toufutsu Lake and rain occurred. When the water level at SP400 was equal to that at Urashibetsu Fishing port, that is, water level gradient difference between SP400 and Masuura fishing port was equal to zero, normal flow changed in reverse flow or reverse flow changed in normal flow. Additionally, the maximum magnitude of reverse flow was faster than that of normal flow for the observation period, and the maximum magnitude of reverse flow was 1.0 m/s at 8:00 of November 25.

For from 4 to 5 on December, $H_{1/3}$ at the Monbestu Minami observatory gradually rose and reached at maximum value at 3.8 m at 12:00 on December 5 as shown in Figure 5(c). However, the magnitude of reverse flow did not increase for the same period. Additionally, $H_{1/3}$ at SP400 was almost zero for observation period owing to disappearance of waves by breaking as shown in Figure 7. These observation data proves that the variation of tidal waves is dominant factor of the flow characteristics at SP400 in river entrance channel.

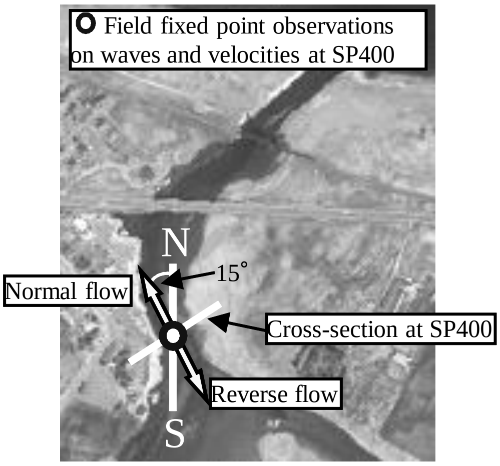

Fig. 6 Definition of Normal flow and reverse flow at SP400

Fig. 7 River mouth at 12:00 on December 5 ($H_{1/3}$:3.8m at Monbestu Minami station)

Observation Results of Cross-Sectional Velocity

As an example of the observation result, Figure 4 shows cross-sectional velocity profile at SP400 for the duration of the flood-tide. The velocities were measured by an ADCP on December 23, 2011. As the tide starts going out, the same thing happened in reverse flow. The location of the maximum velocity for the duration of the flood-tide and ebb-tide was approximately 10 m distance from the left bank side. The magnitude of cross-sectional velocity from the water surface to bottom was nearly the same except the top and the bottom unmeasured zones and near-bank area.

Characteristics of Estuary Sediment

Figure 8 shows the results of grain size distribution observed at each monitoring point in the lake. The surface sediment collected at St.8 in shoreline was composed of medium sand and fine sand. Each of the surface sediment collected at St.5, St.6 and St.7 in the entrance channel was also composed of them. As the result of this survey, we confirm that the entrance channel, which is located in the downstream from Toufutsu Lake, is composed of sea sand. Each of surface sediments collected at St.3 and St.4 was composed of 0.2-0.3 mm in grain size, and each of surface sediments collected at St.1 and St.2 was composed of 0.02-0.08 mm in grain size. According to the Figure 8, it is recognized that there are two types of grain size distribution in Urashibetsu river estuary. The grain size in Toufutsu Lake doesn't increase gradually, and sea sand covered in the northern part of dashed line and silt of black color covered in the southern part of dashed line as shown in Figure 3. As the result of the field survey, the silt was the black tuff produced in the mountain, such as Mt. Mokoto, which is located in the upstream from Toufutsu Lake. As the result of these monitoring, we confirm the sea sand as the main source of sand bars at the entrance channel in Urashibetsu river estuary.

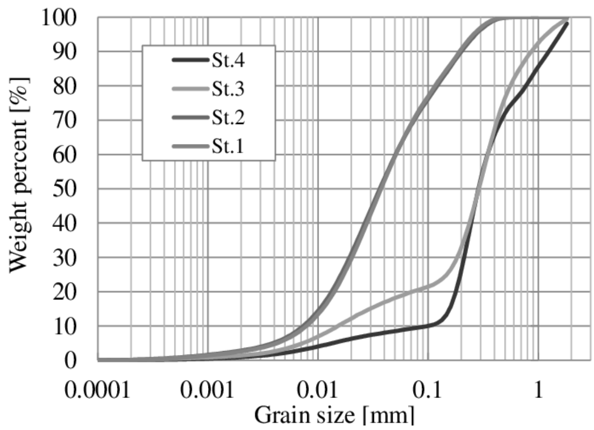

Fig. 8 Grain size distributions at St.1, 2, 3 and 4 in 2011

Observation Results of Network Camera

As an example of the network camera monitoring result, Figure 9 shows the result of morphological changes in the river mouth obtained from No.1 network camera and time series of $H_{1/3}$ at Monbestu minami and water level at Masuura fishing port. The maximum of $H_{1/3}$ was obtained up to 2.5 m on September 26, 2010. At the same period, sea sand was gradually transported and deposited at the right bank side of the river channel in the river mouth, and sand bars was formed during this high waves periods as shown in Figure 9(A).

Unfortunately, the field surveys, such as water level, velocity, were not conducted at SP400 for the same period. Frequent occurrence of sand bars caused by high waves could be observed during the period of network camera monitoring. When $H_{1/3}$ was obtained 1.9 m on October 3, 2010, sand bar began to move to the direction of SP400. After that, from the middle of October, the average height of sand bars gradually lowered and moved to the direction of SP400, as shown in Figure 9(B). Finally, Sand bars disappeared at the river mouth during spring tide as shown in Figure 9(C).

From these results, we find out that sea sand is transported in the section of the river channel where training jetties are installed in during high waves periods and the developmental of sand bars at the entrance channel is caused by flood flow. However, the amount of deposited sand at the outlet to the entrance channel from Toufutsu Lake for the observation period is not clear because the bathymetric survey had not been conducted.

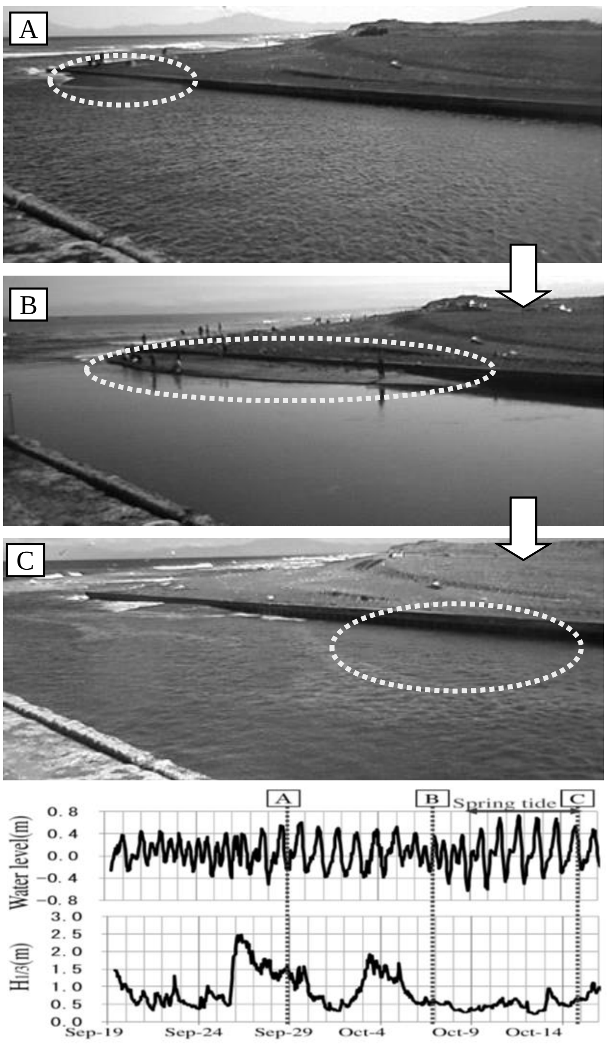

Fig. 9 Relationship between the change of sand bars along the training jetties in right side, significant wave height $H_{1/3}$ at Monbestu minami and water level at Masuura fishing port in 2010

DISCUSSION

As a result of field observations, we find out that a large amount of sand is transported in the section of the entrance channel near the river mouth during high waves and the developmental of sand bars at the outlet to the entrance channel from the lake is caused by flood flow. The purpose of this section is to investigate sand transport rate at SP400 for from November 23, 2011 to December 24, 2011 by analyzing the observation data. Figure 10 shows comparison between velocity u obtained from fixed point observation at SP400 and friction velocity u_* obtained from Eq. (1). As shown Figure 10, the relationship between u and u_* during the period of normal velocity (u >0) is different from that during the period of reverse velocity (u <0). Energy gradient i_e are defined as Eq. (2).

$$u_* = \sqrt{gRi_e} \quad (\fallingdotseq \sqrt{ghi_e}) \tag{1}$$

$$i_e = -\frac{d}{dx}\left(\frac{\alpha u^2}{2g} + H\right) \tag{2}$$

, where g is acceleration of gravity, R is hydraulic mean radius at SP400 and equals to the averaged depth at SP400, α is energy correction coefficient and equals 1.0, H is a difference in water level between SP400 and Masuura fishing port, x is a distance between river mouth and SP400 and equals 400 m.

Total sediment load Q_s passed through at SP400 is calculated referring to the relationship between u and u_*. In order to estimate Q_s at SP400, a method, which is proposed by Brown formula (Eq. (3)), is applied.

$$\frac{Q_b}{u_* d} = 10\left\{\frac{u_*^2}{(s-1)gd}\right\}^2 \tag{3}$$

, where s is relative density of sediment, Q_b is sediment discharge, d is median diameter and approximately equals to 0.17 mm obtained from bed material investigation. As shown in Figure 10, the relationship between u and u_* during the period of normal velocity is different from that during the period of normal velocity, therefore we convert u_* in Eq. (3) into variable u. Substituting Eq. (1) into Eq. (3), Eq. (4) is obtained.

$$Q_b = \frac{10 g^{1/2}}{(\sigma/\rho - 1)^2 d} \cdot R_m^{5/2} I^{5/2} \tag{4}$$

, where R_m is hydraulic mean radius per unit width. Discharge per unit width Q_m is defined as Eq. (5) by applying Manning mean velocity formula.

$$Q_m = \frac{1}{n} R_m^{5/3} I^{1/2} = R_m u_m \quad (5)$$

, where n is the roughness coefficient of Manning formula and approximately equals to 0.015, u_m is velocity per unit width. Sediment discharge rate per unit width Q_{bm} is found by substituting Eq. (5) into Eq. (4).

$$Q_{bm} = \frac{10 g^{1/2} n^5}{(\sigma/\rho - 1)^2 d} \cdot \frac{u_m^5}{R_m^{5/6}} \quad (6)$$

The river cross-section at SP400 is divided into 60 equal parts and Q_{bm} of each parts is calculated by the correlation between velocity u obtained from fixed point observation by Wave and Current Meter and velocity U obtained from cross-sectional velocity profile measurement by ADCP with Bottom tracking instrument for the same time period. The total sediment discharge Q_s along the cross section at SP400 is obtained by summing Q_{bm} of each parts for the entire cross section. As the result of that, the value of Q_s at SP400 equals to -400m^3/30days. The total load transported from the river mouth to Toufutsu Lake for the observation period is not clear because the bathymetric survey had not been conducted, therefore we can't evaluate quantitative evaluation of the value of -400m^3/30days, but Q_s <0 indicates that the total sediment load transported to the river mouth is less than that transported to Toufutsu Lake.

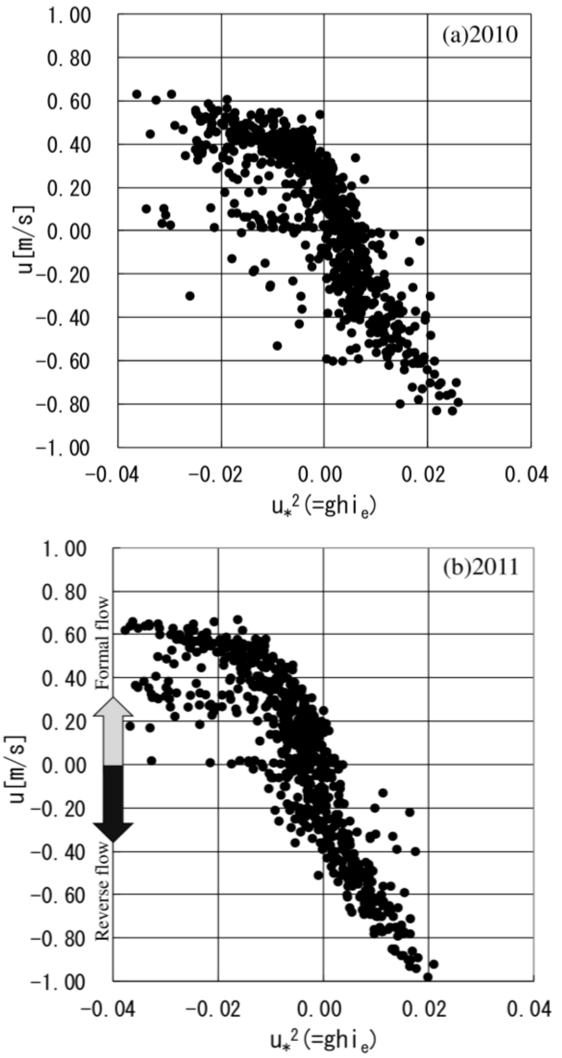

Fig. 10 Comparison of velocity observed at SP400 and friction velocity at SP400

Estuary choking occurs several times in the river mouth every winter, and the dredging is carried out after occurrence of estuary choking. Figure 11 shows the seasonal variations of the wave energy flux in time, E, at Monbestu minami. The total amount of E is the biggest in the Sea of Okhotsk from December to January. Therefore a large amount of sand is transported and deposited in the section of the river channel near the river mouth during these periods. On the other hand, as a result of research conducted in this study, we explain that the developmental of sand bars at the entrance channel is caused by flood flow. The number of high waves from spring until autumn is much less than that in winter. Therefore the sea sand that was carried and deposited in river mouth by high waves from spring until autumn is transported by food flow to the entrance channel before the time the next high waves occur, and estuary choking does not occur. However, high waves continuously attack the river mouth during winter, and the sand is carried and deposited intermittently in river mouth. As the result of that, both tidal prism and cross-sectional velocity in the river channel decreases as the cross-sectional area at the entrance of the estuary decreases, and the developmental of sand bars at the entrance channel stops, but estuary closing occurs in the river mouth. That is, there are correlations between the sediment deposited in the river mouth and the sediment transported to Toufutsu Lake.

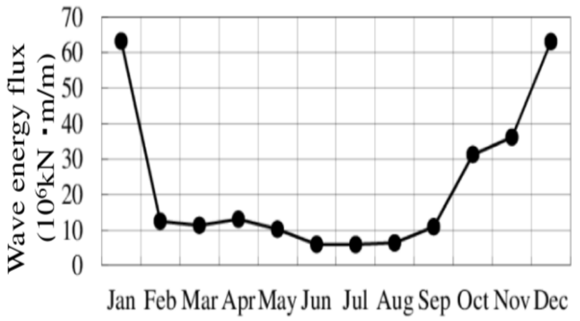

Fig. 11 seasonal variations of wave energy flux at Monbestu minami

RESULT

The main results are as follows.

(1)The maximum magnitude of reverse velocity at St.400 in the entrance channel during the periods of flood-tide was faster than that of normal velocity during the periods of ebb-tide.

(2)The relationship between velocity at SP400 and friction velocity at SP400 during the periods of flood-tide is different from that during the periods of ebb-tide.

(3)The flood tidal sand bars at the entrance channel of Toufutsu Lake were developed by not only sea waves, but also adverse tidal current in the spring-tide.

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