INTRODUCTION

The topology of river mouths, which are defined as regions where river runoff enters an ocean, is characterized by the combined influence of sediment transported by the river and near shore currents associated with tides and sea waves. River mouths along the coast of the Sea of Japan are particularly affected by the action of winter sea waves, and tidal prisms are small. Under these conditions, river-mouth bars tend to develop under conditions of longshore sediment transport, and blocking of river-mouths is frequent. Floods tend to breach the river-mouth bars that develop during dry periods, and complex changes occur in bar behavior during floods and in post-flushing river-mouth channel width. These changes vary depending on flood hydrodynamics, fluvial morphology near the river mouth, and the presence or absence of harbor facilities and other man-made structures along the coast.

Hosoyamada et al. (2006) examined the changes in river-mouth bar morphology during flash flooding by numerical analysis using nonlinear shallow-wave modeling, and quantitatively assessed the stage-lowering effect of sediment flushing, in their study on the river-mouth bars of the Aganogawa River, which were not effectively breached by flooding on a scale of approximately 50% of its design discharge (i.e. 6,000 m³/s). Kuwahara et al. (1996) also performed a two-dimensional analysis of riverbed changes in the Natori River. In response to the strong three-dimensional flow field in the periphery of a river-mouth bar with a complex geometry, Tateyama et al. (1995) recently developed a new analytical method (referred to as the bottom velocity computation (BVC) method) to assess bottom flow velocities without any assumptions of shallow flow, and applied the BVC to analyze and reproduce the changes in bar morphology that occurred during the flooding that occurred in the Aganogawa River flood in 2011 (flow discharge approximately 11,000 m³/s).

On the other hand, in their study on river-mouth channel width of rivers with river-mouth bars, Sato et al. (2004) modeled sediment transport by near shore currents associated with sea waves and tides, as well as by river runoff, and derived predictions of the channel width for different equilibrium states. However, as shown in the results of this study, bar dynamics in times of flooding are affected by the pre-flood fluvial morphology, coastal sea level, and flood discharge. In many cases, the bar is not completely flushed out, even in design-scale floods.

In the Yuragawa River located in the north of Kyoto Prefecture, the mid-west in Japan, as shown in Figure 1, topographic changes of its river-mouth bar are continuously activated by sediment transport due to river flow and sea wave. In October 2004, a large part of the river-mouth bar was eroded by the huge flood flow due to typhoon. The river-mouth bar has developed along the right bank only, and the river-mouth channel has been fixed along the left bank since then. This situation may cause some problems
such as bank erosion, washout of bank protection works and harmful effects on other coastal structures. Even effects of water discharge during flood periods on responses of the river-mouth bar are not clarified. Therefore, the risk of high water level caused by a river-mouth clogging is formidable. In order to avoid these problems and risk, it is important to understand the characteristics of the topographic change of the river-mouth bar and its cause, and to propose a control method of the bar geometry. Miwa et al. (2014) investigated the effects of the flood discharge on the area, height and volume of the river-mouth bar through the numerical simulation. Then, they showed that the bar area and height of the river-mouth bar considerably decrease in the early stage of the flood period, and that the decrease rate after that is relatively small. Over 3,000 m$^3$/s of flood discharge accelerates the erosion of the bar, and it also decreases its area remarkably. Ochi et al. (2015) also investigated the relationship between the sea water level and channel width at the river-mouth, and they clarified that the channel width tended to increase with decreasing sea water level and increasing water discharge, which was in accordance with the analytical results obtained by Kuwahara (1996) in their investigation of the effect of changes in tidal level during flooding on the phenomenon of river-mouth bar collapse.

2 FIELD MEASUREMENT ON RIVER MOUTH TOPOGRAPHY

2.1 Outline of the Yuragawa River

The origin of the Yuragawa River is Mikunidake situated on the borders of three prefectures of Kyoto, Fukui and Shiga. The length of the river is 146 km, and the size of its basin is 1,880 km$^2$. The Yuragawa river system is one of the 109 Class A river systems in Japan. The Yuragawa River can be classified into three reaches. In the upper reaches, V-shaped ravines and river terraces have developed. The width of river increases in the middle reaches and pools and riffles are developed in the main channel of the river. The lower reaches consist of the valley plain, the stream flows along the long and narrow bottom of the mountains. Figure 2 shows the longitudinal bed profile of the lower and middle reaches of the Yuragawa River. The average bed gradient around Fukuchiyama (37 km away from the river-mouth) in the middle reaches is about 1/1,500, whereas the bed gradient in the lower reaches is approximately 1/6,000 to 1/8,000. Therefore, the length of tidal section of the river reaches over 20 km.

2.2 Changes of river-mouth topography for 60 years

Figure 3 shows the changes of river-mouth topography from 1947 to 2009. In 1947 and 1963, the river-mouth bar on the right bank was developed considerably and the width of the river-mouth channel was approximately 80-100 m. The river-mouth bar on the right bank was disappeared and it on the left bank was developed in 1972. The river-mouths on the both bank were developed in 1975 and 1982. The widths of the river-mouth channel were approximately 80-100 m. The river-mouth bar on the right bank was disappeared and it on the left bank was developed in 1972. The river-mouths on the both bank were developed in 1975 and 1982. The widths of the river-mouth channel were approximately 80 m for both years. After that, a large part of the river-mouth channel was flushed out by the flood flow (peak discharge $Q_p=3,600$ m$^3$/s) of the typhoon No.10 in 1982 and 1983, the width of the river mouth channel increased to about 300 m. However, the river-mouth bars were developed as shown in photographs of 1986 to 2001. A large part of the river-mouth bar was flushed out again by the flood flow (peak discharge $Q_p=5,400$ m$^3$/s) of the typhoon No.23 in 2004. The river-mouth bar has developed on the right bank only after then, and the river-mouth channel has been fixed along the left bank (2009). The construction works of detached breakwaters have been carried out from 1967 and there
are 8 detached breakwaters for each bank. The formation of tombolo is confirmed after 1982. Effects of the detached breakwaters on river-mouth bar formation are not clarified.

2.3 Results of field measurements

In order to clarify the effects of river flow discharge and sea wave height on changes in river-mouth topography, survey works were conducted by using GPS periodically. A surveyor walked along the shore line receiving the satellite signals, and registered the signal to the controller at intervals of approximately 10 to 20 m. The number of stations for each survey was about 70 to 100. The area of the bar and its shape were calculated by means of identifying the coordinates of the stations. Basically, the survey was conducted once a month.

Figure 4 shows (a) the temporal variations in the area of the river-mouth bar, (b) the significant wave height at Kyoga-Misaki (30 km far from the river-mouth) and (c) the water discharge at Fukuchiyama for 5 years and 8 months (from May 2010 to December 2015). The datum level was the sea surface at each measurement time, and there was no correction of the datum level because the tidal range was at most 30 cm. The river-mouth bar on the left bank has developed since December 2012 (The survey was started in March 2013). In Figure 4(a), the area of the bar on the right bank shows increases and decreases in the short term, whereas it gradually decreases as a long term tendency. The decreasing rate of the area for four years is approximately 40%. From the short term tendency, it can be seen that the area increased in the winter seasons of 2010, 2012 and 2013, and it decreased in the rainy and summer seasons of 2011 and 2013. As shown in Figure 4(b), Kanda et al. (2012) clarified that the significant wave height over 2.55 m influences the development of the river-mouth bar. Therefore, it can be consid-

![Figure 3. Temporal changes in river-mouth topography in Yuragawa River (1947-2009).](image)

![Figure 4. Temporal variations in (a) river-mouth bar area, (b) significant wave height at Kyoga-Misaki, and (c) water discharge at Fukuchiyama in Yuragawa River.](image)
erated that an increase in the onshore sediment transport may contribute to the increase of the area of the river-mouth bar. A possible reason why the area did not increase in the winter season of 2011 is that the onshore transported sediment from the foreshore may be accumulated on the seabed, where it was eroded by the flood flow in the fall season of 2011. On the other hand, as shown in Figure 4(c), the water discharge over 1,500 m³/s was recorded a total of four times in the summer seasons of 2011 and 2013. In particular, the flood with discharge of about 5,500 m³/s occurred due to the typhoon No.18 in September 2013. The area of the bar was reduced by 17% in 2011 and by 40% in 2013 due to these large flood discharges. Moreover, it is found that the area was gradually reduced in the spring to fall seasons of 2012. The water discharge of 300 m³/s classes had frequently occurred during these seasons, these flows might have eroded the river-mouth bar.

3 FLUME EXPERIMENT AND NUMERICAL SIMULATION FOR RIVER-MOUTH BAR CONTROL BY TRENCH AND SPUR DIKE

3.1 Experimental set-up and procedure

Flume experiments using the large channel, which was modeled based on the Yuragawa River, were conducted in order to clarify the effects of the spur dikes on the control of the river-mouth bar topography. The experiments were conducted in a horizontal rectangular open channel, which was 8.75 m long and 2.87 m wide as shown in Figure 5. The width of this channel corresponds with the 1/150 scale of the Yuragawa River. The channel has a water level adjusting weir in the returning flume in order to control the water elevation at the downstream end of the channel. Nearly uniform coal dust was used in the experiments as bed sediment. The coal dust had a mean grain diameter \( d_m \) of 1.3 mm and a specific gravity \( \sigma \) of 1.47.

The grain size of the river-bed material in the experimental model was larger than that for a scaled-grain replica of the field-site sediment, as its reduction to the scale of 1/150 would have required a grain size of 0.2 mm or less, which would have resulted in suspended-sediment and sand-wave predominance. In this large-grained, and consequently, distorted scale model, similitude (Shields similitude) in the sediment discharge rate was not completely satisfied. In view of the important influence of the critical tractive force of the river-bed material on sediment transport and changes in the river bed around the bar during overflow, we used uniform coal grains with a density of 1.47 g/cm³ and a mean grain size of \( d_m = 1.3 \) mm as the river-bed material, to obtain a correspondence between the river site and the model in the ratio of the shear velocity of the flow to the critical shear velocity of the river-bed material. The critical shear velocity in the model, as calculated by Iwagaki’s equation (Iwagaki, 1956), was \( u_\ast = 1.44 \) cm/s. Experimental measurement of the shear velocity \( u_* \) of the flow in the region upstream of the bar yielded values in the range \( u_\ast = 2.01-2.83 \) cm/s and thus a \( u_\ast/u_\ast \) ratio of approximately 1.4-2.0, indicating the occurrence of a dynamic state throughout that range. Application of these values to river-site flood conditions yielded a grain size \( d \) of approximately 20 mm, which corresponded closely to the maximum grain size of the river-bed material at the river site (mean grain size of 1.24 mm, maximum grain size of 18 mm).

The movable bed was flattened with a scraper and the river mouth-bar model, which was modeled based on the results of the topographical survey, was formed on the channel bed. The river mouth-bar is located on the right bank in the Yuragawa River, but the river-mouth model was set to the left bank in order to avoid the effect of the lateral flow toward the returning flume. The height of the river-mouth bar was 0.02 m, the sea bed behind the river-mouth bar was set to a slope \( I_b \) of 0.05 (1/20). The other part of the bed was made horizontally.

The experimental conditions are listed in Table 1. In the table, \( Q = \) water discharge, \( Q_c = \) corresponding water discharge, \( T = \) experiment duration, \( h_d = \) water surface elevation at the downstream end of the channel, \( B = \) width of trench excavation, \( L = \) length of the spur dike. The discharges in the experiments correspond with the flood discharge of \( Q = 3,300 \) to 4,900 m³/s at the river-site channel. The experiment duration (T=20min) corresponds with the peak discharge duration of 3.7 hours. Runs 13B and 13C are the experiments using trench excavation which set at center of the river-mouth bar as shown in Figure 5. Runs 14A and 14B are the experiments using spur dike, which was made of plywood, and its thickness and height were 0.01 m and 0.12 m, respectively. Three pieces of spur dike were set on the right bank.

Figure 5. Experimental set-up (Trench and spur dikes were set on the corresponding Run).
with intervals of 0.2 cm and placed at an angle of 60 degrees to the wall as shown in Figure 5.

Table 1. Experimental Conditions.

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Q</th>
<th>Qc</th>
<th>T</th>
<th>h_d</th>
<th>B</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>l/s</td>
<td>m^3/s</td>
<td>min</td>
<td>m</td>
<td>m</td>
<td>m</td>
</tr>
<tr>
<td>10A</td>
<td>17.8</td>
<td>4,900</td>
<td>20</td>
<td>0.152</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>10B</td>
<td>17.8</td>
<td>4,900</td>
<td>20</td>
<td>0.139</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>10C</td>
<td>17.8</td>
<td>4,900</td>
<td>20</td>
<td>0.127</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>10D</td>
<td>17.8</td>
<td>4,900</td>
<td>20</td>
<td>0.117</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>13B</td>
<td>17.7</td>
<td>4,900</td>
<td>20</td>
<td>0.122</td>
<td>0.1</td>
<td>-</td>
</tr>
<tr>
<td>13C</td>
<td>17.6</td>
<td>4,850</td>
<td>20</td>
<td>0.144</td>
<td>0.1</td>
<td>-</td>
</tr>
<tr>
<td>14A</td>
<td>12.1</td>
<td>3,300</td>
<td>20</td>
<td>0.128</td>
<td>-</td>
<td>60</td>
</tr>
<tr>
<td>14B</td>
<td>17.9</td>
<td>4,900</td>
<td>20</td>
<td>0.135</td>
<td>-</td>
<td>60</td>
</tr>
</tbody>
</table>

In the experiment, the water was stored slowly in the channel in order to avoid erosion of the bed. The prescribed water discharge was fed into the channel after that. The water surface elevation at the downstream end of the channel was controlled by the water level adjusting weir. Water surface elevations were measured with a point gauge, at intervals of 1 m in the longitudinal direction at the location of Y = 0.8 m of the channel before stopping the flow. The motion of PVC particles (size = 0.05 mm) on the water surface was recorded by a video camera for 20 seconds during the experiment. The surface velocity was obtained from PIV analysis (Fujita et al., 1998). Transverse profiles of the bed surface were measured with a laser sensor mounted on a propelled carriage, at intervals of 4 cm in the longitudinal direction of the channel after stopping the flow. The datum plane for water surface and bed surface elevations was set to the channel-bed surface. Then, initial bed elevation was 0.1 m for the river bed part and was 0.12 m for the river-mouth bar part.

3.2 Experimental results and discussion

Figure 6 shows the river-bed geometry after water passage with a water discharge of $Q=17.8$ l/s and various downstream-end water levels (Runs 10A-10D). The water discharge corresponds to a flood discharge of approximately 4,900 m^3/s at the river-site channel. The area surrounded by the broken line shows the initial shape of the river-mouth bar. In Run 10A with the highest downstream-end water level, the flow converged toward the river-mouth on the right bank, and it developed a deeply scoured topography upstream of the river-mouth bar tip. Although the flow also got over the bar, the erosion of its surface hardly occurs because its velocity was relatively slow. In Run 10B with relatively lower downstream-end water level, the flow into the channel was faster and the channel width was wider. In Run 10C, the water surface gradient increased on the bar and its bed was lowered. Then, a depositional landform was developed downstream of the bar. In Run 10D with the downstream-end water level being lower than the initial bar elevation, the bar was almost entirely eroded and washed away. This may be caused by the increase of tractive force on the bar due to increase of the water surface gradient. The deep scouring was shifted downstream as the downstream-end water level decreased.

Figure 7 illustrates the final situations of river-bed geometry in the case of the trench excavation in the river-mouth bar. The surface velocity distributions on the bed are also shown in Figure 8. The hydraulic conditions of $Q$ and $h_d$ in Run 13B correspond between Runs 10C and 10D, those in Run 13C correspond between Runs 10A and 10B. In Run 13B, the river-mouth bar was eroded at river-mouth channel side. According to the experimental observation, the erosion of bar area divided by the trench was progressed. However, the other area was hardly eroded because the primary flow goes through the river-mouth channel. As a result, the effect of the trench excavation on the river-mouth bar erosion was restrictive. The river-mouth bar was hardly eroded in Run 13C, the trench excavation was not
effective in this case. The technical advantage of trench excavation was not always found in these experiments. Further investigations about width, depth and number of trench are necessary.

Figure 9 illustrates the final situations of riverbed geometry in the case of the spur dike. The surface velocity distributions on the bed are shown in Figure 10. Although the value of $h_{d}$ in Run 14A corresponds to Run 10C, the value of $Q$ was less than that. On the other hand, $Q$ and $h_{d}$ in Run 14B correspond to Run 10B. As shown in Runs 10A and 10B, the flow converged toward the river-mouth on the right bank, and progressed erosion of the river-mouth channel. In Run 14A, the converged flow toward the river-mouth was weakened by setting up the spur dikes. The scour depth of the river-mouth channel became small because the spur dikes strongly redirect the flow toward the river-mouth bar. The redirect flow eroded the river-mouth bar, and the erosion area extended into about half of the bar in spite of relatively low flow discharge in this case. In Run 14B with high water discharge, the primary and redirect flows entirely eroded the river-mouth bar. The scour depth of the river-mouth channel was small too in this case. The effectiveness of spur dike is not only bar control but also reduction of the local scour in the river-mouth channel.

3.3 Simulation model and calculation method

Numerical simulations were conducted in order to not only follow the flume experiments, but also further investigate the control method for the river-mouth. The two dimensional simulation model, Nays2DH (iRIC, 2014), was applied to the investigation in this study. The continuity equation and the
momentum equations for water flow are
\[
\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} = 0
\]
(1)
\[
\frac{\partial (uh)}{\partial t} + \frac{\partial (hu^2)}{\partial x} + \frac{\partial (huv)}{\partial y} = -gh \frac{\partial H}{\partial x} - \frac{\tau_x}{\rho} + D_x
\]
(2)
\[
\frac{\partial (vh)}{\partial t} + \frac{\partial (huv)}{\partial x} + \frac{\partial (hv^2)}{\partial y} = -gh \frac{\partial H}{\partial y} - \frac{\tau_y}{\rho} + D_y
\]
(3)
where \(x, y = \) plane Cartesian coordinates; \(u, v = \) velocity components in \(x\) and \(y\) directions; \(t = \) time; \(h = \) water depth; \(H = \) water elevation; \(g = \) gravity acceleration; \(\rho = \) fluid density; \(\tau_x, \tau_y = \) bed shear stress components in \(x\) and \(y\) directions; and \(D_x, D_y = \) diffusion terms in \(x\) and \(y\) directions.

The continuity equation of sediment transport is
\[
\frac{\partial z}{\partial t} + \frac{1}{1 - \lambda} \left( \frac{\partial q_{bx}}{\partial x} + \frac{\partial q_{by}}{\partial y} + q_{su} + w_f c_b \right) = 0
\]
(4)
where \(z = \) bed elevation; \(\lambda = \) bed porosity; \(q_{bx}, q_{by} = \) bed-load sediment transport rates per unit width in \(x\) and \(y\) directions; \(q_{su} = \) release rate of sediment from bed; \(w_f = \) settling velocity of sediment; \(c_b = \) reference concentration of suspended sediment. As for the bed-load sediment transport equation, the Meyer-Peter & Müller equation (1948) in streamwise direction and Watanabe et al. equation (2001) for calculation of sediment transport vector are employed.

The governing equations mentioned above and others are transformed into discrete forms in a generalized coordinate system. In the simulation model, the advection terms are discretized by the CIP method and the zero equation model is applied as a turbulence model. The bank collapse and deposition model is also introduced in the simulation model.

In the simulation, the research area (5.68 m long, 2.84 m wide) of the channel was divided into 142 and 71 grids for the longitudinal and lateral directions, respectively. Then, the longitudinal grid size (\(\Delta x\)) and the lateral grid size (\(\Delta y\)) were the both 0.04 m. The Manning’s roughness coefficient and the time increment were taken as \(n = 0.02\) and \(\Delta t = 0.01\) second, respectively. Other parameters and hydraulic valuables were the same as the experiments. Suspended sediment was not considered in calculation.

### 3.4 Simulation results and discussion

Figures 11 and 12 illustrate the reproduction calculation results of the flume experiments for the trench excavation and spur dike, respectively. As for the trench excavation (Figure 11), the simulation was successful in reproducing the erosion features observed in Run 13B. However, the bar of river-mouth channel side was eroded by the flow, the simulation was not always enough. On the other hand, as for the spur dike (Figure 12), the flow around the spur dikes is redirected to the river-mouth bar. Therefore, the bar of river-mouth channel side eroded both of Runs 14A and 14B. The reduction of the local scour in the river-mouth channel can be reproduced in the simulation. Moreover, the bar near the left bank of the channel also eroded in Run 14B. These features in simulations are same as the experimental results. The simulation result in Run 14 underestimates the erosion of the bar near the left bank.

The experimental and simulation results suggested that the erosion of river-mouth bar depends on not only construction works such as the trench excavation and spur dike but also hydraulic conditions of water discharge and downstream-end water level. We performed calculations of eroded volume of the river-mouth bar under some conditions of water discharge and downstream-end water level. Figure 13
shows the relationship among them for each construction work. The eroded volume of the bar decreases with increasing downstream-end water level and decreasing water discharge. In the case when the downstream-end water level is high and overflow on the bar is large, the erosion volume after water passage becomes zero independently of water discharge. The calculation results indicated that the trench excavation is not always an effective method for erosion of river-mouth bar in this study. However, the spur dike gives the large effect as a bar control method under the conditions of low downstream-end water level.

The experimental results were also plotted in the Figure 13. Although there were small differences between experiments and simulations for the erosion of river-mouth bar, total amount of eroded volume of the bar could be calculated by the simulation. Suitable conditions of the construction works such as the trench excavation and spur dike must be investigated by using the numerical simulation model.

4 CONCLUSIONS

The results obtained in this study are summarized as follows:

1. Although the bar area and volume of the river-mouth bar showed short-term fluctuations due to flooding, they also showed a tendency to increase on a long-term basis. The flush condition of the river-mouth bar sediments due to flooding does not depend on the width of river-mouth channel and the bar area but on flood discharge. The formation of the river-mouth bar may be mainly activated by an increase of longshore sediment transport rate in winter season; the bar area has a strong correlation with wave height.

2. The trench excavation work was effective to the erosion of the bar area at the river-mouth channel side. However, the effect of the trench excavation on the river-mouth bar erosion was restrictive. On the other hand, the spur dike was effective adequately. The effectiveness of spur dike is not only bar control but also reduction of the local scour in the river-mouth channel.

3. The simulation results could reproduced the tendencies of experimental results. Suitable conditions of the construction works such as the trench excavation and spur dike must be investigated by using the numerical simulation model.

REFERENCES


