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EVALUATING FLOOD DISCHARGE AND BED VARIATION IN THE OTA RIVER FLOODWAY

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Abstract: *The evaluation of bed variations during a flood is important for understanding of physical and ecological environment in river estuaries. The Ota River estuary has the branched section of the Kyu Ota River and the Ota River Floodway. The Ota River Floodway has the tidal flats with habitats for many creatures in the brackish river. To evaluate the bed variations in the Ota River Floodway, we have to understand the discharge ratio in the river bifurcation. The bed variation in the river bifurcation is induced by three dimensional flow due to the river bend, floodgates and divergent flows. So, we apply the unsteady quasi-three dimensional flow and bed variation analysis using time series of the observed water surface profiles in Sep.2005's flood. The bed variation during the flood is investigated in relation to tidal changes by this method. Therefore, the calculation method is found to provide fairly good results for bed variation during the flood. And, the discharge ratio in the river bifurcation is evaluated by this method.*

Keywords: *the Ota River Floodway; river estuary; river bifurcation; bed variation; unsteady quasi three dimensional flood flow and bed variation analysis; time series of observed water surface profiles*

INTRODUCTION

River estuaries with tidal flats are habitats for many creatures. So, it is important to evaluate the bed variation during a flood in river estuaries. Generally, to evaluate bed variations during a flood, we have assumed that longitudinal profile of flood marks indicates the water surface profile in the flood peak discharge. But, those longitudinal profiles are different in river estuaries owing to the tidal changes. So, it is required to develop the unsteady calculation method for estimating flood flows and bed variations during the flood in the estuary.

Fukuoka, Watanabe et al. (2004) indicated the unsteady 2D flow analysis method using time series of observed water surface profiles. The calculation method is able to estimate the temporal changes of hydraulic conditions during the flood (e.g. water levels and discharge hydrograph). Until now, the calculation method has been applied to the several problems in

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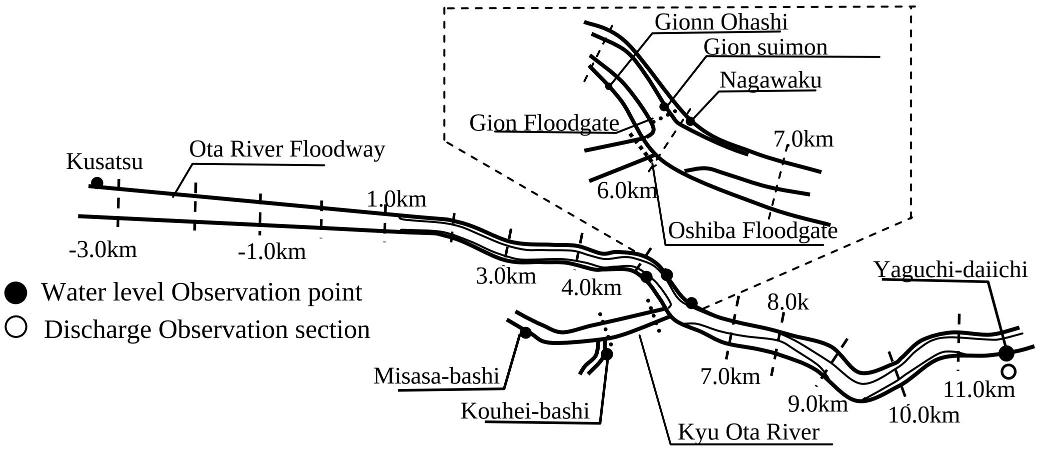

Figure1. Study area of the Ota River

rivers (e.g. Fukuoka, 2005). Kawaguchi, Fukuoka et al. (2009) proposed the unsteady 2D flow and bed variation analysis method using the time series of the measured water surface profiles for evaluating development and decay of the alternate bars in the experimental channels. Suzuki, Fukuoka et al. (2009) evaluated the bed variation and sand transport during the flood in the Chikugo River estuary by the unsteady 2D flow and bed variation analysis method using the time series of the observed water surface profiles. Okamura, Fukuoka et al. (2010) estimated flood flows and bed variations in the Tone River-mouth with sand waves by applying quasi-three dimensional flow and bed variation analysis method using time series of the observed water surface profiles.

In the Ota river estuary, tidal changes are relatively large. The difference in tidal levels between flood tide and ebb tide is about 4m at the river mouth in the spring tide. The tidal changes affect the conditions in the river bifurcation between the Ota River Floodway and the Kyu Ota River. The Ota River Floodway has extensive tidal flats with habitats for many creatures in the brackish river. So, it is required to evaluate the flood flows and bed variations during the flood for comprehension of the physical environment in the Ota River Floodway. This requires us to understand the ratio of flood discharge in the river bifurcation.

Generally, three dimensional flow develops and affects bed variations in river bifurcations (e.g. Murota,A., 1960). The river bifurcation in the Ota River is located just downstream of the river bend. There are floodgates at the each river. Therefore, the three dimensional flow of flood flows is developed due to the river bend and the floodgates in addition to effects of divergent flows. So, we need a practical model, which evaluates the effects of the three dimensional flow, to make clear the ratio of flood discharge in the river bifurcation.

Uchida and Fukuoka (2009) developed unsteady quasi-three dimensional flow analysis which can evaluate velocity distributions near river bed by using the depth averaged horizontal vorticity equations in addition to the shallow water equations.

The objective of this study is to make clear the ratio of the flood discharge in the Ota River bifurcation and to clarify the bed variations during the flood in the Ota River estuary by unsteady quasi-three dimensional flow and bed variation analysis method using time series of the observed water surface profiles.

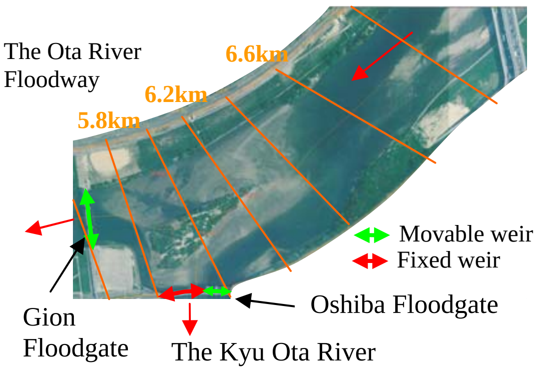

Figure2. Aerial photograph in the river bifurcation

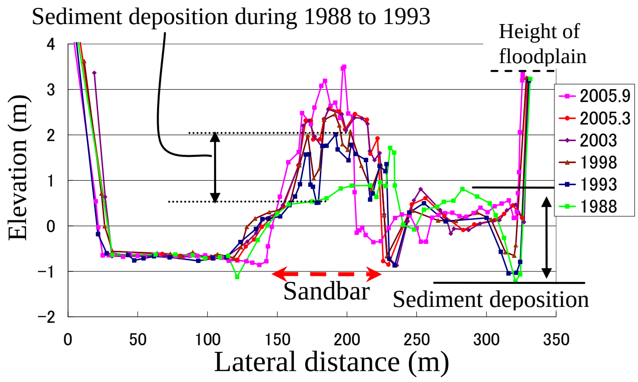

Figure3. Cross section in main channel at 6.0km point

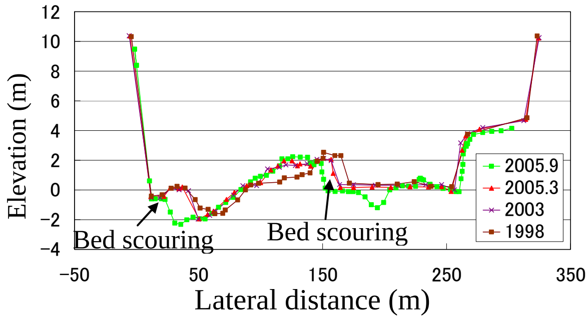

Figure4. Cross section in main channel at 6.2km point

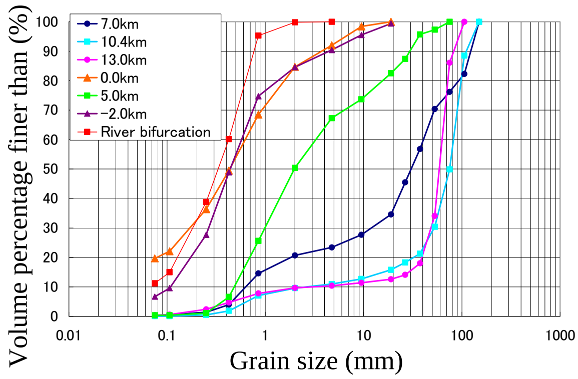

Figure5. Grain size distribution in the Ota River

CHANNEL CONDITIONS AND OBSERVATION SITUATIONS IN THE STUDY AREA

Figure 1 shows the channel conditions and water level and discharge observation points in the Ota River. The Ota River bifurcation was designed so that the ratio of flood discharge is 2 to 1 based on the river improvement planning in 1948 (The Ota River Floodway : 4000(m^3/s), the Kyu Ota River : 2000(m^3/s)).To design the shape of the river bifurcation and the construction of the floodgates, the model experiments were conducted in PWRI from 1958 to 1959 (Kikkawa,H. and Takami,M., 1959). However, the discharge ratio in the river bifurcation is changed by the current river improvement planning. In the current river improvement planning, the design flood discharge in the Ota River Floodway is 4500(m^3/s) and the Kyu Ota River is 3500(m^3/s). So, it is required to evaluate the ratio of flood discharge under the actual conditions for river managements.

The Oshiba-Floodgate located in the Kyu-Ota River consists of the fixed weir and movable weir with the three gates. And, the Gion-Floodgate located in the Ota River Floodway consists of movable weir with three gates. The floodgate is constructed in order to control the ordinary flow discharge. So, the Gion floodgate is full opened if the flood discharge is over 430(m^3/s).

The Ota River Floodway is composed of compound channel from 5.8km to 0.0km and simple channel from 0.0km to -3.4km.

In the Ota River, the medium scale floods occurred in July 1993 and in June and September 1999 (Maximum discharge is about 4000(m^3/s) at Yaguchi-daiichi observation point). And, the large scale flood occurred in September 2005, which is largest flood in the past years (Maximum discharge is about 7200(m^3/s) at Yaguchi-daiichi observation point).

The water levels is measured by automatic water level gauges at Yaguchi-daiichi, Nagawaku, Gionsuimon, Gion-ohashi and Kusatsu observation point. And, the water level gauges were installed at 200m intervals of longitudinal distance from 8.0km to 13.4km in order to investigate the behavior of vegetations during the flood (Gotoh and Fukuoka, 2008). As above, the time series of the water surface profiles were observed in detail with the branched section in the Ota River estuary. The flood discharge hydrograph was observed by floats at Yaguchi-daiichi observation section.

THE TEMPORAL CHANGES IN BED PROFILES

The temporal changes in bed profiles in the Ota River bifurcation

Figure 2 shows the aerial photograph which has been taken in 2003 at the river bifurcation. Figure 3 and Figure 4 show the temporal changes in the observed bed profiles at the section of 6.0km and 6.2km, respectively. In the river bifurcation, the sandbar has been formed upstream of the floodgates due to sediments deposition during the flood. The vegetation on the sandbar began to grow from about 1988. The great amount of sediment deposition on the sandbar was yield by the middle scale flood during the period 1988 to 1993. However, the sandbar was maintained after 1993, because the height of sandbar has become almost same height of the floodplain and the fixed weir of the Oshiba Floodgate. The bed scouring occurred in front of the sandbar and outer bank bed due to the secondary flow by the river bend as shown in Figure 4. Therefore, the calculation method which can evaluate the effect of the three dimensional flow is needed.

Figure 5 shows the grain size distribution in the section studied. The bed materials around 11.0km, where the bed slope is about 1/600, consist of many cobbles and gravel (see the bed slop in Figure 9). And, the bed materials in the Ota River Floodway, where the bed slope is about 1/3300, mainly consist of sands. At the sandbar in the river bifurcation, the bed materials consist almost entirely of sands which are similar to that in the Ota River Floodway.

Temporal changes in bed profiles in the Ota River Floodway

Figure 6 shows the contours of the observed bed profiles in 1994, 2001 and 2005. The contours of the bed profiles indicate the difference from the mean bed elevation of each section in 2001. Figure 7 shows the observed bed profiles of cross section at -0.8km before and after the flood in 2005 and the water level hydrograph at Nagawaku and Kusatsu observation points in 1999's flood and 2005's flood.

In the Ota River Floodway, the main channel was dredged to build the floodway. But, there are extensive tidal flat near the river side, which is about 1m higher than bed elevation of the main channel (see Figure 7). In the main channel of the floodway, the alternate bars with about 1km wavelength are formed as shown in Figure 6. Figure 8 shows the hydraulic conditions during the floods in September 2005 and June 1999 on the bed profiles classification diagram by Kuroki and Kishi (1984). The hydraulic conditions used in the figure are the calculation results by the model of the following the chapter. From this figure, the alternate bars occur during the floods in the Ota River Floodway.

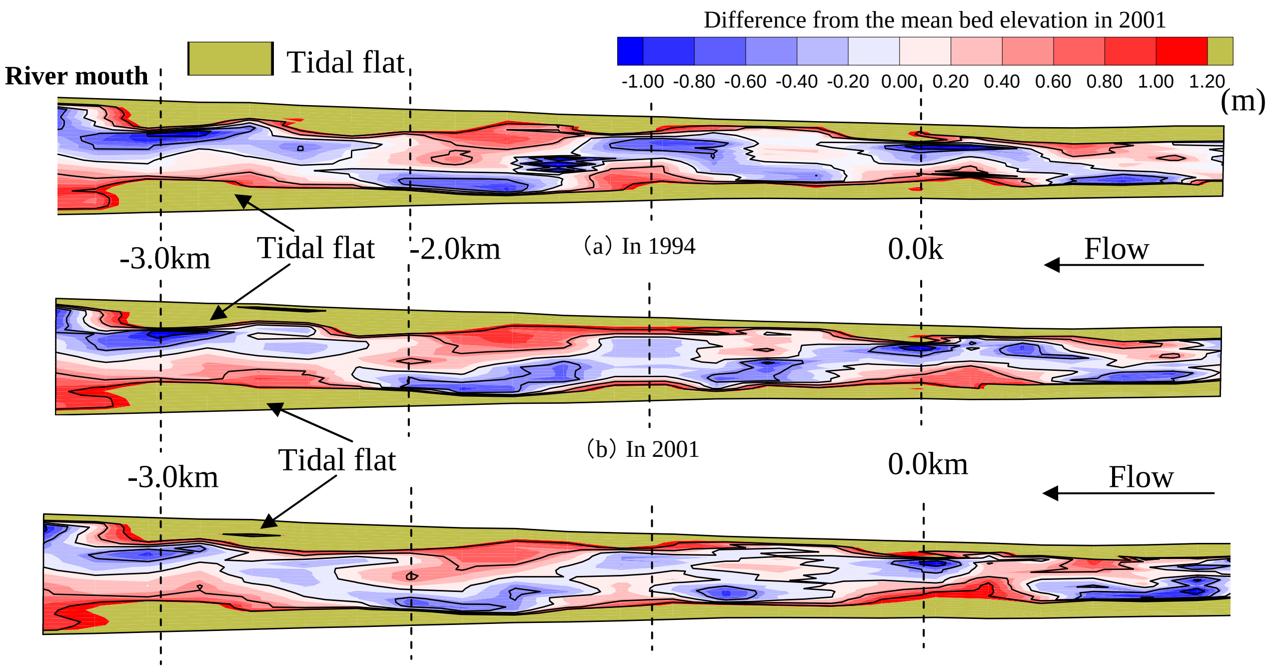

Figure6. Contour of the observed bed profiles in the Ota River Floodway

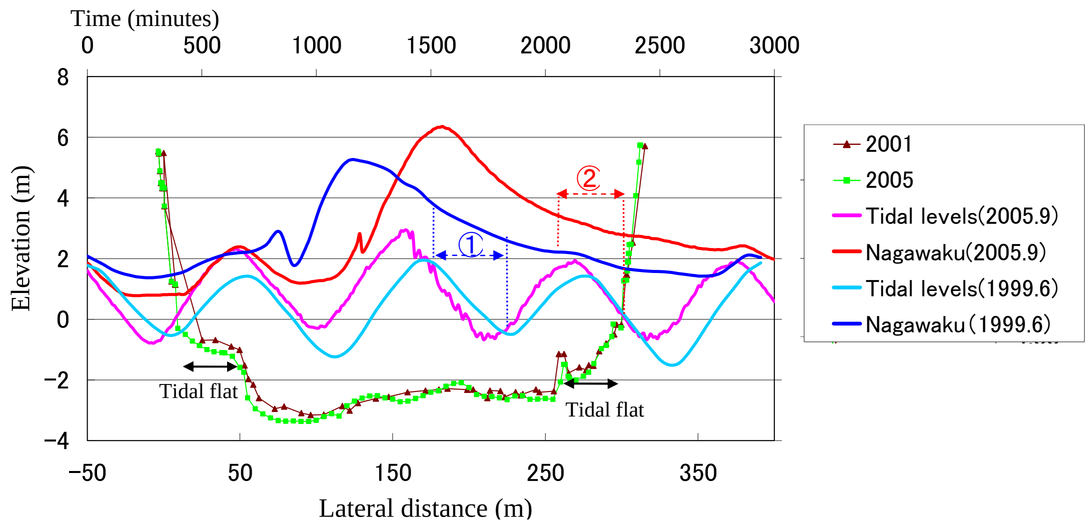

Figure7. The observed bed profiles of cross section at -0.8km before and after the flood and the water level hydrograph of flood in June 1999 and September 2005

In the Figure 8, the relations between τ_* and $(BI_0^{0.2}/h)$ behave on the different loop in these floods due to tidal changes. The flood in June 1999 coincided with the time of the flood peak and ebb tide (see Figure 7). The flood peak of the 2005's flood occurred about two hours earlier than flood tide. In 2005's flood, the plots on the Figure 8 move to the area where the alternate bars occur due to the falling tide in the flood receding period.

Generally, the flood receding period is much longer than flood rising period in case of not only large scale flood but also small and medium scale flood. Ebb tides occur more than once during the flood receding period. Because the water surface profiles become steep by falling tide, the dimensionless shear stress increases and keeps high value in the flood receding

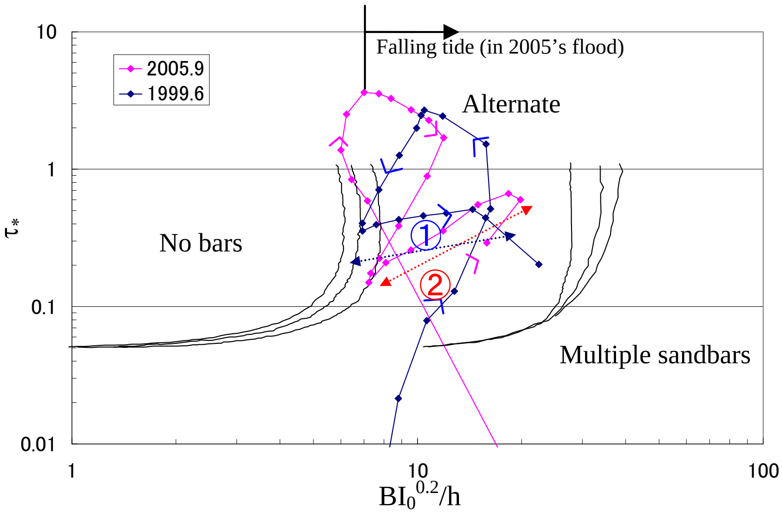

Figure8. Bed profiles classification diagram (Kuroki and Kishi, 1984)

period (period ①,②). Therefore, this fact indicates that displacement, development and deformation of the alternate bars during the flood are affected by falling tide.

THE BED VARIATION DURING THE FLOOD AND THE RATIO OF FLOOD DISCHARGE IN THE OTA RIVER ESTUARY

The unsteady quasi 3D flow and bed variation analysis method using time series of observed water surface profiles

The effects of vegetations, river conditions and bed variations during the flood appear in the observed temporal changes in the water surface profiles. So, the calculation method using the time series of the observed water surface profiles is useful to understand flood flows and bed variations during a flood. Okamura, Fukuoka et al. (2010) have dynamically explained the bed variation in the Tone River mouth during the flood. They conducted the unsteady quasi 3-D flow and bed variation analysis method using the time series of the observed water surface profiles. In the Ota River estuary, the three-dimensional flow by the river bifurcation and the alternate bars is important for the bed variations. Therefore, we conducted the unsteady quasi three-dimensional flow and bed variation analysis method using the time series of the observed water surface profiles. Equations of motion (1), (2), equation of continuity (4) and vorticity equations (5) are as follows. The bed surface velocity is calculated by equation (6). The vertical velocity distributions assumed as quadric curve are obtained by using depth averaged velocity and bed surface velocity, if vertical velocity gradients on the water surface are zero. The bed variation analysis is used conventional method which consists of bed load formula (Ashida and Michiue, 1972) and continuity equations for sediment and grain sizes (Hirano, 1971). The critical tractive force for sediment mixtures is calculated by the modified Egiazaroff formula (Egiazaroff, 1965; Ashida and Michiue, 1972).

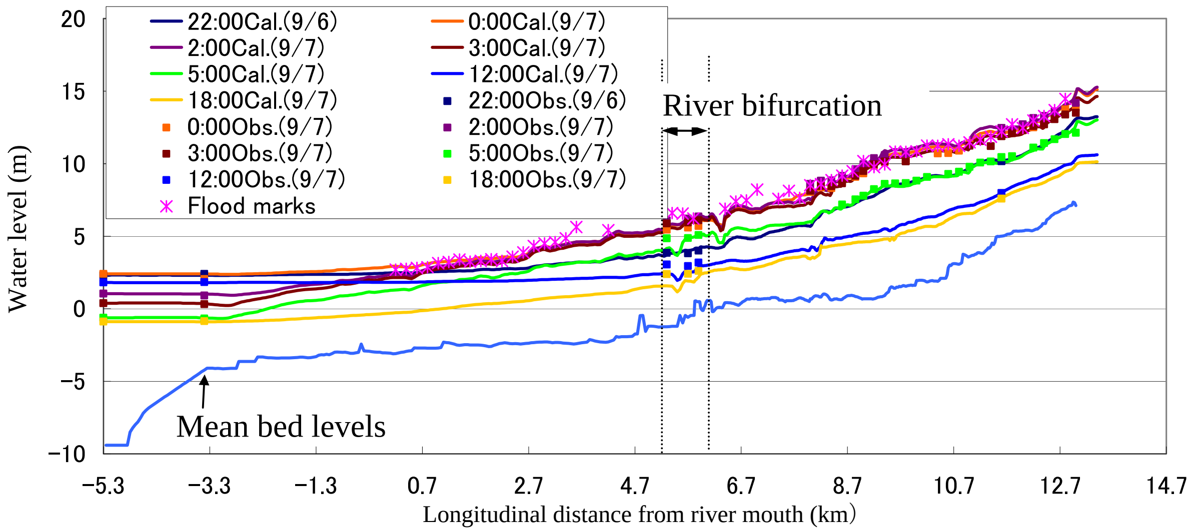

Figure9. Comparison between observed and calculated water surface profiles

$$h\frac{\partial\tilde{U}}{\partial t}+\tilde{U}h\frac{\partial\tilde{U}}{\partial\tilde{\xi}}+\tilde{V}h\frac{\partial\tilde{U}}{\partial\tilde{\eta}}-\tilde{J}\left(\tilde{V}-\tilde{U}\cos\theta^{\eta\xi}\right)\left(\tilde{U}h\frac{\partial\theta^{\xi}}{\partial\tilde{\xi}}+\tilde{V}h\frac{\partial\theta^{\xi}}{\partial\tilde{\eta}}\right) \tag{1}$$

$$=-gh\left(\frac{\partial z_s}{\partial\tilde{\xi}}+\cos\theta^{\eta\xi}\frac{\partial z_s}{\partial\tilde{\eta}}\right)-\tau_{sw\xi}+\frac{1}{J}\left\{\frac{\partial}{\partial\xi}\left(\tilde{J}d\eta\cdot h\tilde{\tau}_{\xi\xi}\right)+\frac{\partial}{\partial\eta}\left(\tilde{J}d\xi\cdot h\tilde{\tau}_{\xi\eta}\right)\right\}-Jh\left\{\left(-\tilde{\tau}_{\xi\xi}\cos\theta^{\eta\xi}+\tilde{\tau}_{\xi\eta}\right)\frac{\partial\theta^{\xi}}{\partial\tilde{\xi}}+\left(-\tilde{\tau}_{\xi\eta}\cos\theta^{\eta\xi}+\tilde{\tau}_{\eta\eta}\right)\frac{\partial\theta^{\xi}}{\partial\tilde{\eta}}\right\}$$

$$h\frac{\partial\tilde{V}}{\partial t}+\tilde{U}h\frac{\partial\tilde{V}}{\partial\tilde{\xi}}+\tilde{V}h\frac{\partial\tilde{V}}{\partial\tilde{\eta}}-\tilde{J}\left(\tilde{U}-\tilde{V}\cos\theta^{\eta\xi}\right)\left(\tilde{U}h\frac{\partial\theta^{\eta}}{\partial\tilde{\xi}}+\tilde{V}h\frac{\partial\theta^{\eta}}{\partial\tilde{\eta}}\right) \tag{2}$$

$$=-gh\left(\frac{\partial z_s}{\partial\tilde{\eta}}+\cos\theta^{\eta\xi}\frac{\partial z_s}{\partial\tilde{\xi}}\right)-\tau_{sw\eta}+\frac{1}{J}\left\{\frac{\partial}{\partial\xi}\left(\tilde{J}d\eta\cdot h\tilde{\tau}_{\eta\xi}\right)+\frac{\partial}{\partial\eta}\left(\tilde{J}d\xi\cdot h\tilde{\tau}_{\eta\eta}\right)\right\}-Jh\left\{\left(-\tilde{\tau}_{\xi\xi}+\tilde{\tau}_{\xi\eta}\cos\theta^{\eta\xi}\right)\frac{\partial\theta^{\eta}}{\partial\tilde{\xi}}+\left(-\tilde{\tau}_{\xi\eta}+\tilde{\tau}_{\eta\eta}\cos\theta^{\eta\xi}\right)\frac{\partial\theta^{\eta}}{\partial\tilde{\eta}}\right\}$$

$$(\tau_{sw\xi},\tau_{sw\eta})=(\frac{gn^2}{h^{1/3}}+\frac{gh}{K^2})\sqrt{u^2+v^2}\,(\tilde{U},\tilde{V}) \tag{3}$$

n : Manning's roughness coefficients, K : Vegetation permeability coefficients

$$J\frac{\partial h}{\partial t}+\frac{\partial\tilde{J}d\eta\tilde{U}h}{\partial\xi}+\frac{\partial\tilde{J}d\xi\tilde{V}h}{\partial\eta}=0 \tag{4}$$

$$J\frac{\partial\Omega_i h}{\partial t}+\frac{\partial\tilde{J}d\eta\tilde{U}\Omega_i h}{\partial\xi}+\frac{\partial\tilde{J}d\xi\tilde{V}\Omega_i h}{\partial\eta}=J\left(ER_i+P_{\omega i}\right)+D_i \tag{5}$$

ER_i : expansion, contraction and rotation term of vorticity vector, $P_{\omega i}$: production term of vorticity vector, D_i: horizontal turbulence mixing and dispersion term.

$$\delta u_i=\frac{2}{3}\Omega_j h,\quad \delta u_i=U_i-u_{bi},\quad u_{bi}\ \text{: Bed surface velocity} \tag{6}$$

Calculation results

Figure 9 shows the comparison between the observed and calculated water surface profiles. Figure 10 and Figure 11 show the comparison between the observed and calculated contours of the change in the bed profiles before and after the flood in the river bifurcation. The stream line of depth averaged velocity and bed surface velocity in the peak discharge is indicated on Figure 11. The calculated water surface profiles with time variation are good agreement with the observed water surface profiles (Figure 9).

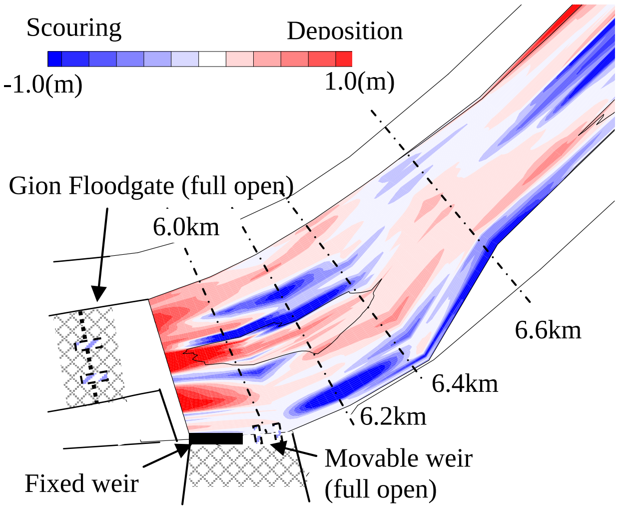

Figure10. Contour of observed change in the bed profiles before and after the flood

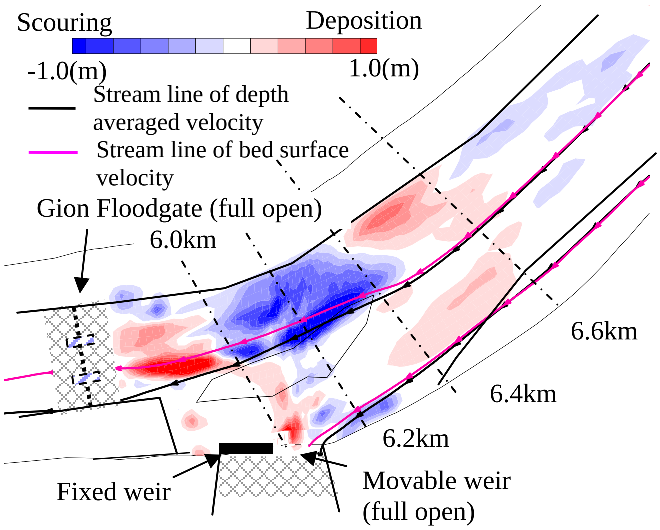

Figure11. Contour of calculated change in the bed profiles before and after the flood

The bed variation in the Ota River bifurcation is characterized by the bed scouring in front of the sandbar and outer bank bed and the sediment deposition just upstream of the Gion Floodgate (see Figure 10). The sediment deposition by the calculation is a little smaller than observed sediment deposition. However, the calculation results explain the observed characteristics of bed scouring in front of the sandbar and at the outer bank bed by evaluating the three dimensional flow.

Figure 12 shows the contour of the observed bed profiles before the flood in the floodway. Figure 13 and Figure 14 show the comparison between observed and calculated change in the bed profiles before and after the flood in the floodway. In the Ota River Floodway, the bed scouring occurred upstream of the sandbars, and the sediment deposition occurred downstream of the sandbars, as shown in Figure 12 and Figure 13. The calculation results in the Ota River Floodway explain the above characteristics of the observed bed variation, as shown in Figure 13 and Figure 14. Therefore, the calculation method using the time series of the observed water surface profiles provide to fairy good estimate the flood flow and bed variation during the flood.

Figure 15 shows the contour of the change in the calculated bed profiles in the peak discharge. Under the peak discharge, the bed variation don't occur so much in the Ota River Floodway. In the flood receding period, the bed variation in the Floodway occurred much more than flood rising period owing to falling tide. So, it is indicated that bed variation in the river estuary varies with tidal changes.

Figure 16 shows the calculated and observed discharge hydrograph and the discharge ratio in the river bifurcation. The discharge ratio is defined as ratio of discharge of the Kyu Ota River to the total discharge. It is indicated that 38% amount of the total discharge is diverged to the Kyu Ota River. This ratio is a little smaller than its resultant of the model experiments (Kikkawa and Takami, 1959) due to the sediment deposition and the vegetation on the sandbar.

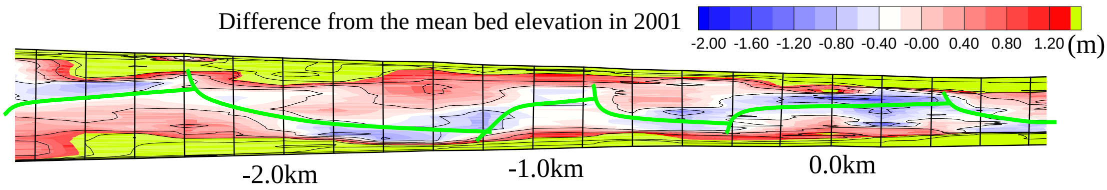

Figure12. Contour of the observed bed profiles in the Ota River Floodway in 2001

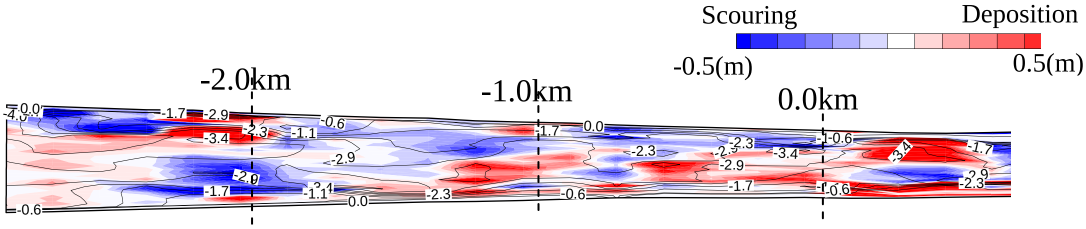

Figure13. Contour of the observed change in the bed profiles before and after the flood

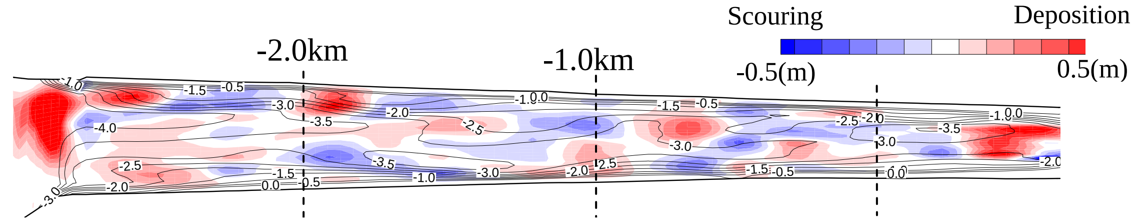

Figure14. Contour of the calculated change in the bed profiles before and after the flood

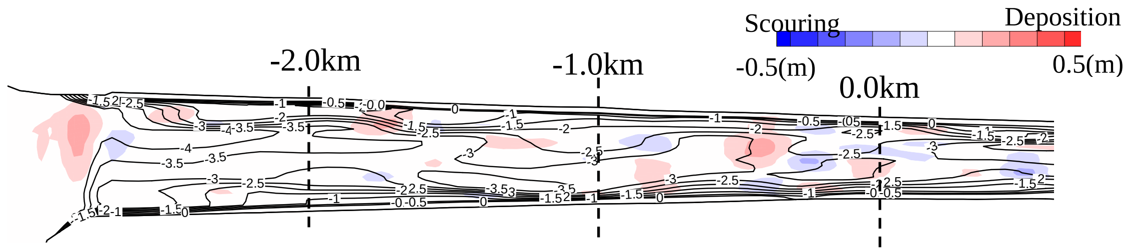

Figure15. Contour of the calculated change in the bed profiles in the peak discharge

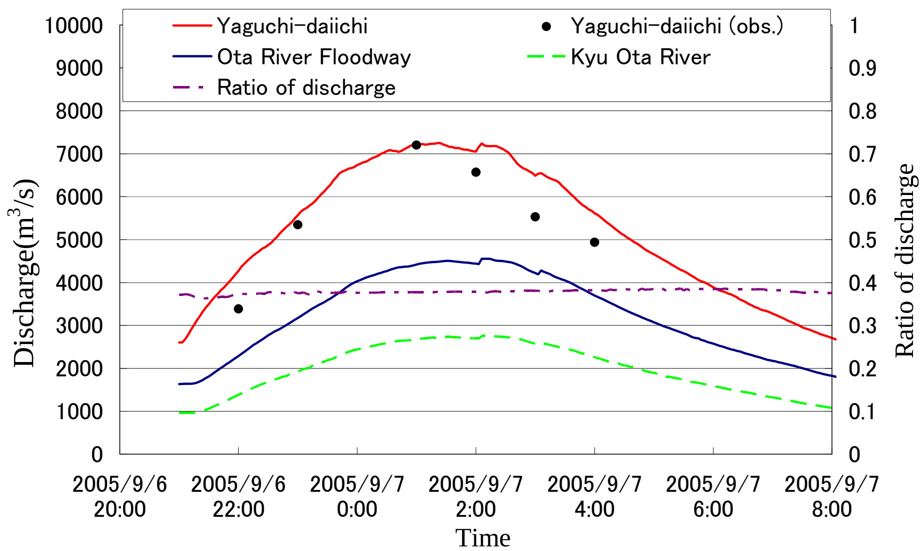

Figure16. Observed and calculated hydrograph and discharge ratio in the river bifurcation

CONCLUSIONS

The following conclusions were derived from the observation and calculation results.

1) Unsteady quasi three dimensional analysis of flood flows and bed variations using time series of observed water surface profiles is found to provide fairly good results for bed variation with branched section in the Ota River estuary. Moreover, the ratio of flood discharge in river bifurcation is evaluated by the calculation method.
2) It is found that alternate bars are formed in the Ota River Floodway by the observed bed profiles. From the bed profiles classification diagram and the contour of the calculated change in bed profiles, the alternate bars are developed in flood receding period due to tidal changes.

REFERENCES

Ashida,K. and Michiue,M. 1972. Study on hydraulic resistance and bed-load transport rate in alluvial streams, *Proceedings of JSCE*, JSCE, Vol.206, pp.59-69.

Egiazaroff, I.V. 1965. Calculation of Nonuniform Sediment Concentration, *Journal of Hydraulics Division*, ASCE, Vol.91, HY4, pp.225-247.

Fukuoka,S. 2005. Flood Hydraulics and Channel Design, Morikita Publishing Company

Fukuoka,S., Watanabe,A., Hara,T. and Akiyama,M. 2004. Highly Accurate Estimation of Hydrograph of Flood Discharge and Water Storage in River by Using an Unsteady Two-Dimensional Flow Analysis Based on Temporal Change in Observed Water Surface Profiles, *Journal of Hydraulic, Coastal and Environmental Engineering*, JSCE, No.761/ Ⅱ-67,pp.45-56.

Gotoh,T. Fukuoka,S. 2008. Mechanism of vegetation destruction Due to a large flood in the compound meandering river, *Advances in Hydro-Science and Engineering,* ICHE, Vol.8, pp.875-884.

Hirano,M. 1971. River-bed degradation with armoring, *Proceedings of JSCE*, JSCE, Vol.195, pp.55-65.

Kawaguchi,H., Todo,M. and Fukuoka,S. 2009. Analysis of River Bed Variation and Discharge Hydrograph Based on Time-series Data of Water Surface Profiles, *Annual Journal of Hydraulic Engineering*, JSCE, Vol.53, pp.751-756.

Kikkawa,H.and Takami,M. 1959. *Report of PWRI*, Vol.105-1.

Kuroki, M, Kishi,T. 1984. Regime Criteria on Bars and Braids in Alluvial Straight Channels, *Proceedings of JSCE*, JSCE, No.342., pp87-96.

Murota,A. 1960. Hydraulic Researches on the Branching Works of Open Channels, *Proceedings of JSCE, JSCE,* Vol.70.

Okamura,S., Fukuoka,S., Takemoto,T. 2010. Bed Form and Bed Variation during Floods of the Tone River Mouth, *Annual Journal of Hydraulic Engineering,* JSCE, Vol.54, pp.751-756.

Suzuki,K., Fukuoka,S. and Matsuo,K. 2009. Bed material structure and sand transport by flood flows in the estuary of the Chikugo River, *Proceedings of the Third international conference on estuaries and coasts*, Volume 1, pp.101-108.

Uchida,T. and Fukuoka, S. 2009. A Depth Integrated Model for 3D Turbulence Flows Using Shallow Water Equations and Horizontal Vorticity Equations, *33rd IAHR Congress: Water Engineering for a Sustainable Environment*, pp.1428-1435.