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EVALUATING FLOOD DISCHARGE AND BED VARIATION
IN THE OTA RIVER FLOODWAY

Takahisa GOTOH[1], Shoji FUKUOKA[2] and Toru ABE[3]

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 estuar   ies. Generally, to evaluate bed variations during a flood, we have assum ed that longitudina l profile of flood m arks 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 m ethod for estim ating flood flows a nd 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. Th   e calculation m ethod is able to estim   ate the temporal changes of hydraulic conditions duri ng the flood (e.g. water levels and discharge hydrograph). Until now, the calculation m ethod has been applied to the several problem s in

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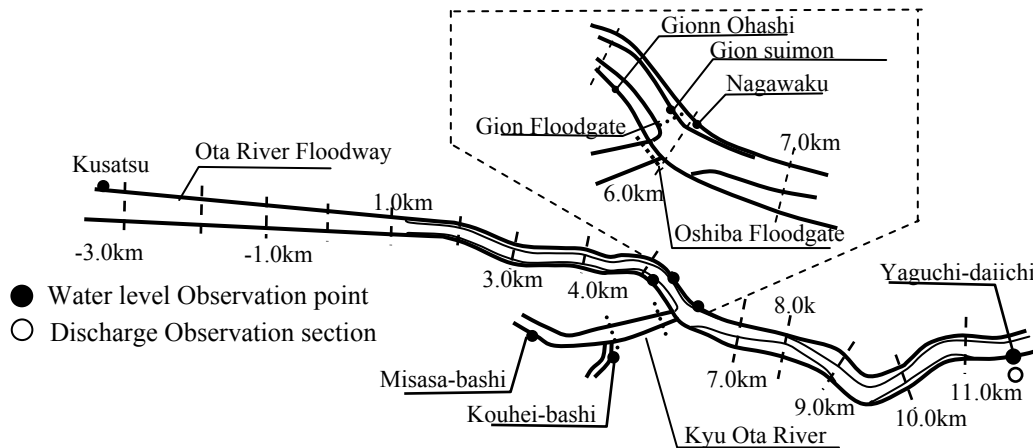
Figure1. Study area of the Ota River

rivers (e.g. Fukuoka, 2005). Kawaguchi, Fukuoka et al. (2009) proposed the unsteady 2D flow and bed variation analysis m ethod using the time series of the m easured water surface profiles for evaluating developm ent and decay of the alternate bars in the experim ental channels. Suzuki, Fukuoka et al. (2009) evaluated the bed variation and sand transport during the flood in the Chikugo River estuary by the uns teady 2D flow and bed variation analysis method using the time series of the observed wa ter 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 rela tively large. The dif ference in tidal levels between flood tide and ebb tide is about 4m at the river m outh 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 ex tensive tidal flats with habitats for m any creatures in the brackish river. So, it is required to evaluate the flood flows and bed variations during the flood for com prehension of the physi cal environment in the Ota River Floodway. This requires us to understand the ratio of flood discharge in the river bifurcation.

Generally, three dim ensional flow develops and affects bed variations in river bifurcations (e.g. Murota,A., 1960). The river bifurcation in th e Ota River is located just downstream of the river bend. There are floodgates at the each ri ver. Therefore, the three dim ensional flow of flood flows is developed due to the river be nd and the floodgates in addition to effects of divergent flows. So, we need a practical m odel, 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 unst eady quasi-three dim ensional 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 m ake 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.
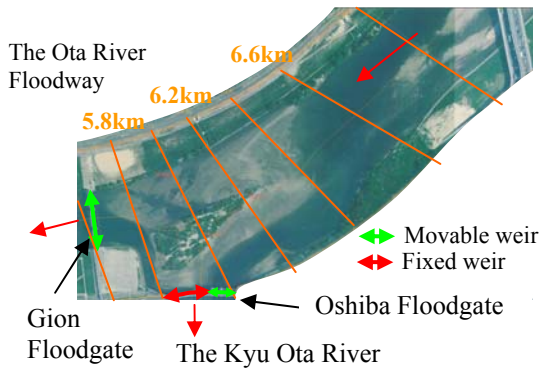
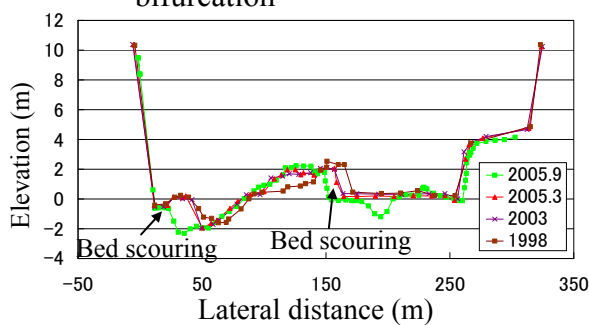Figure2. Aerial photograph in the river bifurcation
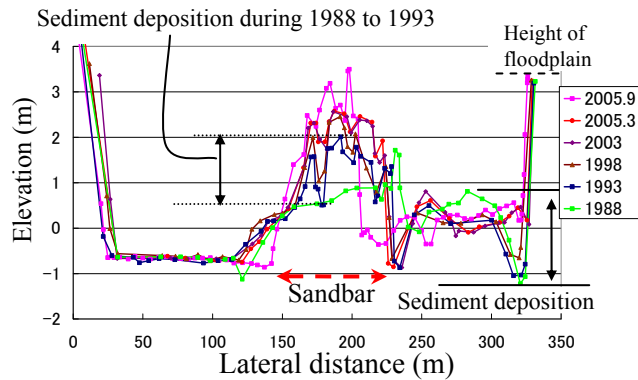
Figure3. Cross section in main channel at 6.0km point

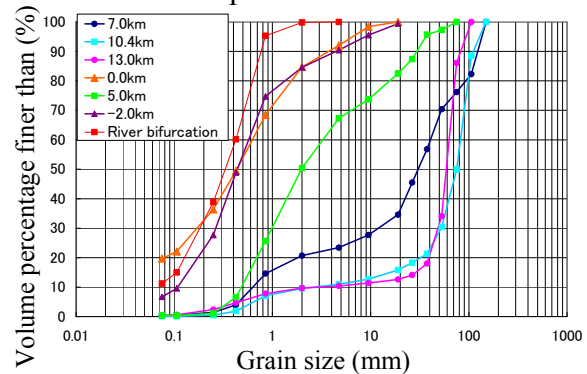Figure4. Cross section in main channel at 6.2km point

Figure5. Grain size distribution in the Ota River

CHANNEL CONDITIONS AND OBSERVATION SITUATIONS IN THE STUDY AREA

Figure 1 shows the channel conditions and wate r 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 Takam i,M., 1959). Howeve r, the discharge ratio in the river bifurcation is changed by the current river im provement 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 com posed of com pound channel from 5.8km to 0.0km and simple channel from 0.0km to -3.4km.

In the Ota River, the m   edium scale floods occurred in July 1993 and in June and September 1999 (Maxim um discharge is about 4000(m ^{3}/s) at Yaguchi-daiichi observation point). And, the large scale flood occurred in Septem ber 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 m   easured by autom atic water level gauges at Yaguchi-daiichi, Nagawaku, Gionsuim on, Gion-ohashi and Kusats u 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 vege tations during the flood (Gotoh and Fukuoka, 2008). As above, the tim e series of the water surf ace profiles were observed in detail with the branched section in the Ota River estuar y. 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 b een taken in 2003 at the river bifurcation. Figure 3 and Figure 4 show the tem poral changes in the observed bed profiles at the section of 6.0km and 6.2km , respectively. In the river bifurcation, the sandbar has been form   ed upstream of the floodgates due to sedim ents 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 m iddle scale flood during the period 1988 to 1993. However, the sandbar was m aintained after 1993, because the height of sandbar has becom e 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 m aterials around 11.0km, where the bed slope is about 1/600, consis t of many cobbles and gravel (see the bed slop in Figure 9). And, the bed m aterials in th e 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 obs erved bed profiles in 1994, 2001 and 2005. The contours of the bed profiles i ndicate the difference from the m ean 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 m ain channel was dredged to build the floodway. But, there are extensive tidal flat near the river side, whic h is about 1m higher than bed elevation of the main channel (see Figure 7). In the m ain cha nnel of the floodway, the alternate bars with about 1km wavelength are form ed as shown in Figure 6.   Figure 8 shows the hydraulic conditions during the floods in Septem   ber 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 m odel of the following the chapter. From this figure, the alternate bars occur during the floods in the Ota River Floodway.
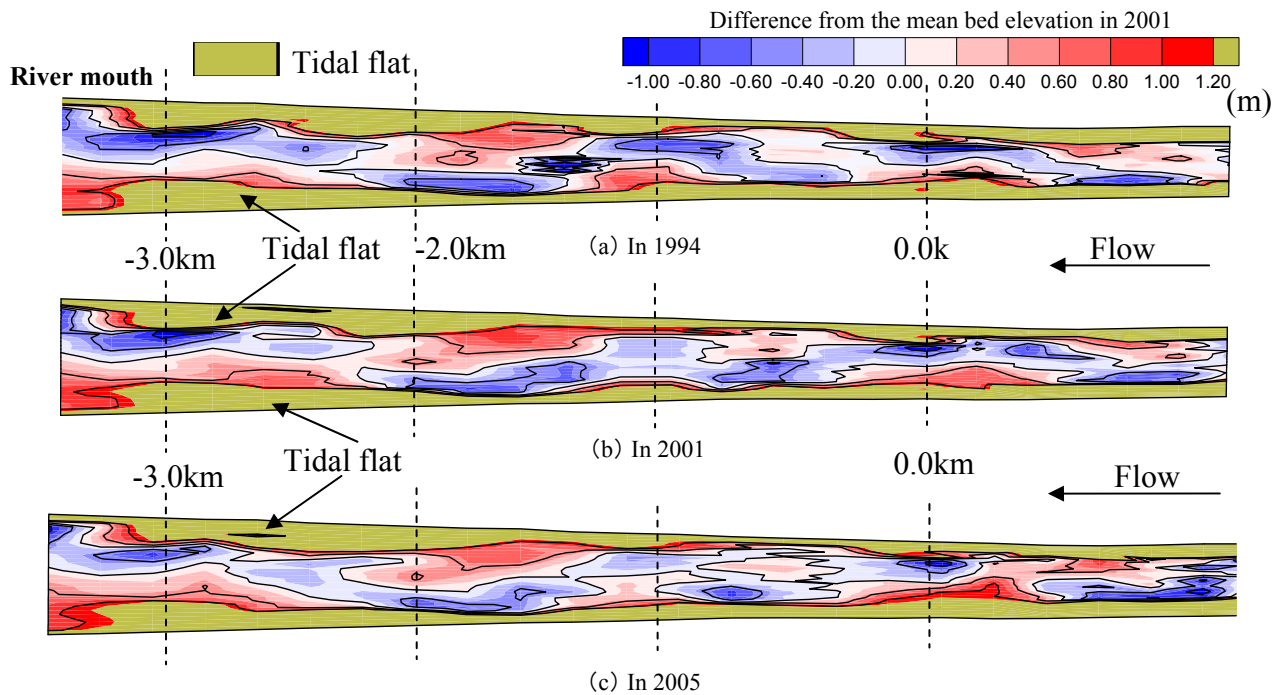
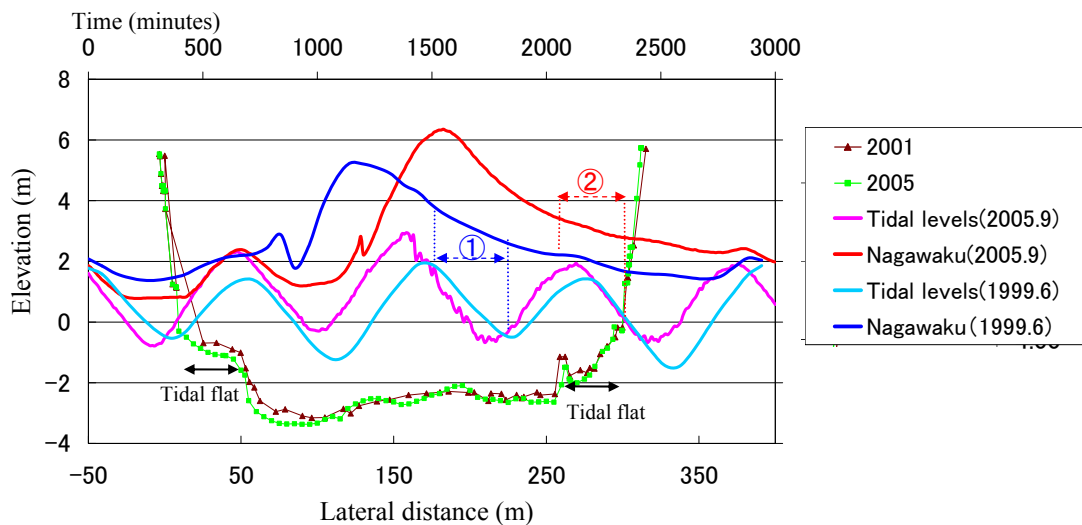Figure6. Contour of the observed bed profiles in the Ota River Floodway

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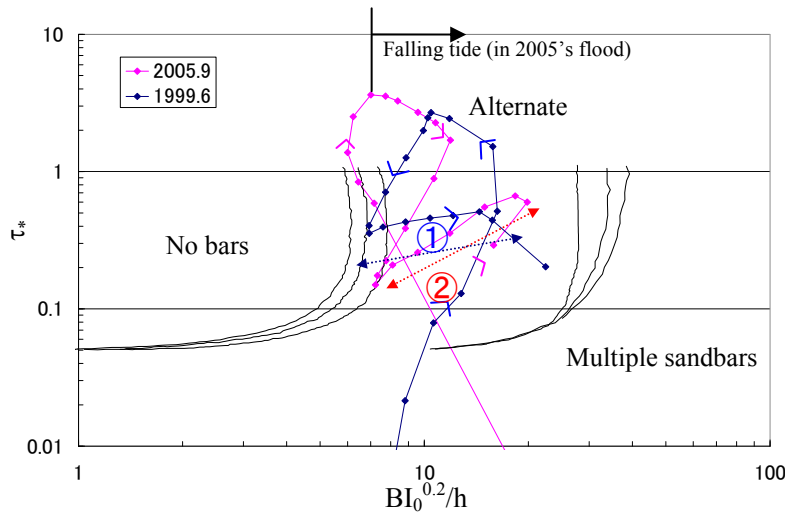
Figure8. Bed profiles classification diagram (Kuroki and Kishi, 1984)

period (period ①,②). Therefore, this fact indicates   that displacem ent, developm ent 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. Okam ura, Fukuoka et al. (2010) have dynam ically explained the bed variation in the Tone River m outh during the flood. They conducted the unsteady quasi 3-D flow and bed variation analysis m   ethod using the tim e series of the observed water surface profiles. In the Ota River estuary, the three-dim ensional flow by the river bifurcation and the alternate bars is im   portant for the   bed variations. Therefore, we conducted the unsteady quasi three-dim ensional flow and be d variation analysis m ethod using the tim e series of the observed water   surface profiles. Equations of m   otion (1), (2), equation of continuity (4) and vorticity equations (5) ar   e as f ollows. The bed surf   ace velocity is calculated by equation (6). The vertical velocity distributions assum   ed 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 form   ula (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 m   odified Egi azaroff form ula (Egiazaroff, 1965; Ashida and Michiue, 1972).
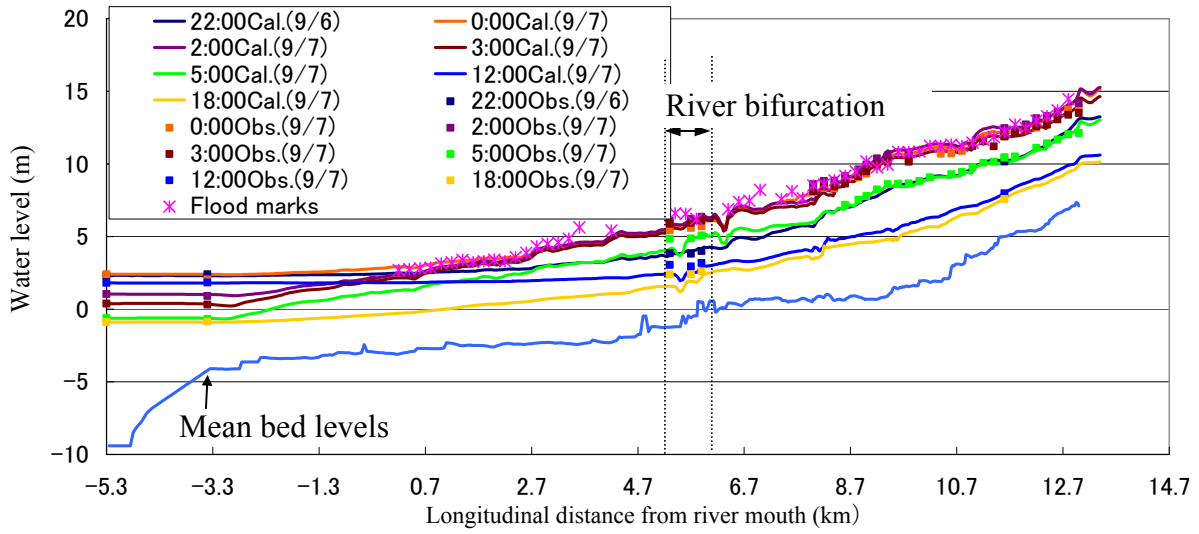
Figure9. Comparison between observed and calculated water surface profiles

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

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

(1)

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

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

(2)

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

(3)

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

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

(4)

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

(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.

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

(6)

Calculation results

Figure 9 shows the comparison between the observed and calculated water surface profiles. Figure 10 and Figure 11 show the com parison 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 ve locity in the peak discharge is indicated on Figure 11. The calculated water surface profiles with time variation are good agreem ent with the observed water surface profiles (Figure 9).
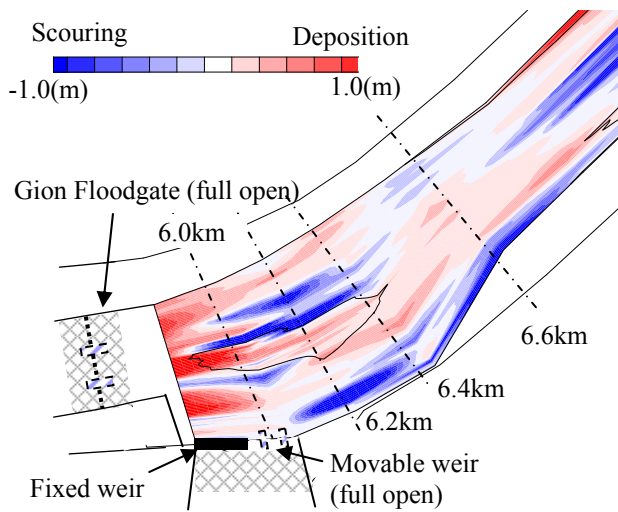
Figure10. Contour of observed change in the bed profiles before and after the flood
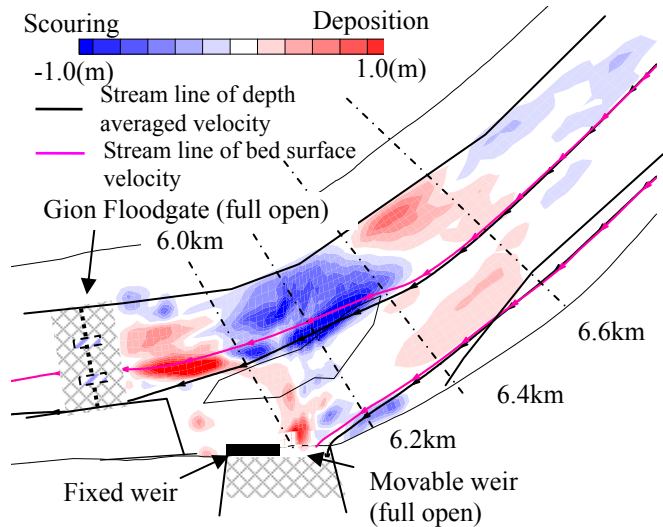

Figure11. Contour of calculated change in the bed profiles before and after the flood

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.
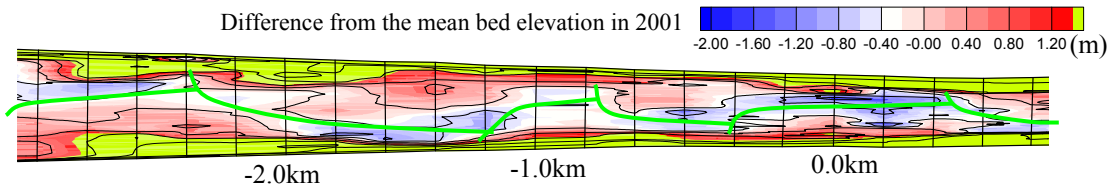
Difference from the mean bed elevation in 2001

-2.00 -1.60 -1.20 -0.80 -0.40 -0.00 0.40 0.80 1.20 (m)

-2.0km　　　　-1.0km　　　　0.0km

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

Scouring　　　　　　Deposition

-0.5(m)　　　　　　0.5(m)

-2.0km　　　　-1.0km　　　　0.0km
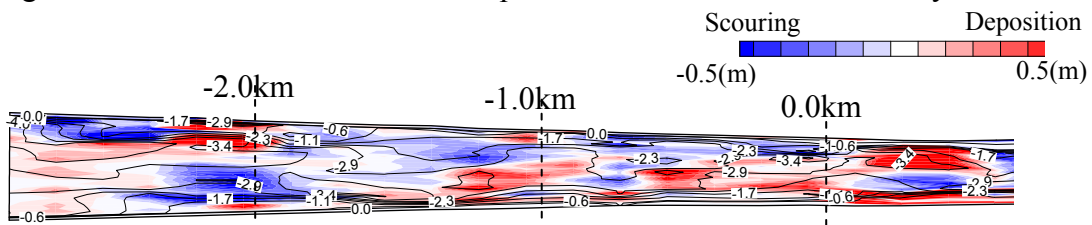
Figure13. Contour of the observed change in the bed profiles before and after the flood

Scouring　　　　　　Deposition

-0.5(m)　　　　　　0.5(m)

-2.0km　　　　-1.0km
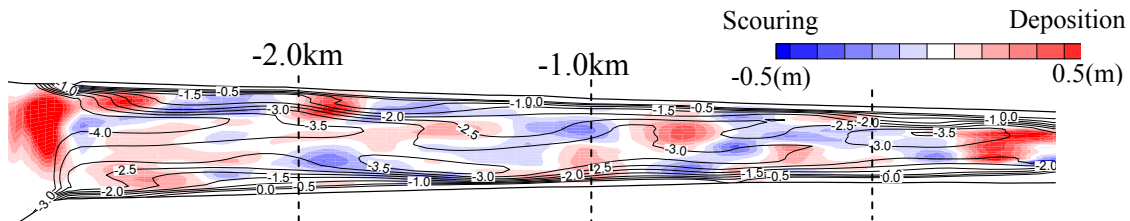
Figure14. Contour of the calculated change in the bed profiles before and after the flood

Scouring　　　　　　Deposition

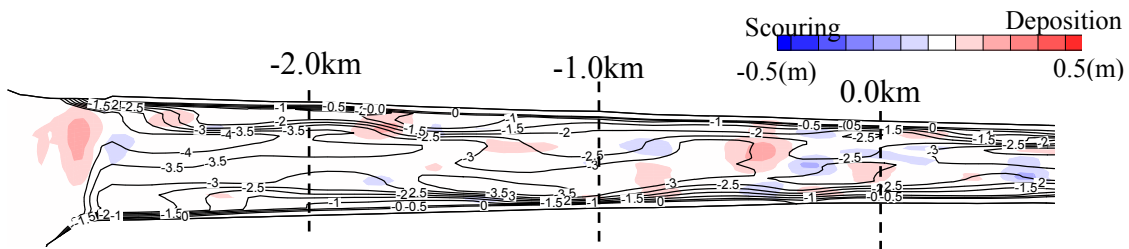-0.5(m)　　　　　　0.5(m)

-2.0km　　　　-1.0km　　　　0.0km

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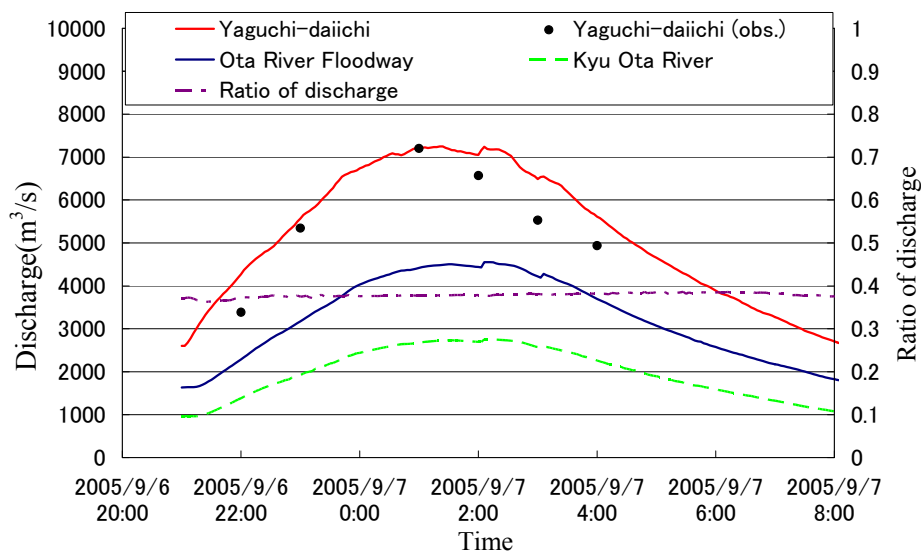

Figure16. Observed and calculated hydrograph and discharge ratio in the river bifurcation

CONCLUSIONS

The following conclusions were derived from the observation and calculation results.
1) Unsteady quasi three dim ensional analysis of flood flows and bed variations using tim e series of observed water surface profiles is found to provide fairly good results for bed variation with branched section in the Ot a 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 form ed 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.

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