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Bed variation during floods in the Chikugo River estuary with complex structures of bed layers

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ABSTRACT: It is known that the vertical structure of the river bed of the Chikugo River estuary makes complex structures of cohesive soil (gata-soil) and sand. In this study, we develop a new model of bed variation analysis in the river estuaries with complex structures of bed layers, and we clarify the mechanism of bed variation in the Chikugo River estuary during a flood. In the model, when the volume ratio of gata-soil is larger than the porosity of sand, bed variations are calculated by the GBVC flood flow analysis method and continuity equation of sediment which takes into account the discharge rate of sand and erosion speed of the cohesive material. On the other hand, when the volume ratio of gata-soil is less than the porosity of sand, variations of the river bed are calculated by continuity equation for sand. This is because sand and mixture of sand and gata-soil have different transportation mechanism and the gata-soil has great influence on the bed variation. The newly developed bed variation model provides good explanations for bed variation in the Chikugo River estuary.

1 INTRODUCTION

Environmental issues of the Ariake Sea which has the largest tideland in Japan attract concern of the public. One of reasons for issues is the lack of sand supply from the Chikugo River which has the largest catchment area out of several rivers flowing into the Ariake Sea. The bed of the Chikugo River estuary is covered with the cohesive sediment such as silty clay called 'gata-soil' which is transported from the Ariake Sea due to a maximum of 6 meters tidal level changes. Therefore it is said that sands may not be transported mostly from the Chikugo River. However it is confirmed that the vertical structure of the river bed is formed by complex structures of bed layers of the gata-soil and sand and sands exist sufficiently in the lower layer of the river bed surface by the core sample survey and supersonic echo sounder around the Chikugo River estuary (see Figs. 1, 3).

Suzuki et al. (2011) developed the bed variation analysis model taking into account the characteristics of sediment transport of gata-soil and sand, focusing on the fact that the water content ratio and particle size distribution of the gata-soil and sand were different. They estimated the mechanism of the bed variation and amount of sand supply from the Chikugo River estuary to the Ariake Sea during a flood. But some problems are remained in the sediment transport model of the gata-soil river bed. In this study, we develop a new analysis method of river bed variation with complex structures of bed layers. And we clarify the mechanism of the bed variation and estimate the amount of sand supply from the Chikugo River estuary to the Ariake Sea during a flood.

2 STUDY OBJECTIVE AREA AND FLOOD

Figure 2 shows plan-form of the objective area and water level and flood discharge observation points. The time series data of the flood discharge are observed at the Senoshita (25.5 km) observation station. The points designated by squares indicate the location of simple pressure-type water level gauges with a built in data logger. Table 1 shows the details of the objective floods that occurred in 2009. The peak discharges of the two floods were greater than the average annual

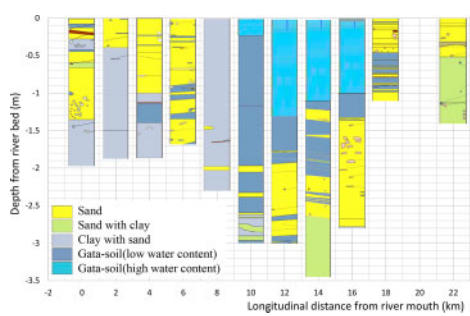


Figure 1. Vertical profiles of river bed material.

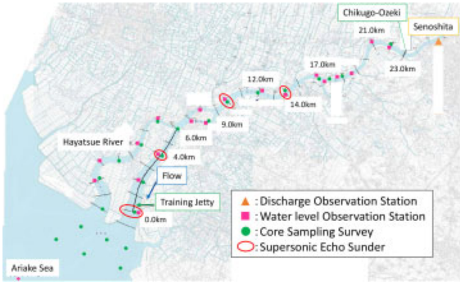


Figure 2. Structure of river bed layer and its materials.

Table 1. Details of objective floods.

	Flood in June	Flood in July
Peak discharge	3850[m³/s]	3650[m³/s]
The number of peaks	2	2
Flood duration time	3 days	3 days
Tide level	neap tide	middle tide
Average annual maximum discharge	2850[m³/s]	
Design flood discharge	9000[m³/s]	

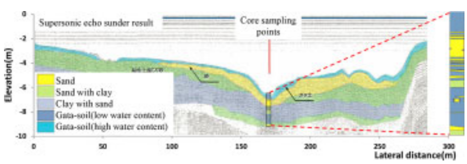


Figure 3. Plan-form and observation points in the objective area of the Chikugo River.

maximum discharge. Floods duration time were about three days. Both of the flood discharge hydrographs had two peaks. Flood in June occurred at the time of neap, and flood in July occurred at the time of middle tide. The river bed profiles before and after 2 floods in 2009 were measured at intervals of 200 m from the river mouth to 23 km including the tidal reach of the Ariake Sea. Also in the same year, the detailed core sampling data of river bed was obtained and used for analysis (see Fig. 1).

3 NUMERICAL ANALYSIS METHOD

3.1 *Flood flow analysis method*

The GBVC method (Uchida & Fukuoka 2012) is able to evaluate vertical velocity distributions and bottom velocities without the assumption of the shallow water flow such as hydrostatic pressure distribution by calculating following Equations (1)~(6). The bottom velocity is obtained in the depth-integrating horizontal vorticity equations (Eq. 1).

$$u_{bi} = u_{si} - \varepsilon_{ij3}\Omega_j h - \frac{\partial Wh}{\partial x_i} + w_s \frac{\partial z_s}{\partial x_i} - w_b \frac{\partial z_b}{\partial x_i} \tag{1}$$

where, $i,j = 1,2$(x,y), u_{bi}: bottom velocity, u_{si} : water surface velocity, Ω_j: depth averaged vorticity, h: water depth, W: depth averaged vertical velocity, z_s : water surface level, z_b: bottom level, w_s, w_b: vertical velocity on water surface and bottom.

To calculate Equations (1), it is required to solve the depth-integrated continuity equations (Eq. 2), the depth-integrated horizontal momentum equations (Eq. 3), the depth averaged turbulence energy transport equations (Eq. 4), the depth-integrated horizontal vorticity equations (Eq. 5) and the water surface velocity equations (Eq. 6).

$$\frac{\partial h}{\partial t} + \frac{\partial U_j h}{\partial x_j} = 0 \tag{2}$$

$$\frac{\partial U_i h}{\partial t} + \frac{\partial U_i U_j h}{\partial x_j} = -gh\frac{\partial z_s}{\partial x_i} - \frac{\partial h dp_0}{\rho \partial x_i} - \frac{dp_b}{\rho}\frac{\partial z_b}{\partial x_i} - \frac{\tau_{bi}}{\rho} + \frac{\partial h \tau_{ij}}{\rho \partial x_j} \tag{3}$$

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = \frac{1}{h}\frac{\partial}{\partial x_i}\left(\frac{v_t h}{\sigma_k}\frac{\partial k}{\partial x_i}\right) + P_k - \varepsilon \tag{4}$$

where, U_i : depth averaged horizontal velocity, g : gravity, dp : pressure deviation from hydrostatic pressure distribution $(dp = p - \rho g(z_s - z))$, dp_0: depth averaged $dp(dp_0 = dp_b/2)$, dp_b : dp on the bottom, τ_{bi} : bed shear stress, τ_{ij}: horizontal shear stress due to turbulence, u_i, u_j : correlation of vertical distributions of horizontal velocities, k : depth averaged turbulence energy, P_k: production term, ε: dissipation term $(\varepsilon = C_\varepsilon k^{3/2}/\Delta)$, $v_t = C_\mu k^2/\varepsilon$, $\sigma_k = 1.0$, $C_\varepsilon/\Delta = 1.7/h(C_\varepsilon = 0.17,\ \Delta/h = 0.1)$.

$$\frac{\partial \Omega_i h}{\partial t} = R_{\sigma i} + P_{\omega i} + \frac{\partial h D_{\omega ij}}{\partial x_j} \tag{5}$$

where, $R_{\sigma i}$: rotation term of vertical vorticity, $P_{\omega i}$: production term of vorticity from the bottom thin vortex layer and $D_{\omega ij}$: horizontal vorticity flux due to convection, rotation, dispersion and turbulence diffusion.

$$\frac{\partial u_{si}}{\partial t} + u_{sj}\frac{\partial u_{si}}{\partial x_j} = -\left\{g - \left(\frac{\partial dp}{\partial z}\right)_{z=z_s}\right\}\frac{\partial z_s}{\partial x_i} + P_{si} \tag{6}$$

where, P_{si}: production term due to shear stress acting on thin water surface layer.

The vertical distribution of velocity is described by Equation (7).

$$u'_i = u_i - U_i = \Delta u_i\left(12\eta^3 - 12\eta^2 + 1\right) + \delta u_i\left(-4\eta^3 + 3\eta^2\right) \tag{7}$$

where, $\eta = (z_s - z)/h$, $\Delta u_i = u_{si} - U_i$, $\delta u_i = u_{si} - u_{bi}$, z : vertical level.

The bottom pressure intensity is given by equation (8) which is derived from the integration of the vertical momentum equation over water depth.

$$\frac{dp_b}{\rho} = \frac{\partial Wh}{\partial t} + \frac{\partial hWU_j}{\partial x_j} + \frac{\tau_{bj}}{\rho}\frac{\partial z_b}{\partial x_j} \tag{8}$$

Time variation in the depth integrated vertical velocity is calculated in Equation (9).

$$k_1 \frac{\partial}{\partial x_j}\left(h^2 \frac{\partial \phi}{\partial x_j}\right) + \phi^p - \phi = 0 \tag{9}$$

where, $k_1 = 1/10$, $\phi = (Wh)^{n+1} - (Wh)^n$, $\phi^P = (Wh)^P - (Wh)^n$, $(Wh)^P$ is calculated by the continuity equation with horizontal velocity field by using predicted bottom velocity $(u_{bi})^P$:

$$(Wh)^P = \frac{\partial}{\partial x_j}\left[(h^2)^{n+1}\{k_2(\Delta u_j)^{n+1} - k_1(\delta u_j)^P\}\right] + h^{n+1}\left(\frac{\partial z_m}{\partial t} + U_j\frac{\partial z_m}{\partial x_j}\right)^{n+1} \tag{10}$$

where, $k_2 = 1/10$, $(\Delta u_i)^P = (u_{si})^{n+1} - (u_{bi})^P$, $(u_{bi})^P$ is evaluated by Eq. (1) with $(Wh)^n$, $z_m = (z_s + z_b)/2$.

3.2 *Bed variation analysis method*

The gata-soil from the Ariake Sea deposit on the river bed of the Chikugo River estuary. Also flood flows from the upstream of the Chikugo River deposit the sand in the Chikugo River estuary. Therefore complex structures of bed layer are formed (see Figures 1, 3). Very loose gata-soil which is about 200% in water content ratio deposits on the river bed in the reach of 10 km to 17 km because the groundsill at 17.2 km prevents salt water intrusion except the spring tide. The thickness of the gata-soil layer is about 2 m at the maximum. The mechanism of bed variations in the Chikugo river estuary is quite different from the sandy or stony bed rivers because the gata-soil has a particular cohesion property. The bed variation analysis of Suzuki is made by erosion speed equation of the cohesive material when the water content ratio of the gata-soil layer is larger than 70%. On the other hand, when the water content ratio of sand layer is less than 70%, bed variations are calculated by continuity equation for sediment taking into account the discharge rate of sand. Also he elucidated the temporal changes in observed water surface profiles and river bed variation in the Chikugo River estuary by adjusting the coefficient of sediment discharge equation of sand. However, in the numerical analysis of Suzuki, the effect of the adhesive strength of the gata-soil on the movement of the sand in the mixed state of gata-soil and sand was not considered, and continuity equation of sand included in a gata-soil layer was not satisfied.

In this study, we develop a new analysis method of river bed variation with complex structures of bed layers taking into account the movement mechanism of the sand and gata-soil and clarify the mechanism of bed variation and the amount of sand supply from the Chikugo River estuary to the Ariake Sea during a flood.

3.2.1 *Sediment transport equations for sand and gata-soil*

The bed load transport rate of each grain size of the sand is calculated by Ashida and Michiue formula (Ashida & Michiue 1972). The critical tractive forces for each particle size and mean particle size are calculated by modified Egiazaroff formula (Ashida & Michiue 1972) and Iwagaki formula (Iwagaki1956) respectively. Effects of bed slope on tractive forces and critical tractive forces of sediments particles are evaluated by Fukuoka and Yamasaka equations (Fukuoka & Yamasaka 1986).

The erosion rate of gata-soil is calculated by erosion speed equation of the cohesive material (Eq. 11) (Nishimori & Sekine 2009).

$$E_s = \alpha \cdot R_{wc}^{\ 2.5} u_*^{\ 3} \tag{11}$$

where, E_s : erosion speed, α: coefficient depending on water temperature, R_{wc} : water content ratio, u_* : shear velocity.

Yokoyama et al. (2008) gave to 0.21×10^{-5} the value of the coefficient α by observing the change of river bed temperature and the erosion rate of gata-soil in the 2006 Chikugo River flood.

3.2.2 *Bed variation analysis*

The variations in river bed elevations are evaluated by two-dimensional continuity equation for sediment transport. Figure 4 demonstrates the concept for the variations of river bed of complex structure consisting of gata-soil and sand. The gata-soil has transport characteristics different from sand and has great influence on the bed variation of the Chikugo River estuary. In other words, the influences of the gata-soil upon the river bed variation depends on whether the rate of volume of gata-soil is larger than the porosity of sand or not.

Figure 4(a) shows the bed variation model of the case that rate of volume of gata-soil is larger than the porosity of sand ($V_G \geqq \lambda$) that is the gata-soil contains the sand. The gata-soil in such a state increases the cohesion of bed layer and has a great effect on the movement of sand. Therefore, variations in river bed are calculated by Equation (12) that is continuity equation for sediment taking into account both discharge rate of sand and erosion speed of the cohesive material.

$$z_b^{\ n+1} = z_b^{\ n} - \left(\frac{q_{i+1} - q_i}{\Delta x}\right)\Delta t - V_G \cdot E_s \Delta t \tag{12}$$

where, z_b: bottom level, q : discharge rate of sand (particle size 75 μm or more), V_G : Volume ratio of gata-soil (particle size less than 75 μm) in the river bed layer.

On the other hand, Figure 4(b) indicates the state that the volume ratio of gata-soil is less than the porosity of sand ($V_G < \lambda$). In other words, the gata-soil is contained in the porosity of sand. So it is able to be assumed that the gata-soil is flushed with the transport of the sand and washing away of the gata-soil hardly has effect on the variation of river bed. Then, variations of the river bed are calculated by continuity equation for sand as expressed in Equation (13).

$$z_b^{\ n+1} = z_b^{\ n} - \frac{1}{1-\lambda}\left(\frac{q_{i+1} - q_i}{\Delta x}\right)\Delta t \tag{13}$$

where, λ: porosity of sand (0.4).

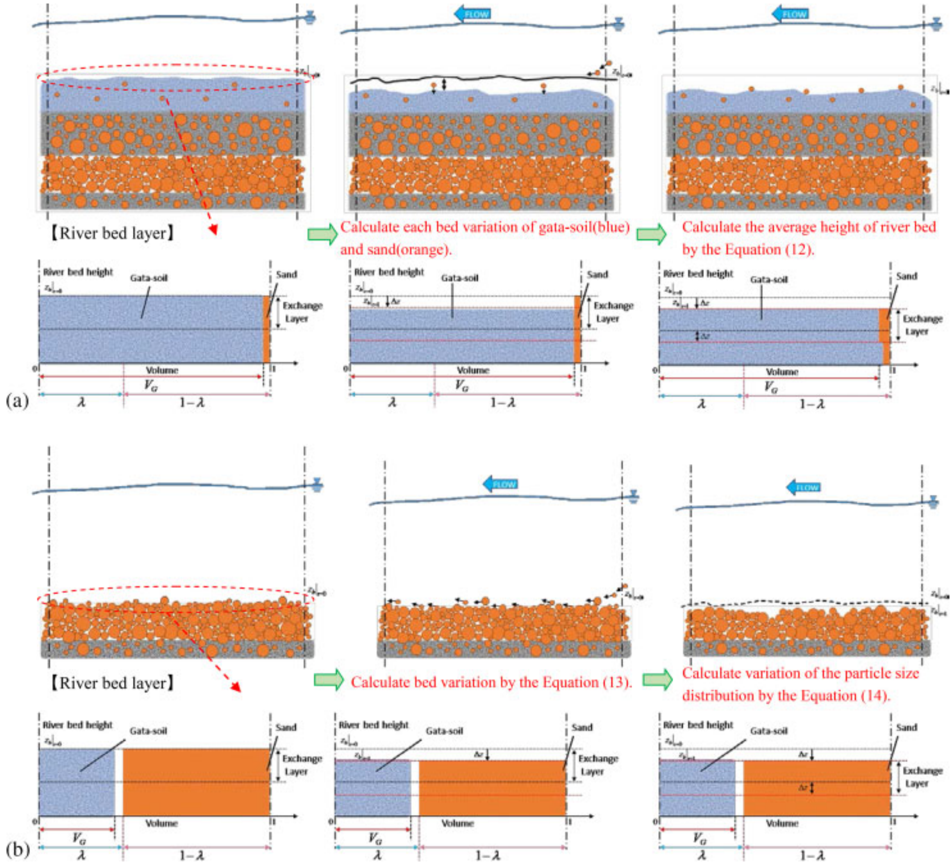


Figure 4. (a) Model of the variation of river bed consisting of complex structure of gata-soil and sand. ($V_G \geqq \lambda$). (b) Model of the variation of river bed consisting of complex structure of gata-soil and sand. ($V_G < \lambda$).

3.2.3 *Variation of the particle size distributions*

The variation of the particle size distributions is calculated by Equation (14), which is the continuity equation for particle size ratio using a bed variation calculated by Equations (12) and (13) (see Figure 5).

$$\frac{\partial P_k}{\partial t} + \frac{\partial (wP_k)}{\partial z} = 0 \tag{14}$$

where, $w = -\Delta z/\Delta t$: time variation of the river bed elevation (downward positive), P_k: the existing proportion of particle size k. V_G is calculated from the water content ratio of gata-soil and the particle size ratio estimated by Equation (14). In addition, the gata-soil is assumed not to deposit again on the channel bed once it starts to be transported.

3.3 *Analysis conditions*

Boundary conditions at the upstream and downstream ends of the Chikugo river estuaries are given by observed water-level hydrographs of –0.2 km point and 22 km point, respectively. The Manning's roughness coefficients are determined so as to agree with observed temporal changes in water surface profiles of June and July floods in 2009. The equilibrium sediment discharge at the downstream of the Chikugo weir where the ground elevation change is relatively small, is given as the upstream boundary condition of sediment. Initial conditions of bed layers are set at the pitch of 10 cm in vertical downward direction from river bed surface. The particle size distribution and water content in each layer are given by the core sampling data of river bed materials.

4 RESULTS AND CONSIDERATIONS

Figure 6 shows comparisons between observed and calculated temporal changes in water surface profiles and calculated mean bed elevations in the Chikugo River estuary. The calculated water surface profiles agree well with observed ones. Also the calculated mean bed elevations in the section from 10 km to 17 km decrease about 1.5 m in the rising period of June flood. This is because the gata-soil deposited on the river bed was flushed away during the flood. Figure 7 shows observed and calculated discharge hydrographs

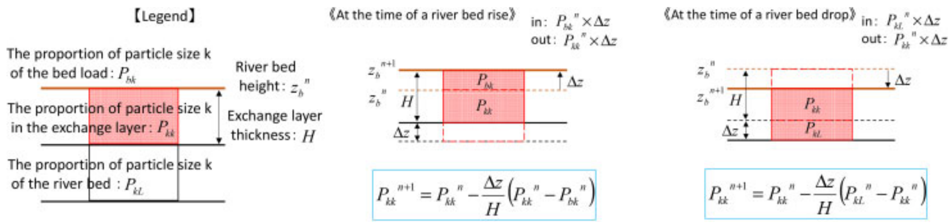
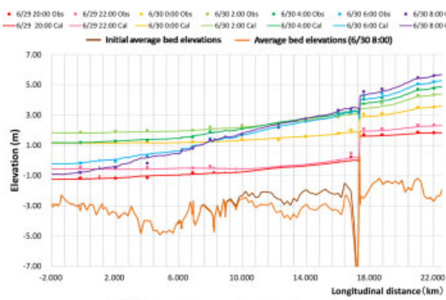
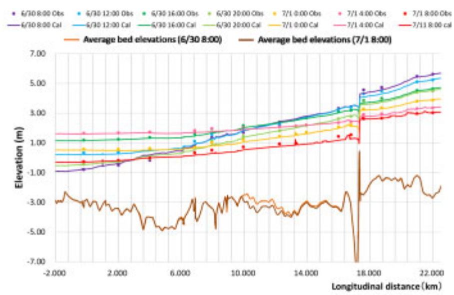


Figure 5. Method of calculation for the variation of the particle size distribution in the exchange layer.

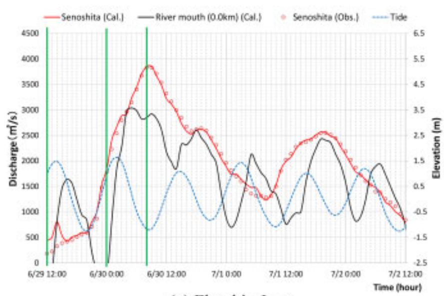


(a) Water rising period in June flood.

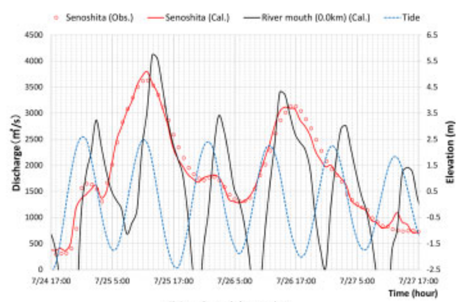


(b) Water falling period in June flood.

Figure 6. Comparisons between observed and calculated water surface profiles and calculated mean bed elevations.

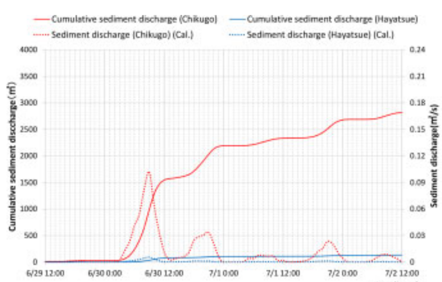


(a) Flood in June.

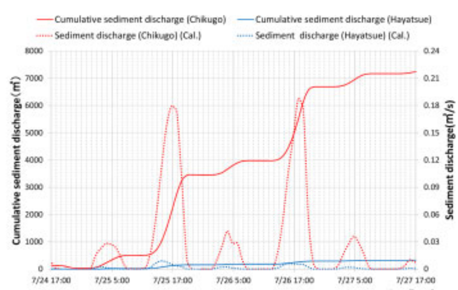


(b) Flood in July.

Figure 7. Discharge hydrographs at Senoshita (25.5 km) and river mouth (0.0 km).



(a) Flood in June.



(b) Flood in July.

Figure 8. Sediment discharge hydrographs and cumulative sediment discharge at the Chikugo River and Hayatsue River (0.0 km).

at Senoshita (25.5 km) observation station and 0.0 km point. The solid and dash lines in Figure 7 indicate the temporal changes in the calculated discharge and observed tidal level, respectively. The newly developed numerical method is found to explain observed discharge hydrograph at Senoshita observation station. It is also found that flood discharge hydrograph at the river mouth (0.0 km) strongly receives the influence of

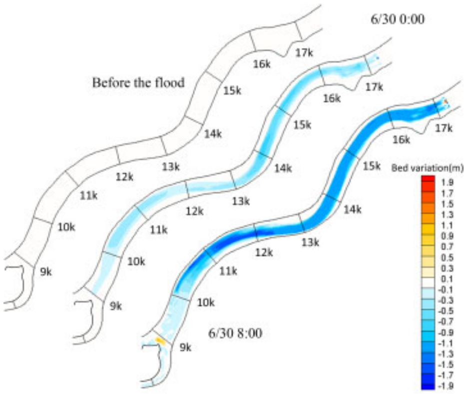


Figure 9. Contours maps of time change of bed variation from 9.0 km to 17 km.

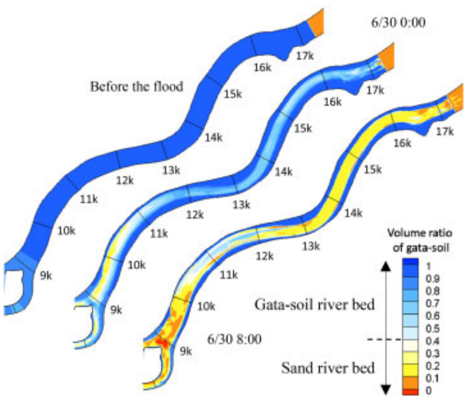
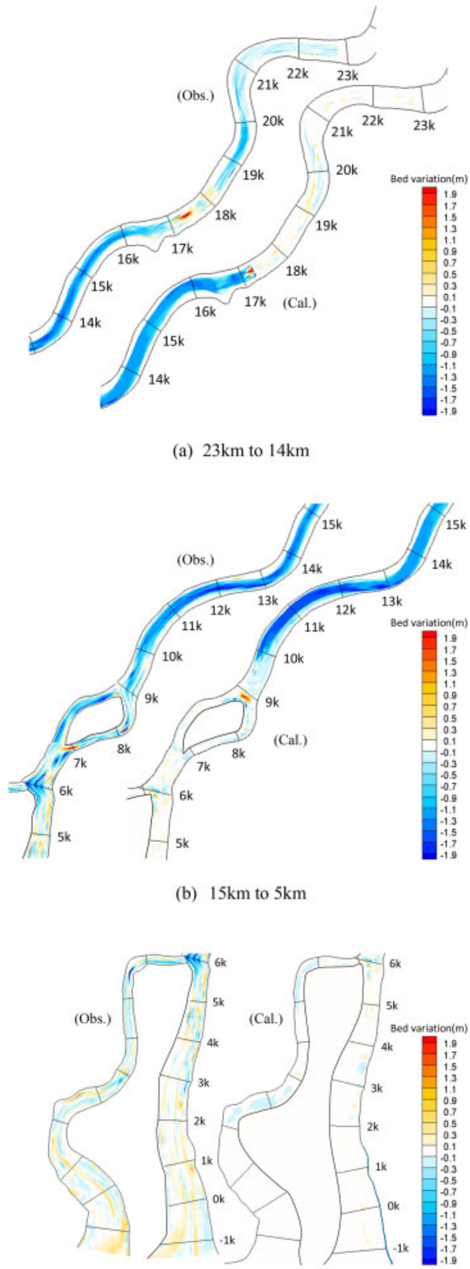


Figure 10. Contours maps of time change of volume of gata-soil on the bed surface from 9.0 km to 17 km.

the tidal level change of the Ariake Sea and the peak discharge appears at the time of ebb tide.

Figure 8 shows calculated sediment discharge hydrographs and cumulative sediment discharges at 0.0 km points of the Chikugo River and Hayatsue River. The dash and solid lines in Figure 8 indicate the calculated sediment discharges and cumulative sediment discharges, respectively. In this figure, sediment discharge from the Chikugo River estuary to the Ariake Sea varies with the tidal level changes as well as discharge at the river mouth (0.0 km) and most of the sand flows out at low tide period. About 2,800 m^3 and 7,200 m^3 sand flowed out from the Chikugo River into the Ariake Sea during June and July floods, respectively. Although the peak discharges at Senoshita (25.5 km) of the June and July floods are comparable, cumulative sediment discharge from the Chikugo River estuary to the Ariake Sea of July flood is more than 2.5 times as much as the cumulative sediment discharge of June flood. This is because July flood 4,000 m^3 peak discharge flowed out from the river mouth but June flood 3,000 m^3.

Figure 9 shows the contour map of the bed variations from 9.0 km to 17 km at the time indicated by the



(c) 6km to Ariake Sea

Figure 11. Contours maps of bed variation from Ariake Sea to 23 km before and after the flood.

green lines in Figure 7 (a). Figure 10 shows the volume ratio of the gata-soil on the river bed surface. The range from white to red and white to blue in Figure 10 indicate the sand bed and gata-soil bed, respectively. In this figure, the gata-soil which deposited in the section from 10 km to 17 km is flushed all during the flood rising period in June and the sand is exposed on the river bed surface at the time of flood discharge peak. The roughness coefficient of this section are increased with the time from 0.021 to 0.028 whose values reproduce the observations of temporal water surface profiles in this section during the flood. Figure 11 shows comparisons between observed and calculated contour map of the bed variations from the Ariake Sea to 23 km during the 2009 June flood. In this analysis, calculation results of the bed variations almost agree with observed ones in the section from the 10 km to 17 km where a lot of gata-soil deposit and the change of the particle size distribution is large in the vertical direction. However, calculation results of the bed variations in the downstream from 6 km are smaller than observed ones. This reason may be that the gata-soil in the river bed weakens the engagement effect among sands, which makes the sand easier to move actually compared with a general sand bed river.

5 CONCLUSIONS

1. The numerical analysis results reproduce the temporal changes of the observed water surface profiles, discharge hydrographs at the observation points and the bed variations before and after the 2009 flood. It is concluded that the present computation method gives better understanding of bed variations in the river estuary which has the complex bed structures consisting of cohesive sediment and sand.
2. About 10,000 m^3 sand (June: about 2,800 m^3, July: about 7,200 m^3) flows out from the Chikugo River into the Ariake Sea during 2 floods occurred in 2009.

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