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DYNAMICS OF FLOOD FLOWS AND BED VARIATIONS IN RIVER SECTIONS REPAIRED TO SHIP-BOTTOM SHAPED CHANNELS FROM COMPOUND CHANNLS

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ABSTRACT

Compound channels have caused some undesirable problems on flood controls and river environments in recent years. In order to deal with these problems, one of the authors has proposed that the ship-bottom-shaped channel is a desirable cross-section of rivers for both flood controls and river environments. The Onga River in Japan challenged to change a part of channel sections to ship-bottom shaped channels from compound channels in the view of river environments. However, there have been no ideas how much the ship-bottom shaped channels improve the discharge capacity and channel stability against large floods. A large flood occurred in 2010 after completion of the ship-bottom shaped channel in the Onga River. In this study, effects of river improvements to ship-bottom shaped channels were investigated and clarified by comparing observed data and flood computation results. Velocity distributions of flood flows are improved and longitudinal bed variations decreased markedly in the ship-bottom-shaped channels compared to compound channel.

Keywords: ship-bottom shaped channel, compound channel, flood flow, bed variation, cross-sectional shape

1. INTRODUCTION

Channel dredgings and riverbed excavations in compound channels have been conducted for the increase in flood discharge capacity. However, excessive channel dredgings and excavations have made level of the low-water channel drop, which have resulted in unstable river bank and excessive growth of vegetation on flood channels. Therefore, it is important to do research on stable river channels which are desirable for flood controls and river environments. In the previous studies, there are a lot of regime equations to describe relations between river width, water depth and discharge on natural stable alluvial rivers (e.g. Singh (2003)). Ikeda et al. (1986) proposed relationship between river width, water depth and channel forming discharge in straight channels based on sediment hydraulics consideration. However, these equations couldn't explain mechanics of width of stable rivers which have various scales, plain forms and grain sizes (Fukuoka (2010)).

Fukuoka (2010, 2012) proposed dynamic relation equations (Fukuoka's equations) between dimensionless river width, dimensionless depth and dimensionless channel forming discharge derived by dimensional analysis. Moreover, Fukuoka proposed river improvement technique using Fukuoka's equations and numerical simulations of flood flows and bed

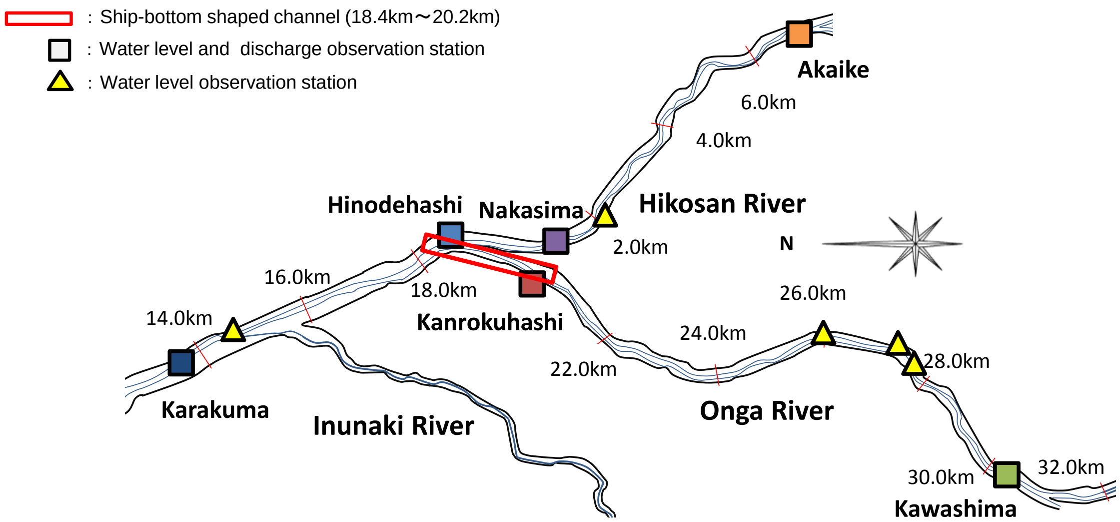
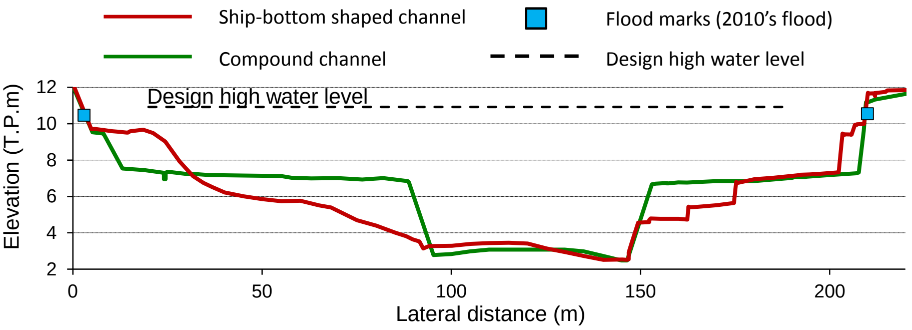


Figure 1 Objective are and observation stations

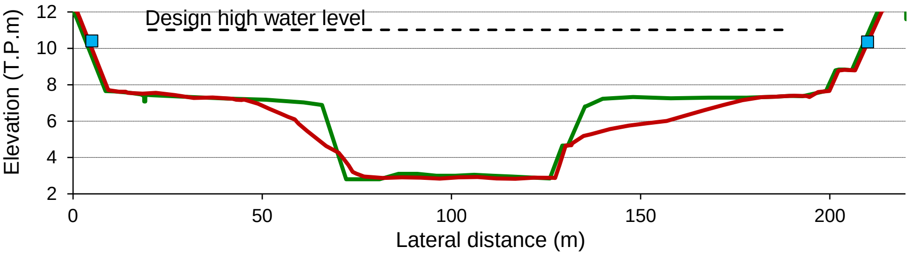
variations in the Satsunai River where the channel was narrowed and eroded by a series of spur dikes and vegetation growing. This study proved that cross-sectional shapes of dynamic stable channels determined by his river improvements method became similar to the ship-bottom shape which can be seen in the natural stable alluvial rivers (Fukuoka (2013)). These cross-sectional shapes are described as follows. The river bed profiles have continuous and gradual changes of bed boundary and river widths continuously change in correspondence of water level rising. In this study, we call such a cross-sectional bed profiles as the ship-bottom shaped channel. Gotoh et al. (2014) presented the method of river bank protection for preserving tidal flats in ship-bottom shaped channels of the Ota River floodway. However, effects of river improvements from compound channels to ship-bottom shaped channels have not really been evaluated in actual rivers.

The Onga River was repaired from compound channels to ship-bottom shaped channels for river environments (see Figure 1, 2 and 3). Figure 2 shows cross-sectional bed profiles of the ship-bottom shaped channels at 19.6km and 19.8km. We can see in these figures that cross-sectional bed profiles have continuous and gradual changes in bed boundary (Higuchi et al. (2007)). After the completion of the ship-bottom shaped channels, we have experienced a large flood in July 2010.

The objective of our study is to clarify effects of the river improvements from compound channels to ship-bottom shaped channels. Therefore, we conducted the quasi-three-dimensional flow analysis and bed variation analysis in order to understand dynamics of flood flows and bed variations in ship-bottom shaped channel. Flood flows and bed variations in the compound channel before the river improvement works are compared with those in ship bottom shaped channels by using the calculation results and Fukuoka’s equations.



(a) 19.6 km



(b) 19.8 km

Figure 2 Cross-sectional profiles of ship-bottom shaped channel at 19.6km and 19.8km

Figure 3 Ship-bottom shaped channel in the Onga River

2. Objective area and flood

2.1 Objective area and characteristics of ship-bottom shaped channel

Figure 1 shows a plan form and observation stations in the objective study area. River improvements to the ship-bottom shaped channels were conducted near the confluence with the Hikosan River. Revetments of the main channel were removed for the purpose of river environments and river-landscape (see Figure 3). The cross-sectional shapes of the compound channel were repaired so that the flood channels have mild slopes longitudinally and laterally (see Figure 3). Figure 4 shows contour-lines of the flood channel in the ship-bottom shaped channel. The flood channel of the left bank was designed to have longitudinal and lateral undulations for considering visitor's behavior and river-landscape (Higuchi et al. (2007)).

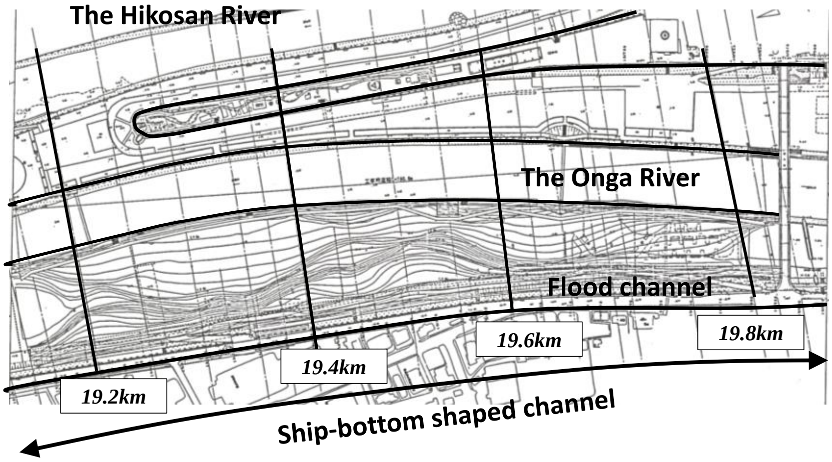
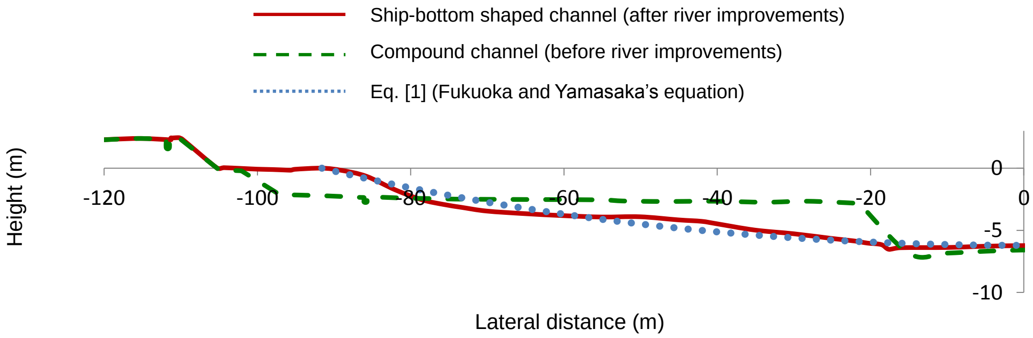


Figure 4 Undulations on flood channel of the Onga River

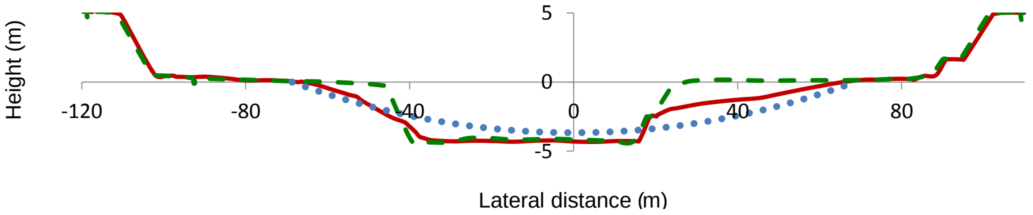
Figure 5 shows comparisons between cross-sectional bed profiles in stable straight channels described by Eq. [1] and the ship-bottom shaped channels at 19.6km and 19.8km. This equation was derived on the basis of experiments of a straight channel with bank erosions (Fukuoka and Yamasaka (1984))

$$\frac{h}{H}=1-\left\{\exp\left(-\frac{b-y}{D}\right)+\exp\left(-\frac{b+y}{D}\right)-\exp\left(-\frac{2b}{D}\right)\right\} \qquad [1]$$

Where h: water depth, b: half of river width, y: distance from the center of channel, H and D: coefficients which are determined cross-sectional area and lateral slope of riverbed. From these figures, cross-sectional bed profiles of the ship-bottom shaped channels in the Onga River seem to be described by Eq. [1].



(a) 19.6 km (left bank)



(b) 19.8 km

Figure 5 Comparison between cross-sectional shape of stable straight channel and ship-bottom shaped channel

2.2 Objective flood

After the completion of improvement works, large-scale flood occurred in July 2010. For evaluating effects of changes to ship-bottom shaped channel, we used the time series data of the water levels measured at five observation stations and drainage pump stations (see Figure 1). Flood marks were also obtained and almost comparable with design high water level (see Figure 2). Discharge hydrographs were observed at five observation stations. Figure 6 shows the flood discharge hydrographs observed by floats and H-Q curves at Hinodebashi (18.7km) observation station. The flood discharge hydrographs had three peaks. The flood duration time was about three days. The peak discharge recorded at about 3000 m^3/s.

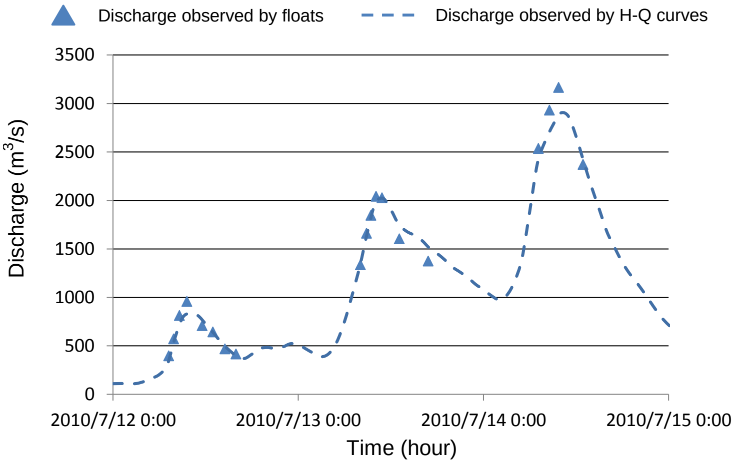


Figure 6 Discharge hydrographs at Hinodebashi observation station

3. Calculation method

3.1 Procedure of calculation

In recent years, Fukuoka (2011) proposed general method calculating flood flows and bed variations using time series data of water surface profiles during a flood. The calculation method is based on the idea that influences of cross-sectional forms, plane forms and bed variations during floods appear clearly in the observed temporal changes in the water surface profiles. Moreover, Uchida and Fukuoka (2011) developed the quasi-three-dimensional flow analysis method (the Bottom Velocity Computation (BVC) method) which can estimate vertical velocity distributions and bed surface velocities. And, Fukuoka (2011) has clarified characteristics of flood flows and bed variations in various rivers by the calculation method using both observed temporal changes in water surface profiles and the BVC method.

It is necessary to clarify three-dimensional structures of flood flows and stability of river beds in the ship-bottom shaped channel in order to evaluate effects of river improvements. First, the BVC method is applied to clarify flood flows and bed variations in the ship-bottom shaped channel of the Onga River in July 2010’s flood. Second, effects of the ship-bottom shaped channels are investigated by comparing velocity distributions and bed variations in the ship-bottom shaped channels with those of compound channels, which was channel before the river improvement works.

3.2 Governing equations

The BVC method (Uchida and Fukuoka (2011)) enable to estimate vertical velocity distributions and bed surface velocities by calculating Eq. [2]~[6]. The bed surface velocity is obtained by the Eq. [2], which is derived by depth-integral horizontal vorticity.

$$u_{bi} = u_{si} - \Omega_j h \qquad [2]$$

Where u_{bi}: bed surface velocity, u_{si}: water surface velocity, Ω: depth-averaged vorticity and h: water depth.

To calculate Eq. [2], it is required to solve the depth-integral continuity equations (Eq. [3]), depth-integral horizontal momentum equations (Eq. [4]), the depth-integral horizontal vorticity equations (Eq. [5]) and water surface velocity equations (Eq. [6]).

$$\frac{\partial h}{\partial t} + \frac{\partial U_j h}{\partial x_j} = 0 \qquad [3]$$

$$\frac{\partial U_i h}{\partial t} + \frac{\partial U_i U_j h}{\partial x_j} = -gh\frac{\partial z_s}{\partial x_i} - \frac{\tau_{bi}}{\rho} + \frac{\partial h \tau_{ij}}{\rho \partial x_j} \qquad [4]$$

Where, U_i : depth-averaged horizontal velocity, g: gravitational acceleration, z_s: water level, τ_{bi}: bed shear stress, τ_{ij}: horizontal shear stress due to turbulence and vertical velocity distribution.

$$\frac{\partial \Omega_i h}{\partial t} = ER_{\sigma i} + P_{\omega i} + \frac{\partial h D_{\omega ij}}{\partial x_j} \qquad [5]$$

Where ER: rotational term of vertical velocity, P_w: production term of vorticity from bottom thin vortex layer and D_{wij}: horizontal vorticity flux due to convection, rotation, dispersion and turbulence diffusion.

$$\frac{\partial u_{si}}{\partial t} + u_{sj}\frac{\partial u_{si}}{\partial x_j} = -g\frac{\partial z_s}{\partial x_i} + P_{si} \qquad [6]$$

Where P_{si}: the production term of surface velocity (shear stress under the water surface layer).

The variations in river bed elevations are evaluated from two-dimensional continuity equation for sediment transport. The bed load transport rate of each grain size is calculated by Ashida and Michiue formula (Ashida and Michiue, 1972). The critical tractive forces for each particle size and mean particle size are calculated by modified Egiazaroff formula (Ashida and Michiue, 1972) and Iwagaki formula (Iwagaki,1956), respectively. Effects of bed slope on tractive forces and critical tractive forces of sediments particles are evaluated by Fukuoka and Yamasaka equations (Fukuoka and Yamasaka (1986)). The transports of suspended sediments are computed by two-dimensional advection and diffusion equations. The vertical distributions of suspended load, pickup rate of suspended load from river bed and sedimentation velocity are calculated by using Lane-Kalinske formula (Lane and Kalinske, (1941)), Kishi and Itakura formula (Itakura and Kishi (1980)), Rubey formula (Rubey,1933), respectively.

3.3 Calculation conditions

3.3.1 After river improvements (the ship-bottom shaped channel)

Boundary conditions at the upstream and downstream ends of the Onga River are given by observed water-level hydrographs at Kawashima (30.5km) and Karakuma (13.7km) observation stations shown in Figure1. The upstream boundary condition of the Hikosan River is given by observed water level hydrograph at Akaike (7.5km) observation station. Initial conditions of bed forms are the cross-sectional bed forms measured at intervals of 200 meters in 2009. The undulations contour lines of flood channels shown in Figure4 are drawn by using cross-sectional bed profiles measured at intervals of 50 meters. The Manning's roughness coefficients and vegetation permeability coefficients are determined so as to agree with observed temporal changes in water surface profiles during 2010's flood. These coefficients are shown in Table1 (a). Figure7 shows grain size distributions of observed data and calculation.

Table 1 The Manning's roughness coefficient and vegetation permeability coefficient of objective rivers

(a) After river improvements

Section	**Manning roughness coefficient ($m^{-1/3}$・s)**		**Vegetation permeability coefficient (m/s)**
	main channel	flood channel	
Onga River (12.6km~18.8km,19.4km~31.2km)	0.029	0.04～0.043	30～70
Hikosan River (0.0km~7.8km)	0.029	0.040	30～70
Near the confuluence	0.033	0.040	25～70

(b) Before river improvements

Section	**Manning roughness coefficient ($m^{-1/3}$・s)**		**Vegetation permeability coefficient (m/s)**
	main channel	flood channel	
Onga River (12.6km~18.8km,19.4km~31.2km)	0.029	0.04～0.043	30～70
Hikosan River (0.0km~7.8km)	0.029	0.040	40～70
Near the confuluence	0.030	0.040	30～70

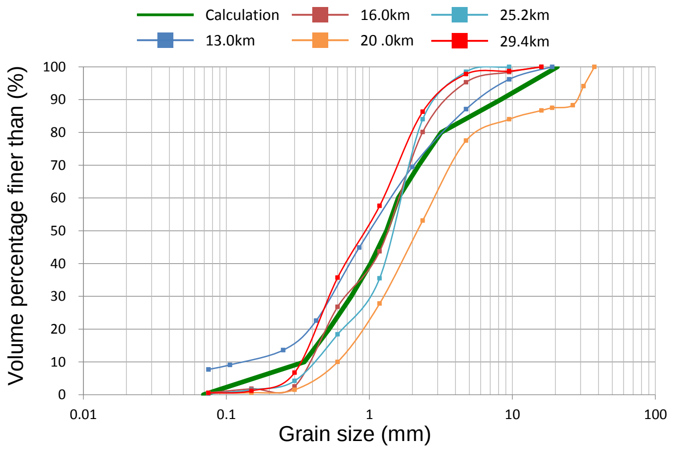


Figure 7 Particle grain size distributions of observed data and used for the calculation

3.3.2 Before river improvements (the compound channel)

Boundary conditions at the upstream end of the Onga River and Hikosan River are given by discharge hydrographs determined above the calculation at Kawashima (30.5km) and Akaike (7.5km) observation stations. Boundary condition at downstream end is given by observed water level hydrographs at Karakuma (13.7km) in 2010 flood. Initial bed profiles are made by cross-sectional profiles measured in 2002. Table 1 (b) shows the Manning's roughness coefficients and vegetation permeability coefficients. These coefficients are determined so as to reproduce time series of observed water surface profiles during 2003's flood.

4. Calculation results

4.1 Calculation results of the ship-bottom shaped channel

Figure 8 shows comparisons between observed and calculated temporal changes in water surface profiles and mean bed elevation in the Onga River. The calculated water surface profiles and mean bed elevations almost agree with observed ones. However, the observed water levels at Hinodebashi (18.7km) observation station are higher than the calculated ones due to water level increased by bridge pier. From observed data and calculated results shown in Figure 8, changes in mean bed variations in the ship-bottom shaped channel are understood to be small.

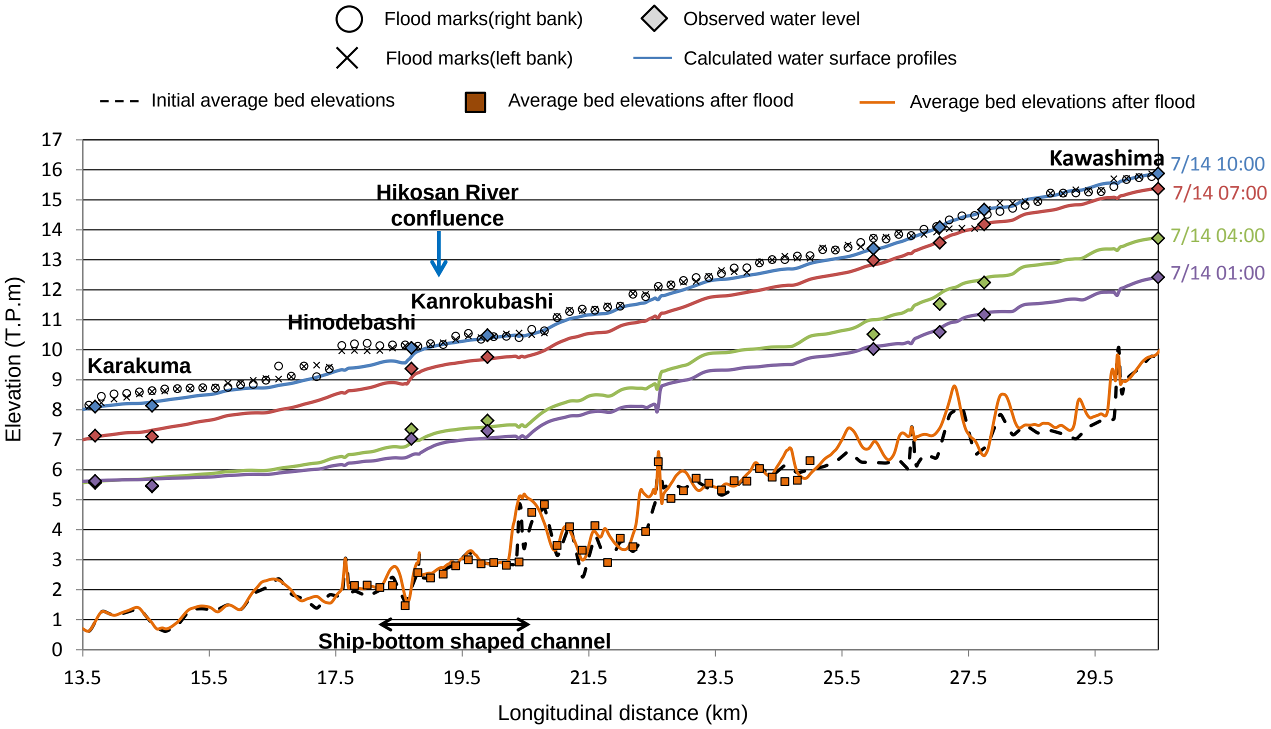


Figure 8 Comparisons between observed and calculated water surface profiles and mean bed elevation

Figure 9 shows observed and calculated discharge hydrographs at Hinodebashi (18.7km), Kanrokubashi (19.8km) and Nakashima (1.2km) observation stations. In this figure, our numerical method can explain observed discharge hydrographs at three observation stations, although calculated peak discharge at Hinodebashi (18.7km) observation station is lower than observed data.

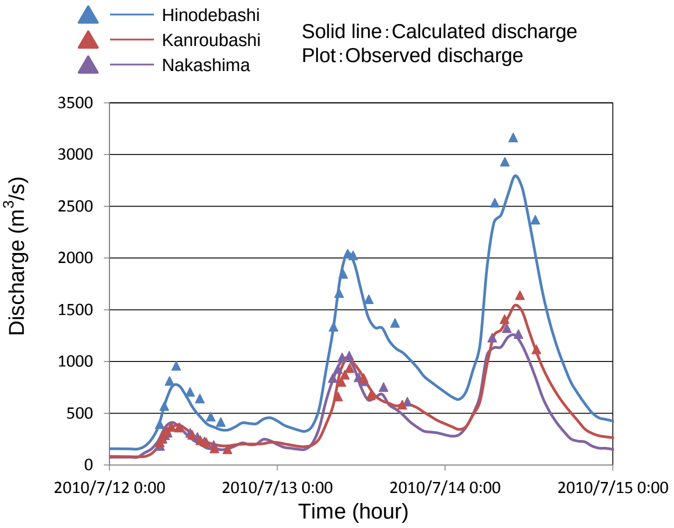


Figure 9 Discharge hydrographs at Hinodehashi observation station

Figure 10 shows the contour map of water depth and the temporal changes in shore lines of the ship-bottom shaped channel in the Onga River and compound channel in the Hikosan River. The water surface width of compound channels in the Hikosan River quickly spreads to the levee from 06:00 to 08:00, but that of ship-bottom shaped channels in the Onga River gradually spreads with water level increasing. Lateral and longitudinal undulations on the flood channel in the ship-bottom shaped channel create divers changes in the shore lines and present beautiful landscape during the flood.

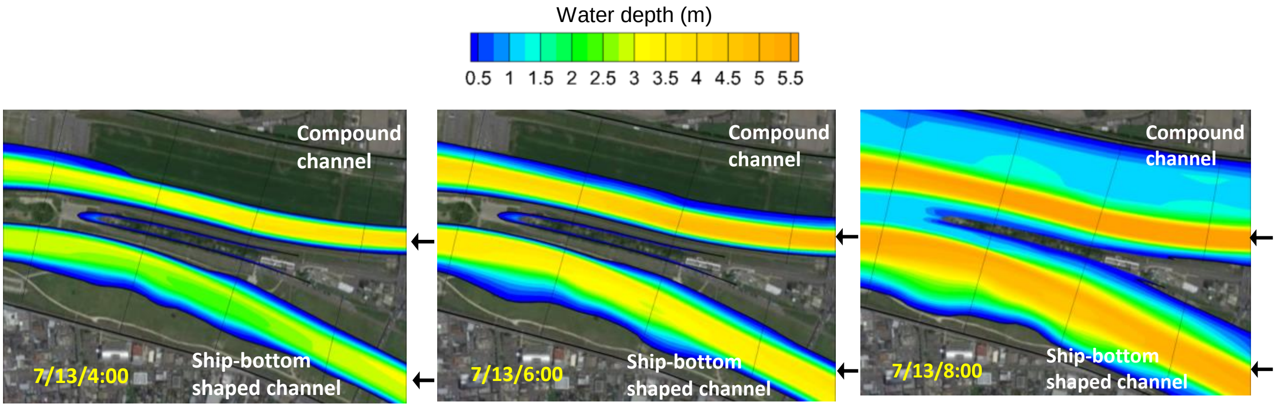


Figure 10 Temporal changes in shore lines

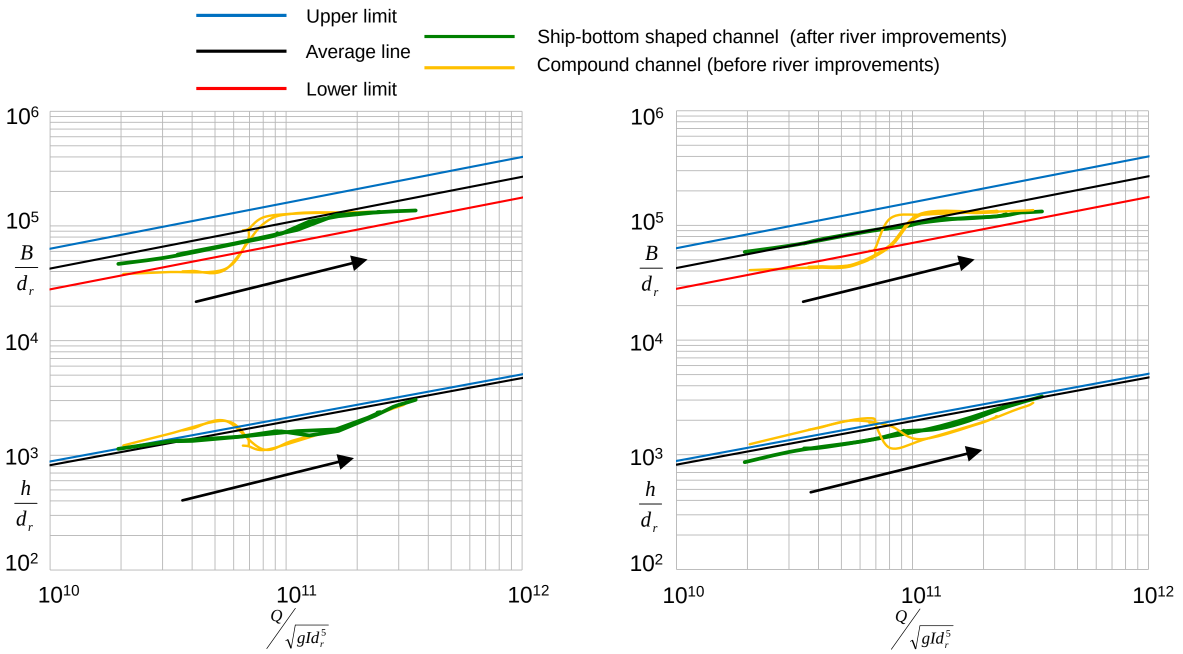
4.2 Comparison hydraulic characteristics between the ship-bottom shaped channel and the compound channel

Fukuoka (2010, 2012) has indicated that the relations between dimensionless cross-sectional profiles and dimensionless discharge in stable alluvial rivers are descried by Eq. [7], [8] (Fukuoka's equation).

$$2.80\left(\frac{Q}{\sqrt{gId_r^5}}\right)^{0.40} \le \frac{B}{d_r} \le 6.33\left(\frac{Q}{\sqrt{gId_r^5}}\right)^{0.40} \qquad [7]$$

$$\frac{h}{d_r} \le 0.14\left(\frac{Q}{\sqrt{gId_r^5}}\right)^{0.38} \qquad [8]$$

Where Q = channel-forming discharge, B = river width, h = water depth, g = gravitational acceleration, I = energy gradient and d_r = representative grain diameter. We compare relationships between dimensionless river width, dimensionless depth and dimensionless channel forming discharge in the ship-bottom shaped channel with those in the compound channels before the river improvements. Figure 11 shows temporal changes in the relationships between dimensionless width, dimensionless depth and dimensionless channel-forming discharge at 19.6km and 19.8km in the flood rising period.



(a) 19.6km (b) 19.8km

Figure 11 Relationships between dimensionless width, dimensionless depth, and dimensionless channel-forming discharge

From these figures, the dimensionless width of the compound channel (yellow solid line) becomes smaller than the lower limit line (red solid line) around the bank-full condition of the main channel and rapidly changes with increasing discharge. On the other hand, the dimensionless width of the ship-bottom shaped channel (green solid line) increases in almost parallel to average line (black solid line) with increasing dimensionless channel-forming discharge. It is expected from above results that cross-sectional profiles of ship-bottom shaped channels make velocity distribution within a cross-section improve and a stable channel against flood flows.

Figure 12 shows longitudinal distributions of cross-sectional area at the peak discharge in the Onga River. At the river sections from 19.6km to 20.2km, the cross-sectional area of the ship-bottom shaped channels are larger than those of the compound channels. Therefore, discharge capacity of the improved river channels increases from that of the previous channels.

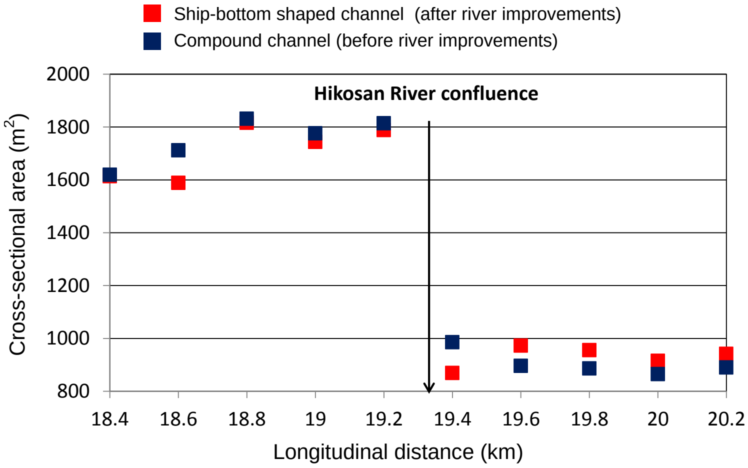
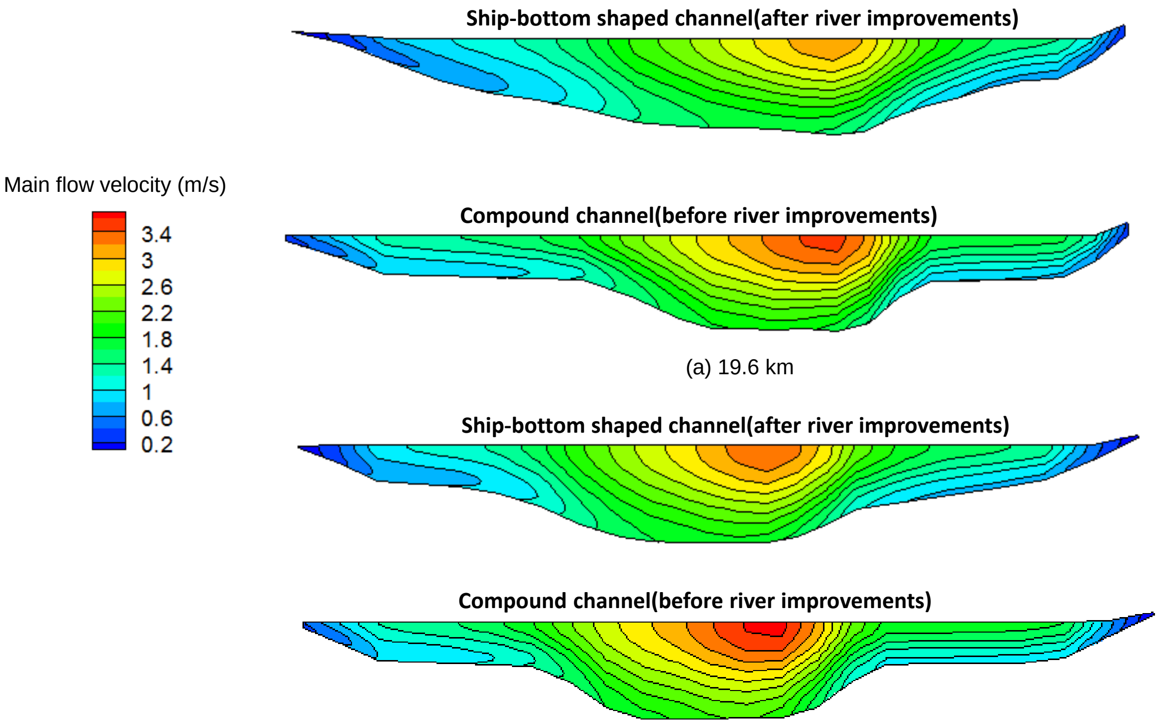


Figure 12 Longitudinal changes in cross-sectional area

Next, we investigate three-dimensional structures of flood flows and bed variations in the ship-bottom shaped channel and the compound channels. Figure 13 shows contour lines of velocity distributions in cross-sections at 19.6km and 19.8km at the peak discharge. From these figures, it is found that maximum velocity of the ship-bottom shaped channels is smaller than that of the compound channels. And, lateral velocity gradient between main channel and flood channel of the ship-bottom shaped channels is milder than that of the compound channels. In compound channels, momentum exchanges between high-velocity flow in the main channel and low-velocity flows in the flood channels occur and increase hydraulic resistances. Therefore, hydraulic resistances of ship-bottom shaped channels are found to be relatively smaller than those of the compound channels. Moreover, velocities near embankment of the ship-bottom shaped channel remain low velocities in the peak discharge.

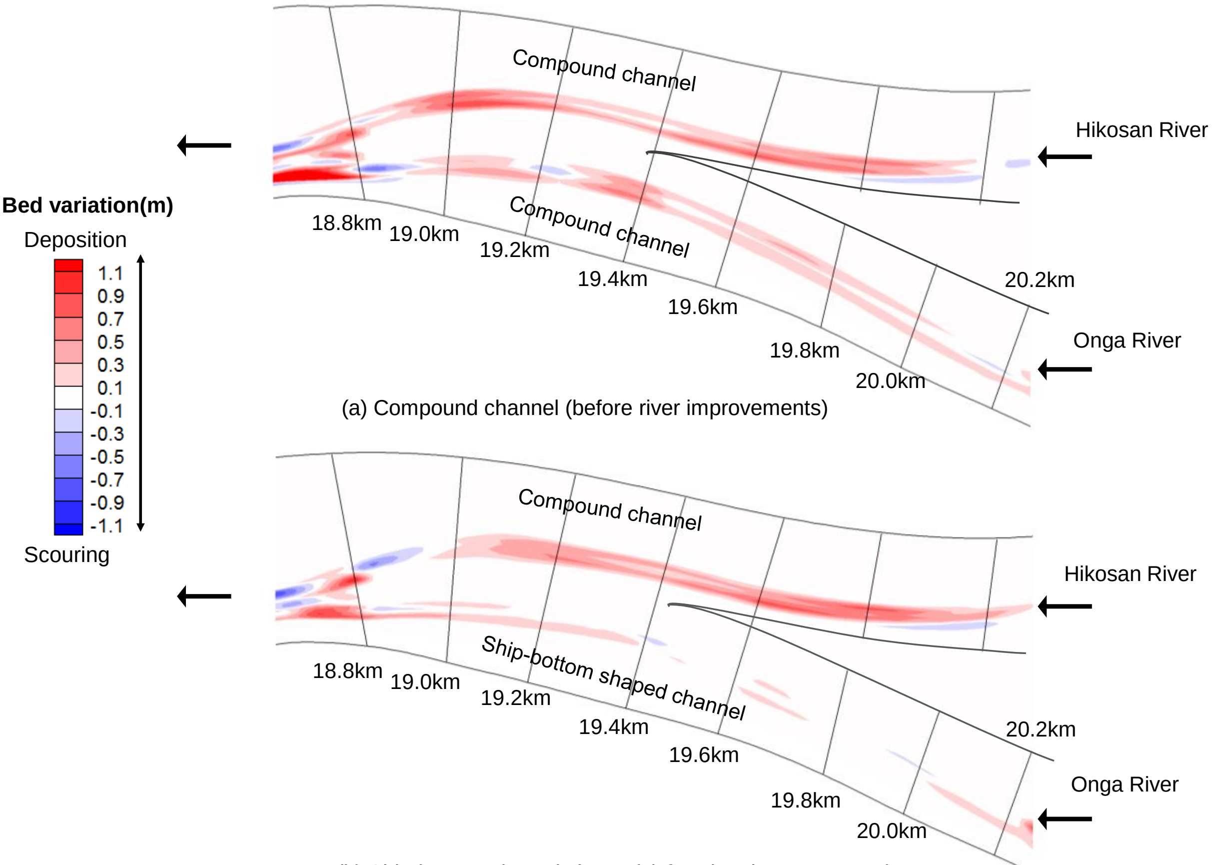


(a) 19.6 km

(b) 19.8 km

Figure 13 Main flow velocity contours in cross-sections

Figures 14(a) and (b) show contour lines of longitudinal bed variations near the confluence of the Onga River and the Hikosan River after the flood. Bed variations in the ship-bottom shaped channel shown in Figure 14(b) become less than those in compound channel shown in Figure 14(a).



(a) Compound channel (before river improvements)

(b) Ship-bottom shaped channel (after river improvements)

Figure 14 Bed variations contour lines in the main channels after the flood

Figure 15 shows longitudinal distributions of bed load. Longitudinal changes in bed load at the peak discharge and rising period in the ship-bottom shaped channels (shown by solid lines) become smaller and more uniform than those of compound channels. Therefore, it is concluded that river bed of the ship-bottom shaped channel improved in the Onga River are relatively stable against flood flows.

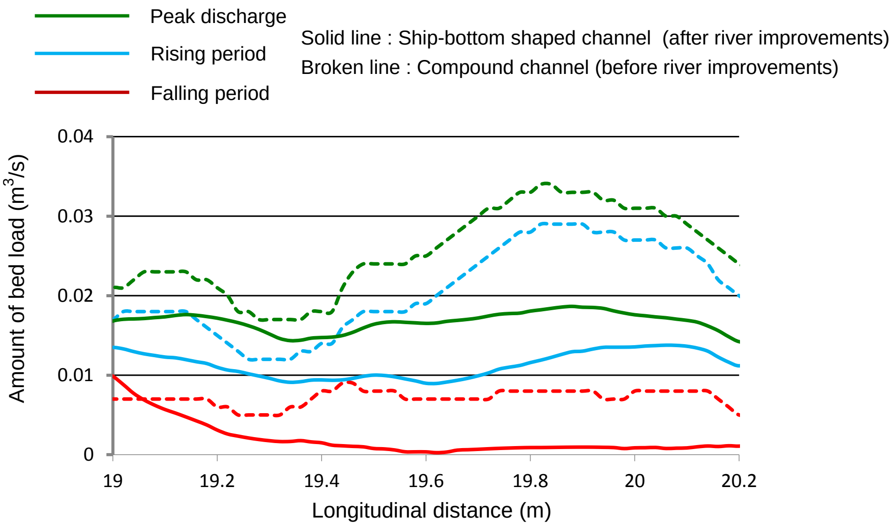


Figure 15 Longitudinal distributions of bed load

5. CONCLUSIONS

Effects of river improvements to the ship-bottom shaped channels from the compound channels are investigated by applying the BVC method using observed water surface profiles in the Onga River. Moreover, Calculation results of ship-bottom shaped channels are compared with those of the compound channels. The following conclusions were derived in this study.

(1) From the relationships between dimensionless width, dimensionless depth and dimensionless channel-forming discharge in the Onga River, the ship-bottom shaped channels have desirable cross-sectional bed profiles satisfying Fukuoka's equations which accord with cross-sectional profiles in stable natural rivers.

(2) We clarified three-dimensional structures of flood flows in the ship-bottom shaped channels and the compound channels by developed numerical model. From these results, it was found that velocity distributions of flood flows in the ship-bottom shaped channels become more uniform. Therefore, hydraulic resistances of the ship-bottom shaped channels are less than those of the compound channels.

(3) Longitudinal changes in bed load transports in the ship-bottom shaped channels become smaller than those in compound channels. Ship-bottom shaped channels improve markedly hydraulic characteristics compared to those of compound channels.

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