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Effect of River Improvement on Flow and Sedimentation in Shirakawa River, Japan

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Abstract **-** In the Shirakawa River, remarkable deformation due to sediment deposition was observed after river channel improvement works. In this research, a model experiment and a quasi-three-dimensional numerical simulation were conducted in order to evaluate the effect of river bend curvature variation caused by improvement works on channel response and flow capacity. In the model experiment, large sandbars were formed, and the channel became narrower. In the numerical simulation, flood flew over sandbars and gravel deposited on sandbars, which caused decreasing of flow capacity. The gravel deposition was most active when the flow charge was in its peak.

Keywords**:** Flood disaster, Deposition, Topographical changes, Hydraulic model experiment, Quasi-3D flood flow model

1. Introduction

In disaster restoration, it is important to establish a disaster prevention system. However, there were many cases that an area was damaged by floods frequently [1]. One of the reasons is that the disaster restoration was carried out without sufficient consideration of river channel characteristics.

The Shirakawa River (a class-A river), which flows through Kumamoto prefecture, is one of the river which floods often occurs. From July 11 to 13, 2012, heavy rain hit northern part of Kyushu due to the stagnation of the seasonal rain front [2], [3], [4]. The flow discharge was 2300m^3/s, which was much larger than the flood capacity. Highest water level was also recorded at the Yotsugi Bridge (12.3km from river mouth of the Shirakawa River). The Shirakawa River overflowed due to this heavy rain, and some areas in Kumamoto City were seriously damaged by the flood (figure 1 [3]).

Fig. 1: Flood of July 2012 at the Shirakawa river.

After this flood, an improvement work to reduce the sinuosity of the Shirakawa River was carried out. This work took 5 years, and the Shirakawa River switched to the new channel (figure 2 [2]) in July 2017.

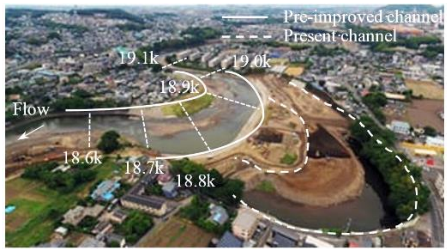

Fig. 2: New channel of the Shirakawa river.

On the other hand, the shape of the river channel gradually changes with time. There was a previous research about the environment and channel property of a river after improvement work (the Kitagawa River at Miyazaki prefecture) [5], [6], [7], [8].

In case of the Shirakawa River, about 200m long sediment accumulation was occurred on the inner side of the bend of the new channel by the flood after the improvement work (figure 3 [2]). In disaster management, it is very important to consider about the river morphology change and flood capacity.

Fig. 3: Sediment accumulation at the Shirakawa river.

In this research, a model experiment and quasi-3D numerical analysis was conducted in order to simulate the river morphology change by a flood, and the effect of the river morphology on flood capacity.

2. Hydraulic model experiment

The hydraulic model experiment was conducted in order to evaluate the effect of sediment accumulation on floods and channel morphology. The target area of the model experiment was 18.5km ~ 19.6km section from the river mouth. The scale of the hydraulic model was set to 1/100 scale according to Froude number similarity. The Froude number of the hydraulic model was set to the same value with the actual Shirakawa river. In order to eliminate the effect of surface tension, the model was moistened before the experiment.

The Manning's roughness coefficient of the channel bed was 0.034$m^{-1/3}s$. The corresponding Manning's roughness coefficient in the model was 0.016 $m^{-1/3}s$. The Manning's roughness coefficient in the model was controlled by paving sand (median particle size = 5mm) on the channel bed of the model. The model was assumed to be no erosion.

3. Flow analysis

For the quasi-3D flood flow analysis model [9], [10], [11], [12], we used a quasi-three-dimensional model based on the solution of three-dimensional incompressible Reynolds averaged Naiver-Stokes equation with the assumption of Boussinesq approximation and hydrostatic pressure. The continuous equation and the equation of motion used for calculation are shown below. For the calculation, the formula was differentiated using the finite volume method.

$$\frac{\partial U}{\partial t}+\frac{\partial F_x^I}{\partial x'}+\frac{\partial F_y^I}{\partial y'}+\frac{\partial F_\sigma^I}{\partial \sigma}+\frac{\partial F_x^V}{\partial x}+\frac{\partial F_y^V}{\partial y}+\frac{\partial F_\sigma^V}{\partial \sigma}=S \tag{1}$$

$$\begin{gathered}
U=[h,hu,hv]^T\\
F_x^I=\left[h\overline{u},hu^2+\frac{1}{2}g(h^2-d^2),huv\right]^T\\
F_x^V=\left[0,hA\left(2\frac{\partial u}{\partial x}\right),hA\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right]^T\\
F_y^I=\left[h\overline{v},hvu,hv^2+\frac{1}{2}g(h^2-d^2)\right]^T\\
F_y^V=\left[0,hA\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right),hA\left(2\frac{\partial v}{\partial x}\right)\right]^T\\
F_\sigma^I=[h\omega,h\omega u,h\omega v]^T\\
F_\sigma^V=\left[0,\frac{v_t}{h}\frac{\partial u}{\partial \sigma},\frac{v_t}{h}\frac{\partial v}{\partial \sigma}\right]^T\\
\mathrm{S}=\left[0,g\eta\frac{\partial d}{\partial x}-\frac{h}{\rho_0}\frac{\partial p_a}{\partial x'},g\eta\frac{\partial d}{\partial y}-\frac{h}{\rho_0}\frac{\partial p_a}{\partial y'}\right]^T
\end{gathered} \tag{2}$$

where I is the inviscid flux, V is the viscous flux, t is time. x,y and z are Cartesian coordinates. η is water level. d is water depth, $h=\eta+d$ is total water depth. u,v are flow velocity of x,y direction. g is gravitational acceleration. v_t is vertical (or eddy) turbulence viscosity. p_a is atmosphere pressure. ρ_0 is water density.

In order to verify the validity of the flow analysis model, the water level and flow velocity acquired by model experiment and numerical simulation were compared. Figure 4 shows the comparison of the numerical analysis value and the water surface profile in the vertical direction of the river channel measured by the point gauge in the model experiment. Both water levels are well matched, except the right side of 19.0km ~ 19.1km section, and the left side of 18.6km ~ 18.7km section.

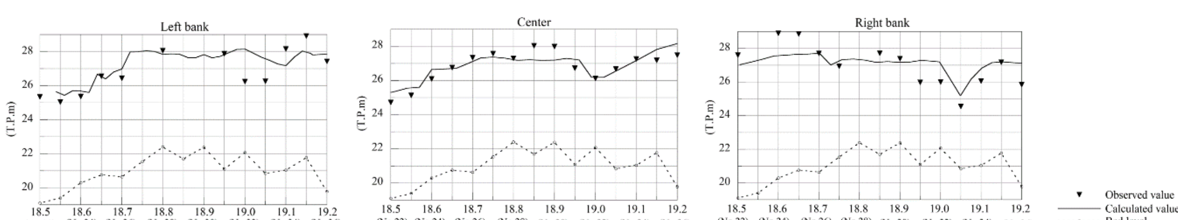

Fig. 4: Comparison of the numerical analysis value and the measured value of the water surface profile in the vertical direction of the river channel.

Figure 5 shows the surface flow velocity vector at the flood discharge of 2300m^3/s by the model experiment using Particle Image Velocimetry (PIV). Figure 6 shows the surface flow velocity distribution by numerical simulation. As a result, similar results were obtained by the model experiment and the numerical simulation. The maximum velocity reached to 7.5m/s.

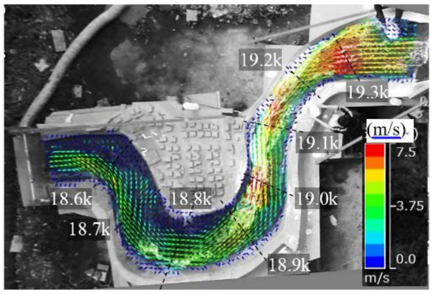

Fig. 5: Surface flow velocity vectors at the flood discharge of 2300m^3/s measured by PIV.

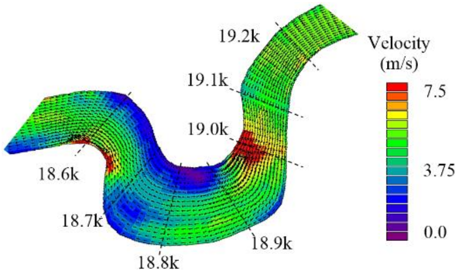

Fig. 6: Surface flow velocity distribution by numerical simulation.

4. Response Characteristics of River Channels

4.1. Verification of Analysis Model

In order to verify the validity of the riverbed variation analysis model, the riverbed variation by a flood of 2000m^3/s in the model experiment was reproduced. In the hydraulic model experiment, water (flow rate = 2.0L/s) and sand (particle diameter d_{50} = 1.7mm) were fed for 2 hours. Figure 7 shows the surface flow velocity distribution 2 hours later under the above conditions. The channel of 18.8km ~ 19.0km section became narrow due to sediment accumulation, and the flow velocity at the point of 19.0km become faster (5~6m/s). Figure 8 shows the flow velocity distribution by numerical simulation. Similar result was obtained for the hydraulic model experiment and the numerical simulation. Figure 9 shows the measured value and calculated value of the thickness of the sediment accumulation. Similar result was obtained for the hydraulic model experiment and the numerical simulation.

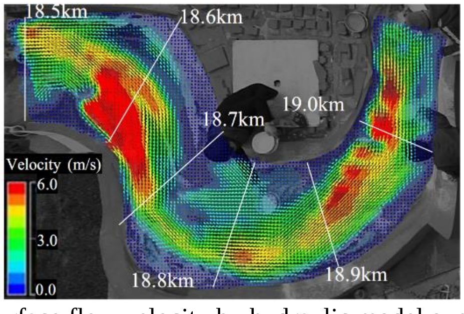

Fig. 7: Surface flow velocity by hydraulic model experiment.

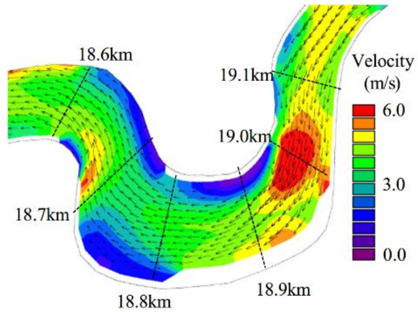

Fig. 8: Flow velocity distribution by numerical simulation.

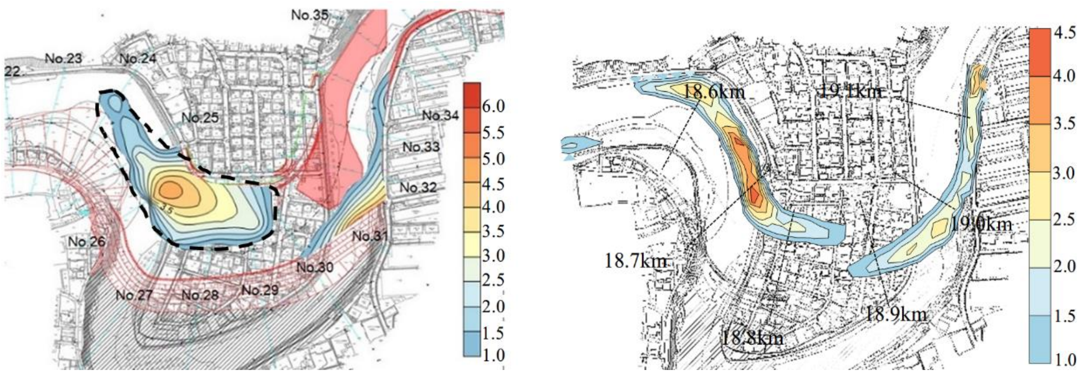

Fig. 9: Measured value (left figurer) and calculated value (right figurer) of the thickness of the sediment accumulation.

4.2. Prediction of Topographic Variation

Figure 10 shows the simulation of channel shape variation after 8 times of the flood of July 2012. The hydrograph is shown in Figure 11. After 8 times of floods, there was sediment accumulation of 3m thick at 18.7km point. Figure 12 shows the cross-sectional morphology of the channel along the dotted line shown in figure 13 (b). The rate of sediment accumulation become slower as flood repeated.

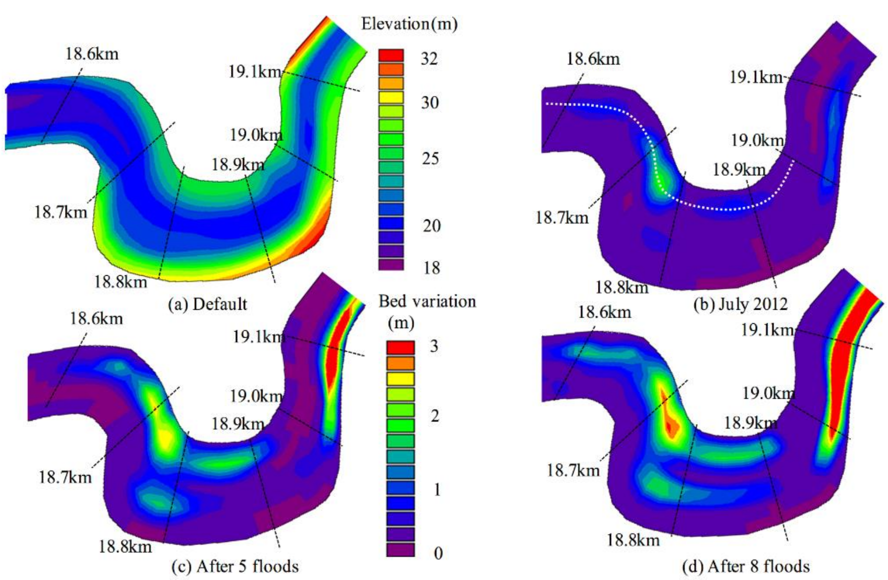

Fig. 10: Simulation of channel shape variation after 8 times of the flood of July 2012.

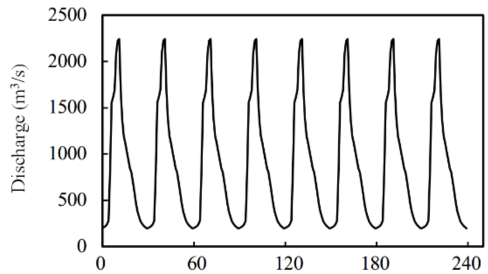

Fig. 11: Hydrograph of numerical simulation about channel shape variation.

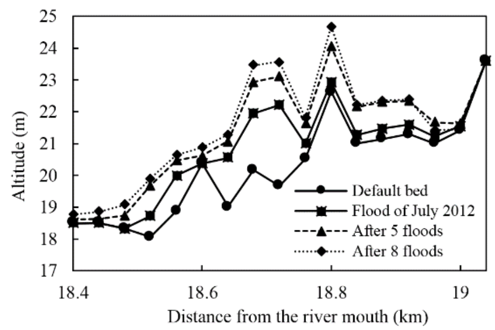

Fig. 12: Cross sectional morphology of the channel.

4.3. Effect of Sediment Accumulation on Flood Capacity

Figure 13 shows the water level along the center line of the channel. There was little variation from 13.9km point toward the lower reach. On the other hand, the water level increased for 1.5m at the upper reach of the channel after 8 times of floods. This result suggests that sediment accumulation has a negative effect on flood capacity.

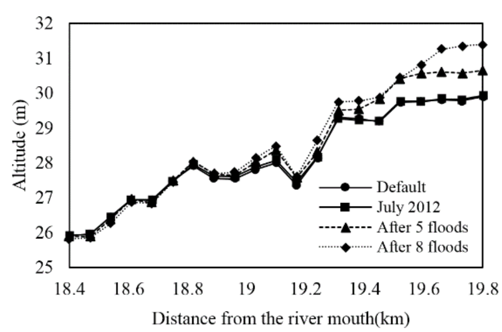

Fig. 13: Water level along the center line of the channel.

5. Conclusion

In this study, the effect of channel variation on the flood capacity was evaluated. The results obtained are as follows.

(1) Sediment accumulated on the new channel of the Shirakawa River. The thickness of the sediment accumulation was about 3.0m.

(2) The sediment accumulation caused water level elevation of 1.5m in the upstream area.

(3) According to the riverbed variation analysis by simulated floods, further accumulation will proceed in the sandbar

of the channel of the Shirakawa River, and the flood capacity is expected to be decreasing by further sediment accumulation.

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