Impact of River Improvement on Sand-Bar Behavior and Stream Regime in the Shirakawa River

Xiang CHEN¹, Ryuichi HIRAKAWA² and Terunori OHMOTO³

¹Dept. of Civil and Environmental Engineering, Maebashi Institute of Technology, Maebashi City, Japan
²Dr. Eng., Dept. of Civil and Environmental Engineering, Maebashi Institute of Technology, Maebashi City, Japan
³Dr. Eng., Graduate School of Science and Technology, Kumamoto University, Kumamoto City, Japan

*Corresponding author

Keywords: Meandering, Gravel bed river, Inflow sediments, Sediments deposit, Alluvial fan.

Abstract. Sandbars make meandering of flow and cause the local scouring and deposition on riverbeds. The sandbars formed on riverbeds are closely related to river disasters. It is very important subject on river management works to understand the bed variation caused by the sandbars. The flood by the local heavy rainfall, which is increasing in recent years, has a large variation of water level with time. In order to understand the behavior of sandbars during flood, it is necessary to take the unsteadiness of flow into consideration.

Introduction

A bend of a river channel is the place which floods or meandering are often seen. In order to prevent water hazards, it is very important to understand bends of river channels. On the other hand, previous river improvement works are only for acquiring the capacity for planned floods. However, the effect of river improvement works for floods which exceed the plan is not well discussed. In order to maintain and economically design river channel, reasonable design and plans are needed.

In order to discuss about river channel disaster and river condition, it is very important to understand formation and deformation of sandbars. In past researches about behavior of sandbars, most of them were conducted to study about river control. In most of them, water flow was treated as steady flow, because the time to form sandbar is much longer than the time that flow discharge varies. However, recently the frequency of flood disasters caused by local heavy rain has increased. In floods caused by local heavy rain, water level will be changed rapidly, and it is necessary to consider unsteady flows to study the behavior of sandbars. For example, Tubino et al.[¹] conducted non-linear analysis and tried to clarify the mechanism of sandbar formation at unsteady flow. Uchijima et al.[²] showed the mechanism of sandbar formation and sandbar deformation by the water flow on sandbars experimentally. Miwa et al.[³] flushed large discharge and low discharge of flow alternatively, and found that the behavior of deformation of sandbars is strongly affected by formation of water path. Watanabe et al.[⁴] discussed about the formation of sandbar when flow discharge is continuously changing. They found that the behavior of sandbar formation by steady flow is completely different from that by unsteady flow. It is important to consider about the speed of sandbar formation and the speed of water level variation. When water level changes drastically, the shape of sandbar will not be only determined by hydraulic variables, but also be determined by history of flow.

On the other hands, in actual river it is not clear about the relationship between the riverbed change on meandering area and planer shape of river. In Tatsudajinnai area, which was heavily damaged by the flood of July, 2012, the river channel is meandering, and flood water flowed across the floodplain and flowed to downstream of Shirakawa River[⁵]. The improvement works which create new channel
that can shortcut the meandering area of Shirakawa River is in progress (figure 1). Figure 2 shows the plane view of river channel of Shirakawa River. In Shirakawa River, huge amount of sediment was supplied from Aso caldera. When heavy flow occurred, huge amount of sediment flows downstream with flood flow. Moreover, in earthquake of April, 2016 in Kumamoto, huge amount of sediment are thought to flow to river channel due to landslip and liquefaction. The increase of sediment in river channel and downstream will cause overflow when local heavy rain strikes.

The purpose of this research is to clarify the behavior of excess flow in improved river channel. The target area is a part of the river channel of Shirakawa River, which is a bend located between 18.5km to 19.4km away from river mouth and have been improved. The model experiment was conducted first; water was flush at the peak discharge of flood (probability of once in 150 years) and the process of sandbar formation was reproduced. In the next, the size of sediment particle was changed, and the relationship between both flow discharge and particle size, and sedimentation was studied in order to reveal the behavior of river channel and capacity of improved river channel under heavy flow.

Method

Experiment

In this experiment, a 1/100 scale of distortion free model was used. The target area is a part of the river channel of Shirakawa River, which is between 18.5km to 19.4km away from river mouth,
including the whole floodplain of Tatsudajinnai 4-chome, north district, Kumamoto city. There is
high levee along the left bank, and the overflow only occurs on the right bank. The ground level was
decided according to the data of aerial laser survey. The ground level of river channel is according to
the previous research[6]. Considering the law of similarity, the Froude number of model was matched
with that of full size river channel. When the model scale is small, the results will be affected by scale
effect due to viscosity and surface tension of water. In this research, the model was moistened in order
to reduce the effect of surface tension. The scale ration of each parameter is shown in table 1. The
roughness length of river channel is $0.034 m^{-1/3}$, and in 1/100 scale model, the corresponding value is
$0.016 m^{-1/3}$. In order to control the roughness length of the model, the river channel in model was
paved with silica sand which the median particle size $d_{50}$ is 5mm. The roughness length of the model
was verified experimentally by measuring normal depth of channel which has given roughness.

Table 1. Scale ratio of parameters.

| Fundamental quantity      | Dimension | Reduction | Scale (1/100) |
|---------------------------|-----------|-----------|---------------|
| Length, depth             | $L$       | $S$       | 1/100         |
| Discharge                 | $L^3 \cdot T^{-1}$ | $S^{5/2}$ | 1/100000      |
| Velocity                  | $L \cdot T^{-1}$ | $S^{3/2}$ | 1/10          |
| Time                      | $T$       | $S^{1/2}$ | 1/10          |
| Resistance coefficient    | $L^{-1/3} \cdot T$ | $S^{1/6}$ | 1/1.25        |

Table 2. Experimental case.

| Case | Discharge [$l/s$] | Time [min] | Average grain size [cm] |
|------|-------------------|------------|-------------------------|
| S-1  | 200               | 120        | 0.2                     |
| S-2  | 230               | 120        | 0.2                     |
| S-3  | 300               | 120        | 0.2                     |

Figure 3. Velocity vector ($Q = 200[l/s]$).

Figure 4. Gravel deposition in stable state.

In this experiment, bed erosion was not considered, because in river improvement works the river
bed was paved with huge stones in order to prevent bed erosion. Silica sand of 2mm particle size was
used. The values of flow discharge were set according to following conditions; in the flood control
plan of Shirakawa River, probability of a heavy flood was assumed to be once in 150 years. The flow discharge is $3400\text{m}^3/\text{s}$ at Yotsugi bridge, and reduced by Tatsuno dam from $3400\text{m}^3/\text{s}$ to $3000\text{m}^3/\text{s}$. However, according to the Shirakawa River improvement plan, the maximum capacity of Shirakawa River is about $2000\text{m}^3/\text{s}$. The maximum flow discharge of the flood in July 12, 2012 was $2300\text{m}^3/\text{s}$. In this research, we set the value of flow discharge to $2300\text{m}^3/\text{s}$ and $3000\text{m}^3/\text{s}$. The experiment conditions are shown in table 2.

In flow velocity measurement, surface flow velocity was measured in PIV (Particle Image Velocimetry) method, and bed flow velocity was measured in Electromagnetic flow meter. In PIV method, images from the CCD camera were saved in the PC in the format of 30fps, 720×480 pixel, and monochromatic image. Here, the minimum size of 1 pixel is 2.08mm. The sampling rate is 30Hz, the number of images is 200 for each area, and the measurement time is 10 sec. In this experiment, nylon particles (particle size = 100m, specific gravity = 1.02) were used as tracer.

Results

Figure 3 shows the flow velocity vector of S-1 condition according to the result of PIV method. Fast flow was observed in the right bank which is the river bank of the area between No.33 and No.29, the left bank near No.28, and the left bank of the area between No.26 and No.24. On the other hand, slow flow was observed along the right bank of upper reach of No.30. Figure 4 shows the sedimentation condition after sediment stabilized. Figure 5 shows the distribution of sediment thickness after water flowed. Sediment was observed along right bank between No.30 and No.24. Thickest sediment was observed in right bank in No.28~No.27. Sediment was also observed along left bank between No.33 and No.31. This result is suggested to due to the width of the river channel become larger by river channel improvement works.

Simulation Model

Calculation of Flow

In flow calculation, the flow was assumed to be two-dimensional planar flow, and continuity equation and shallow-water equation were applied. The following equations were applied for the calculation.

$$\frac{\partial h}{\partial t} + \frac{\partial h\bar{u}}{\partial x} + \frac{\partial h\bar{v}}{\partial y} = 0$$  \hspace{1cm} (1)

$$\frac{\partial h\bar{u}}{\partial t} + \frac{\partial h\bar{u}^2}{\partial x} + \frac{\partial h\bar{u}\bar{v}}{\partial y} = -gh \frac{\partial \eta}{\partial x} - \frac{gh^2 \partial \rho}{2\partial x} + \tau_{bx} - \frac{\partial}{\partial x}(hT_{xx}) + \frac{\partial}{\partial y}(hT_{yy})$$  \hspace{1cm} (2)

$$\frac{\partial h\bar{v}}{\partial t} + \frac{\partial h\bar{u}\bar{v}}{\partial x} + \frac{\partial h\bar{v}^2}{\partial y} = -gh \frac{\partial \eta}{\partial y} - \frac{gh^2 \partial \rho}{2\partial y} + \tau_{by} - \frac{\partial}{\partial x}(hT_{xy}) + \frac{\partial}{\partial y}(hT_{yy})$$  \hspace{1cm} (3)

$$h\bar{u} = \int_{-d}^{h} udz$$  \hspace{1cm} (4)

$$h\bar{v} = \int_{-d}^{h} vdz$$  \hspace{1cm} (5)

where $h = \eta + d$, $h$ is depth, $\eta$ is water level, $d$ is static depth, $\bar{u}, \bar{v}$ are depth-averaged velocities, $\rho$ is density, $T_{ij}$ is viscous friction, and $A$ is vortex viscous coefficient.

$$T_{xx} = 2A \frac{\partial \bar{u}}{\partial x}$$  \hspace{1cm} (6)

$$T_{xy} = A \left( \frac{\partial \bar{u}}{\partial y} + \frac{\partial \bar{v}}{\partial x} \right)$$  \hspace{1cm} (7)

$$T_{yy} = 2A \frac{\partial \bar{v}}{\partial y}$$  \hspace{1cm} (8)
Where $T_{xx}$, $T_{xy}$, $T_{yy}$ are bottom face shearing forces in the $x$- and $y$-directions, and given by following equations;

$$\frac{\bar{t}_b}{\rho} = C_f \bar{u}_b |\bar{u}_b|$$  \hspace{1cm} (9)

$C_f$ is drag coefficient, and $u$ is flow velocity of riverbed.

$$C_f = \frac{g}{(Mh^{1/6})^2}$$  \hspace{1cm} (10)

$M$ is Manning’s roughness coefficients, and $h$ is depth.

**Calculation of River Bed Fluctuation**

In calculation of river bed deformation, the amount of sediment transport was calculated from Peter and Müller formula according to the result of flow simulation. The continuity equation of river bed deformation in flat two-dimensional rectangular coordinates is

$$-(1 - n) \frac{\partial z}{\partial t} = \frac{\partial S_x}{\partial x} + \frac{\partial S_y}{\partial y} - \Delta S$$  \hspace{1cm} (11)

Where $z$ is bed height, $n$ is bed porosity, $t$ is time, and $S_x$, $S_y$ are unit width sediment transport. Sedimentation rate $\Delta S$ is given by following formula;

$$\Delta S = \Phi_0(\eta_0)w_s(c - c_e)$$  \hspace{1cm} (12)

Where $f$ is sediment concentration, $\eta_0$ is initial bed height, $w_s$ is sediment rate of suspended sediment, $c$ is depth-averaged sediment concentration, $c_e$ is depth averaged equilibrium sediment concentration. Unit width sediment transport $S_{bl}$ is given by following formula;

$$\sum h = S_{bl} = 8(\theta' - \theta_c)^{1.5} \sqrt{s - 1} gd^2_{50}$$  \hspace{1cm} (13)

Where $\theta'$ is valid dimensionless tractive force, $\theta_c$ is critical tractive force.

**Calculation Condition**

In this research, target cases are shown in Table 2. The studied area was divided into 20m×10m meshes. At the edge of upstream, the flow discharge was set according to Figure 5, and at the edge of downstream, the water level was set according to the result of unsteady calculation as boundary conditions. Sediment was fed from upper reach 1 hour after the calculation started. Bed change was assumed to be 0. The time duration is 0.2sec. The total calculation period is 17 hours. The waveform.
of flood of probability of once in 150 years and once in 20-30 years were calculated according to the actual waveform of flood in July 12, 2012.

**Results**

**Model Verification**

Figure 6 shows the profile of flow according to numerical calculation and model experiment. The water level led by flow attacking point (No. 34, 19.1km) and channel bends (No. 32 ~ 25, 19.0km ~ 18.7km) is quite close.

![Figure 6. Profile of flow by numerical calculation and model experiment.](image)

In order to verify the bed deformation model is proper, a model experiment that attempt to reproduce the bed deformation by flood in July 2012. Figure 7 shows the result of bed deformation when flow discharge is $2300\text{m}^3/\text{s}$ acquired by model experiment, and Figure 8 is the result acquired by simulation. Dotted line in figure shows the area of sandbars. The formation of gravel pile along the right bank in No. 24, and gravel deposition around levee normal line around No. 27 were reproduced in this simulation. However, the maximum thickness of sediment on sandbar calculated (3.5m) is smaller than actual thickness (4.0m).

![Figure 7. Gravel deposition thickness distribution.](image)  
![Figure 8. Situation of bed deformation by simulation.](image)
Prediction of Sandbar Deformation

Figure 9 shows the condition of the bed morphology variation by simulated flood. Gravel is deposited and gravel pile which have crest was formed on the flat river channel due to the channel meandering. As flow discharge increased, the size of gravel deposition become larger, and when flow discharge started decreasing, the edge of sandbar moved toward downstream, and stopped at No. 24.

Figure 10 shows the variation of sandbar length, and Figure 11 shows the variation of sandbar height of dotted line in Fig. 7. The thickness of sandbar increased drastically by flood in July 2012, and become maximum when the flow discharge started to decrease. On the other hands, the length of sandbar is become larger when the flow discharge increased, and it was still increasing after the peak flow. Although the height of sediment is not clear because it will be affected by the size of gravel and channel roughness variation, according this simulation, sedimentation in the new improved river channel in Tatsudajinnai area was observed, and the size of sediment will become larger as flood water flow.

Conclusion

In this research, the effect of river channel improvement on channel morphology and behavior of water flow was discussed. The conclusion is as follows:

Gravel pile was formed in the inside of improved channel, and it grew when flood water flowed. The maximum thickness is estimated to be 4m in the flow discharge of flood in July 2012.

According to the analysis of bed variation by simulated flood, sedimentation on Tatsudajinnai area will proceed, and it will cause the decline of channel capacity for flood and increase of water level on upstream.
References

[1] Tubino, M., (1991). Growth of alternate bars in unsteady flow. Water Resources Research, Vol.27, No.1, pp. 37-52.

[2] Hayakawa, H. (1987). Characteristics Deformation of Alternate Bars due to Low Flow, Annual journal of hydraulic engineering, pp.683.

[3] Miwa, H., (2003). Development and transformation of alternate bars under unsteady flow conditions, Annual journal of hydraulic engineering, pp. 619-624.

[4] Watanabe, Y., Sato, K., and Oyama, F. (2002) Experimental study on Formation under unsteady flow conditions, Annual journal of hydraulic engineering, pp. 726-730.

[5] Haruhiko Y., Toshiaki Y., Minori Y., and Hokuto K. (2014). Characteristics of Heavy Rainfall and Flood Disaster in Kumamoto Prefecture on July 12, 2012, Journal of Natural Disaster Science, pp.83-100.

[6] Ohmoto, T., Hirawa, R., Nishi, S., Nakagawa, H., Chen X. (2016). Hydraulic model experimental study of disaster in the Shirakawa river on July, 2012, Annual Journal of Hydraulic Engineering, pp. 1381-1386.