Simulation of the process of inflow, deposition and discharge of sediment in the bypass facility of Koshibu Dam

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Abstract

Sediment bypass is an excellent reservoir sedimentation countermeasure which can achieve both reduction of sediment flowing into the reservoir and supply of sediment to the downstream of the dam. Sediment bypass facility has been completed at the Koshibu Dam in the Tenryu River, and test operation was conducted in 2016. In order to optimize the bypass operation, further study is needed in sediment transport at the diversion facility. Then, full three-dimensional calculation depending on the operation of sediment bypass facility was performed using the improved model that can calculate the bed deformation and complex flow around the diversion facilities. Based on this calculation, time depending changes in bypassing volume of sediment, and the sediment bypassing ratio based on the river bed level were investigated. Finally, the process of inflow, deposition and discharge of sediment in the bypass facility was described, and the effective conditions that can increase the bypassing ratio were proposed.

Keywords: reservoir sedimentation, sediment bypassing, three-dimensional sediment transport model

1 Introduction

Sediment bypass method is one of the sedimentation countermeasures aimed at balancing the sustainability of the reservoir and the continuity of the sediment system, and as one of the useful and versatile sand technologies conforming to the river situation in Japan, and implementation cases are increasing. Sediment bypassing operation is carried out at Asahi Dam in Shingu River and Miwa Dam in Tenryu River etc., and under construction of sediment bypass facilities is advanced in Koshibu dam and Matsukawa Dam in the same Tenryu River. As a direct regulator improvement project, the sediment bypass tunnel installation project was started in 2000 at the Koshibu Dam in the Tenryu River. The sediment bypass tunnel body was completed in September 2013 and the experimental operation of the bypass tunnel was carried out in 2016 (see Figure 1).

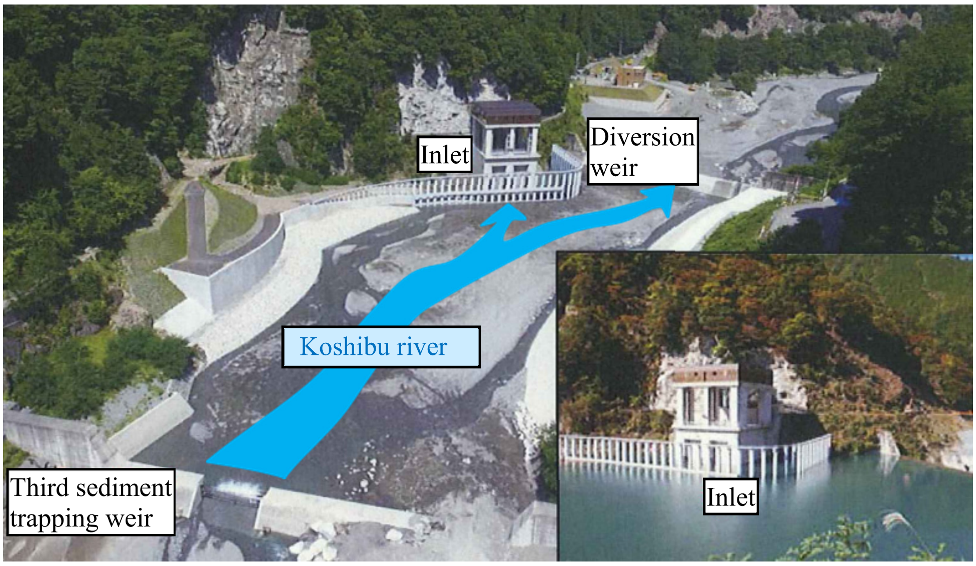


Figure 1: Sediment bypass facility of Koshibu Dam (source: Tenryu River Dam Integrated Management Office)

Sediment and bypass facilities are excellent sedimentation countermeasures that can prevent sediment inflow into reservoirs and ensure continuity of sediment transport at the dam site. But because of the high construction cost, clarification of the sediment transport phenomena during the sediment bypass operation is needed for reducing the total operation cost. Specifically, to analyze the flow rate, water level, sedimentation level, etc., it is necessary to grasp the conditions, such as the monitoring of continuous water and sediment during operation, and also an artificial adjustment such as gate discharge of the bypass tunnel and water level. It is considered that by studying and predicting the diverting water and sediment discharge efficiency when the conditions are changed, it is possible to increase the sediment discharge more efficiently during the flood.

The mechanism of sediment transport in the sediment bypass facility is gradually being clarified by the previous studies, with a few actual observations and monitoring examples of sediment bypass in actual dams. Kashiwai *et al.* (1995) show more sediment can be captured and guided to the bypass tunnel depending on the diversion method in the case of large particle size from the hydraulic model test results. Harada *et al.* (1998) have been studying the pressure fluctuations due to sediment deposition in the bypass tunnel from hydraulic model tests.

However, a detailed study on the three-dimensional topography change around the bypass facility at the time of flood and the guidance and discharge process of sediment to the bypass tunnel has not yet been sufficiently accumulated. That study is necessary for operation and maintenance of long-term sediment bypassing.

Therefore, in this study, the sediment transport analysis at the time of bypass operation was performed on the sediment bypass facility of Koshibu Dam using the three dimensional sediment transport model. We will investigate the distribution of flow around the inlet of the earth and sand bypass tunnel and the phenomenon of topography change and examine how bed level and the amount of sediment discharged from the tunnel and water/sediment sharing ratio will change. In addition, based on the analysis results, measures were shown to efficiently discharge sediment during the sediment bypass operation of Koshibu Dam.

2 Numerical modeling of bypass facility flow and sediment transport analysis

2.1 Flow model

In this study, an analytical model incorporating the sediment transport process was used based on the three-dimensional non-hydrostatic pressure analysis model with the Reynolds average Navier-Stokes equation as the basic equation developed by Yoneyama *et al.* (2009). According to the verification calculation by Kubota *et al.* (2015), it has been confirmed that this analysis model can reproduce the splitting characteristics of water and sediment to bypass, when sediment transport and diversion flow rate are changed around the diversion weir. Continuous equation [1] and equation of motion [2], which are fundamental equations of flow, are shown below. The basic formula is described by Einstein's summary convention in tensor notation.

$$\frac{\partial u_i}{\partial x_i} = 0 \qquad [1]$$

$$\frac{\partial u_i}{\partial t} + u\frac{\partial u_i}{\partial x_j} = f_i - \frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu\frac{\partial^2 u_i}{\partial x_j \partial x_j} + \frac{1}{\rho}\frac{\tau_{ij}}{\partial x_j} \qquad [2]$$

Where $u_i\left(i = 1,2,3\right)$ is average flow velocity, x_i is Cartesian coordinate, ρ is water density, ν is kinematic viscosity coefficient, p is pressure, f_i is volume force, τ_{ij} is Reynolds stress. Reynolds stress is expressed as a linear equation of the standard $k-\varepsilon$ model.

2.2 Sediment transport model

In consideration of application to reservoirs and rivers, this model introduces a mixed gravel model to express the sediment classification process and river bed coarsening and refinement phenomena, and calculates sediment volume for each grain size. For sediment transport modes, bed load and suspended load are considered. As for suspended load, a non-equilibrium model which solves three dimensional advection diffusion equation concerning sedimentation erosion/deposition process and suspended sediment concentration are used with reference to study on turbid behavior by Yoneyama *et al.* (2001). Changes in riverbed height are calculated by the continuous equation of sediment flow shown in Eq. [3] using the sediment volume obtained for each grain size and transport mode.

$$\frac{\partial z_b}{\partial t} = \frac{-1}{(1-\lambda)} \sum_k \left\{ \frac{\partial q_{bxk}}{\partial x} + \frac{\partial q_{byk}}{\partial y} + (E_{sk} - D_{sk}) \right\} \quad [3]$$

Where z_b is riverbed height, q_{bxk}, q_{byk} are bed load of grain sizes d_k per unit area near bed of x and y-directions, E_{sk}, D_{sk} are erosion and deposition fluxes of the suspended load with grain size d_k per unit area near bed.

2.2.1 Bed load model

Bed load q_{bxk}, q_{byk} are calculated by the following formula developed by Ashida and Michiue (1972).

$$\frac{q_{bk}}{\sqrt{sgd_k^3}} = 17 p_{bk} \tau_{*ek}{}^{3/2} \left(1 - \frac{\tau_{*ck}}{\tau_{*k}}\right)\left(1 - \sqrt{\frac{\tau_{*ck}}{\tau_{*k}}}\right) \quad [4]$$

Where s is specific gravity of soil, g is gravitational acceleration, $\tau_{*k}, \tau_{*ck}, \tau_{*ek}$ are non-dimensional shear stress, critical shear stress, and effective shear stress of kth grain.

2.2.2 Suspended load model

Suspended load is calculated from balance of erosion flux E_{sk} and deposition flux D_{sk}. E_{sk} is calculated by the following formula.

$$E_{sk} = W_{sk} C_{ek} \quad [5]$$

Where W_{sk} is settling velocity of kth grain, C_{ek} is concentration of kth grain at an equilibrium datum plane. C_{ek} is calculated by the following formula developed by Ashida and Michiue (1970).

$$C_{ek} = 0.025 P_{bk} \left[\frac{g(\xi_0)}{\xi_0} - G(\xi_0) \right] \quad [6]$$

$$g(\xi_0) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{1}{2}\xi_0^2\right) \quad [7]$$

$$G(\xi_0) = \frac{1}{\sqrt{2\pi}} \int_{\xi_0}^{\infty} \exp\left(-\frac{1}{2}\xi^2\right) d\xi \quad [8]$$

$$\xi_0 = \frac{W_{sk}}{0.75 u_*} \quad [9]$$

Where P_{bk} is percentage of k th grain in bed material, u_* is shear velocity.

D_{sk} is calculated by the following formula.

$$D_{sk} = W_{sk} C_{ak} \quad [10]$$

Where C_{ak} is concentration of k th grain at 5% of depth above riverbed. Sediment concentration of k th grain C_k is calculated from the three-dimensional advection diffusion equation.

2.2.3 Grain size distribution model

As for material changes in the river bed, The multi-layer model of Ashida, Egashira, and Liu *et al.* (1991), which takes into account the vertical change of the particle size distribution of the exchange, transition, and sediment layers was used (shown in Figure 2). The content of bed material at each grain in the riverbed surface (transition layer) is assumed to be changed by riverbed fluctuations and can be evaluated by the following equation.

$$\frac{\partial P_{bk}}{\partial t} - \frac{1}{E_m}\frac{\partial z_{bk}}{\partial t} + \frac{1}{E_m}\frac{\partial z_b}{\partial t}(\eta P_{bk} + (1-\eta)P_{bko}) = 0 \quad [11]$$

Where z_{bk} is bed height of k th grain eroded or deposited after time interval Δt, $\sum z_{bk} = z_b$, are percentage of k th grain in transition layer or top layer of deposit strata when the bed surface is eroded ($\partial z_{bk} / \partial t \leq 0$), η is identification factor as follows.

$$\eta = \begin{cases} 1 & \partial z_b / \partial t > 0 \\ 0 & \partial z_b / \partial t < 0 \end{cases} \quad [12]$$

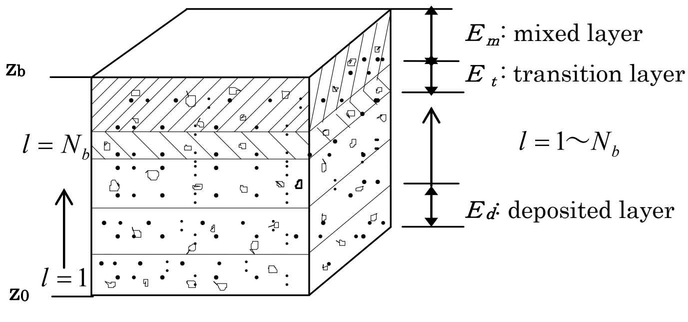


Figure 2: Multi-layered grain distribution model

Also, it is possible to collapse and redeposition process of sediment from the sediment shoulder when the slope of the riverbed is greater than the angle of repose in the water. In this study, the angle of repose in the water is set at 30-degree. The above shows the model configuration in Table 1.

Table 1: Model configuration

Flow model	3-dimensional non-hydrostatic analysis model
Free water surface	VOF (Volume of Fluid) method
Turbulence model	Standard $k-\varepsilon$ model
Sediment transport forms	Consider the bed load and suspended load (For suspended load : using a non-equilibrium model to solve the advection-diffusion / erosion / deposion)
Gravel model	mixed gravel model of multiple grain size
Bedload formula	Ashida-Michiue formula(1972)
Suspended load formula	Ashida-Michiue formula(1970)
Bed height change model	Equation of continuity of sediment
Bed material change model	Multi-layer model by Ashida, Egashira, and Liu et al. (1991)
Bank erosion model	Consider the collapse and redeposition process of sediment when bed slope is equal to or greater than the angle of repose

2.3 Analysis condition

Three dimensional sediment transport analysis around the sediment bypass facility of Koshibu Dam was carried out using the above model. The structure of sediment bypass is a form that sets up a splitting facility of water and sediment upstream of the dam reservoir and bypasses the reservoir by flowing water containing sediment to the bypass channel which becomes a tunnel structure at the time of flooding. Figure 3 shows a schematic diagram of the sediment bypass facility of the Koshibu Dam. As shown in Figure 3, among the inflow Q1 from the upstream of the third sediment trapping weir, the split flow Q2 is guided to the bypass tunnel and the overflow Q3 from the diversion weir downstream of the bypass inflow is guided to the Koshibu Dam.

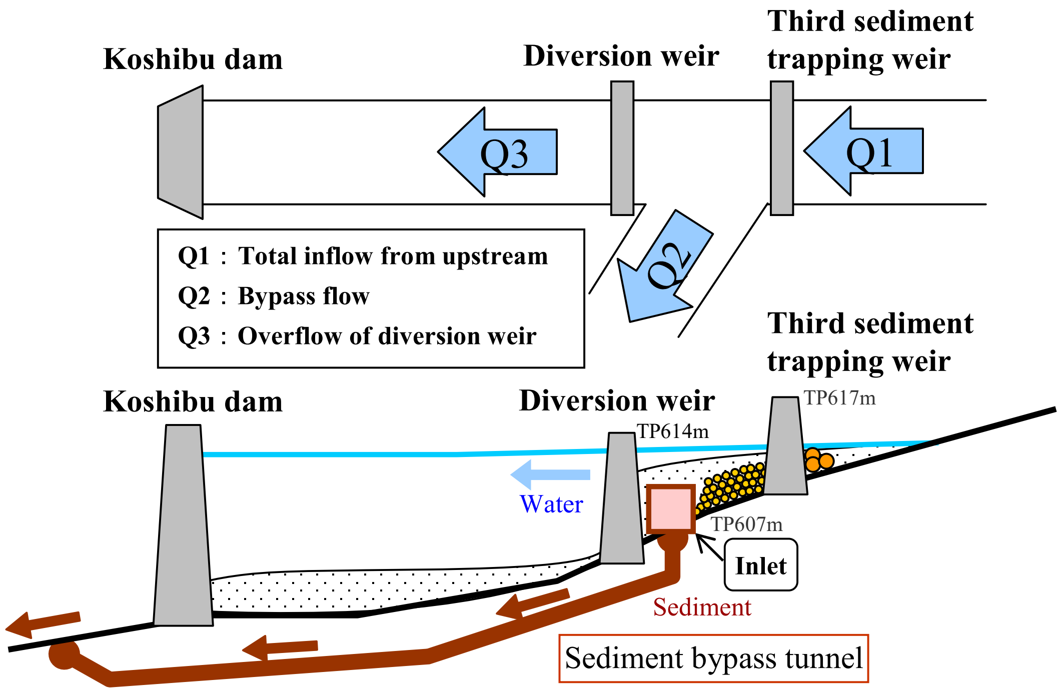


Figure 3: Schematic diagram of sediment bypass facilities

The purpose of this research is to clarify the change of the sediment level and sediment bypass's split ratio for the transition process while the diversion weir is full from the empty state. The calculation area is a region of 400 m × 450 m including the sediment bypass flow inlet and sediment trapping area from the downstream of the diversion weir to upstream of the third sediment trapping weir. The river bed height was set based on the survey result in 2010. The height at the top of the weir of the split weir is TP 614 m (this part is important for sediment and water splitting). The initial sedimentation level of the third sediment weir from the shedding weir was set to TP 607 m which is the same as the bed height of the bypass inflow port (assuming just after the excavation). The mesh size was finely set to calculate the flow and topography change around the bypass tunnel inlet, diversion weir and third sediment trapping weir at high resolution (see Figure 4). Regarding riverbed materials, the particle size distribution close to diversion weir was set from the 2004 survey results (see Table 2 and Figure 5). For the calculated input discharge, the discharge at the time of large-scale flooding was used, and for the discharge of 300 m^3/s or more, 300 m^3/s was constantly applied for 30 hours continuously. This is a setting to make it easier to extract essential sedimentation / erosion phenomena around the bypass facility (see Figure 6). For the inflow amount exceeding the flood control start discharge (200 m^3/s), the ratio of the bypass discharge does not change. The conditions of inflowing sediment were given using the discharge curve and sediment inflow rating curve prepared from the riverbed material survey results in 2004 (see Table 3). The above is summarized in Table 4.

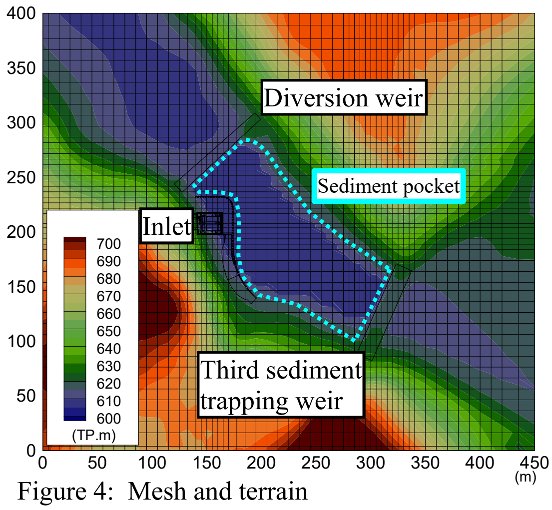


Figure 4: Mesh and terrain

Table 2: Grain size distribution of bed material

Grain size (mm)	Average grain size (mm)	Bed material Grain size distribution(%) Percent finer	Content rate
37		63.3	
	8.60		82.5
2		17.5	
	0.39		17.2
0.075		0.3	
	0.034		0.3
0.015		0.0	

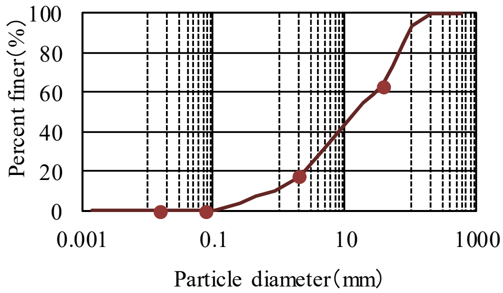


Figure 5: Grain size distribution of bed material

Table 3: Rating curve of sediment inflow

Average grain size(mm)	L-Q Rating curve $Q_s = \alpha Q^{\beta}$ Coefficient α	Multiplier β
8.60	9.339E-09	3
0.39	9.009E-07	2.2
0.034	5.110E-06	2.22

Q_s :Sediment inflow(m³/s), Q :Discharge(m³/s)

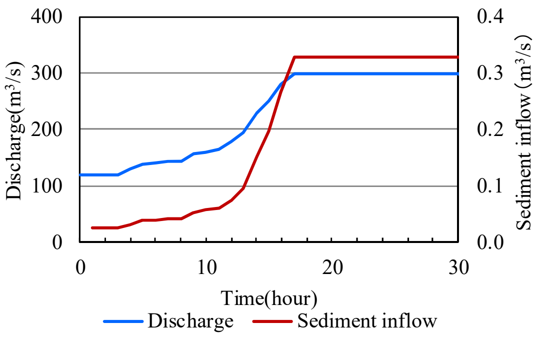


Figure 6: Time series of discharge and sediment inflow

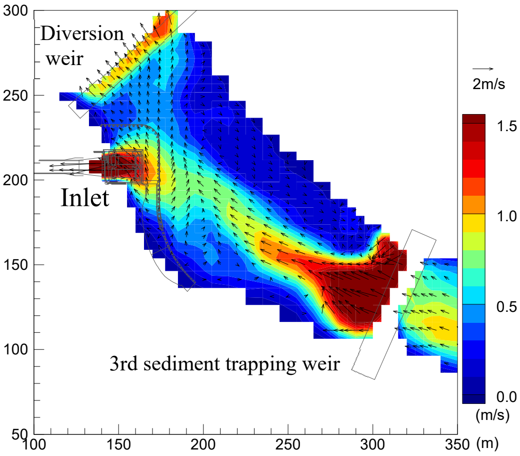
Table 4: List of calculation conditions

Item	Condition
Calculation period	31hours
Calculation interval	Upstream and downstream of the diversion weir : 400m×450m
Total mesh number	124,384
Mesh size	Δx : 5m (Around weir) 3m (Around inlet) 10m(others) Δy : 5m(Around weir) 10m(others) Δz : 0.5m
Discharge	Large flood (300m³/s when the discharge is 300m³/s or more)
Grain size Sediment inflow L-Q rating curve	Results of 2004 survey
Angle of repose	30°

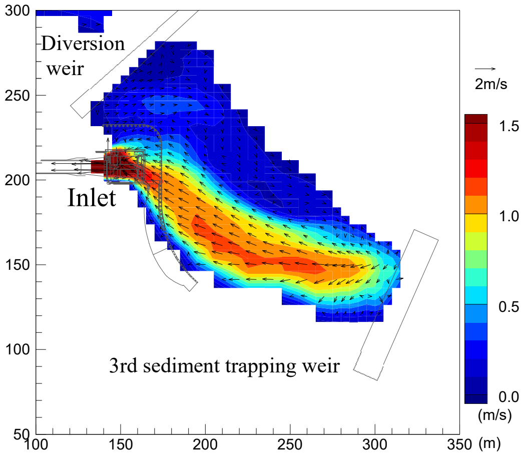
3 Analysis result

3.1 Flow

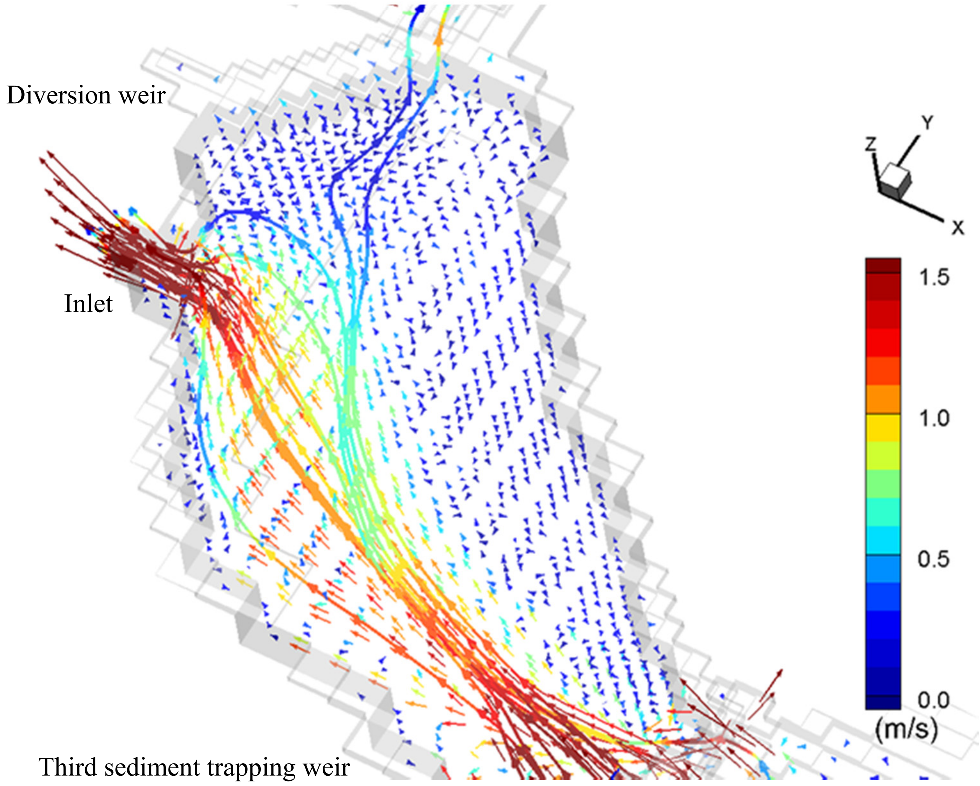
Figure 7 shows the flow velocity distribution in the surface layer, bottom layer and three dimensional bird's eye view at the flow rate of 300 m³/s. At the surface layer a very strong flow is generated around the bypass inlet and downstream of the third sediment trapping weir. The flow coming from the third sediment trapping weir is divided into a bypass flow inlet and a diversion weir. In the bottom layer, a flow from the downstream of the third sediment weir to the bypass flow inlet is formed. From the three dimensional bird's-eye view it can be confirmed that a helical flow is generated from the third sediment weir toward the inlet in the vicinity of the bypass inlet. Nagata *et al.* (2001) have revealed that local scouring caused by flow and flow caused by pressure non-equilibrium around such a hydraulic structure can be reproduced by three-dimensional solution method. In the area where multiple flows are generated by multiple hydraulic structures such as weirs and bypass gates, which are the subject of this study, the complex flow having strong three-dimensionality and the non-hydrostatic pressure three dimensional sediment transport model is effective.



(a) Surface layer (TP 614.5 m)



(b) Bottom layer (TP 607.5 m)



(C) Bird's eye view

Figure 7: Flow velocity distribution (discharge Q = 300 m^3/s)

3.2 Time series in river bed height, discharge, diversion ratio of water and sediment

Figure 8 shows the planar distribution of bed height changes from the beginning 5, 10, and 20 hours after the start of operation. Figure 9 shows the time series of river bed height at the front of the sediment bypass inlet, sediment discharge to the bypass tunnel and distribution ratio of water and sediment. Assuming that the sediment flowing to the bypass tunnel is Q_{s2} and the sediment flowing from the upstream of the third sediment trapping weir is Q_{s1}, the diversion ratio of sediment γ_s is calculated by the equation [13]. Likewise, if the sediment flowing to the bypass tunnel is Q_{w2}, and the sediment flowing in from the upstream of the third sediment trapping weir is Q_{w1}, the split ratio γ_w of sediment is calculated by the equation [14].

$$\gamma_s = \frac{Q_{s2}}{Q_{s1}} \qquad [13]$$

$$\gamma_w = \frac{Q_{w2}}{Q_{w1}} \qquad [14]$$

1) 0-5 hours

As shown in Figures 9a and 9c, as the bypass discharge amount increases, the discharge sediment volume from the bypass tunnel gradually increases. As shown in Figures 8a and 9b, sedimentation occurs at the front of the inlet of the bypass tunnel (point A in Figure 8) due to accumulation of sediment flowing in beyond the third sediment trapping weir.

2) 5-17 hours

As shown in Figure 8b, with regard to the river bed height on the front of the tunnel inlet, sediment disappears and erosion occurs. The reason for the erosion is that a waterway is formed in the main stream from just under the third sediment trapping weir to the bypass tunnel inlet, and the flow toward the inlet gate develops to accelerate erosion of the river bed. In addition, sedimentation is increasing on the upstream of the diversion weir and downstream of the third sediment trapping weir and on the right bank side of the bypass tunnel inlet. As shown in Figure 9b, the river bed height at the front of diversion weir (point B in Figure 8) gradually rises from TP 607 m and eventually reaches the height of the crest of the weir TP 614 m. As shown in Figure 9c, the discharge of sediment from the bypass tunnel during the above period is unstable, and the discharge of sediment fluctuates corresponding to the change of bed level on the front of the bypass tunnel inlet.

3) After 17 hours

As shown in Figure 8c, the main flow path from just under the third sediment trapping weir to the bypass tunnel inlet further develops. As shown in Figure 9b, bed level is in a dynamic equilibrium state in the vicinity of TP 605 m which is slightly lower than the bottom height of the bypass tunnel inlet. In the area other than the main flow passage, an area sedimentating up to the TP 614 m which is the top end height of diversion weir has occurred. The sedimentation in the above area will not be introduced to the tunnel and is not discharged even if the bypass operation is continued even after 17 hours, it will be left in the same place. As shown in Figure 9c, the discharge of sediment from the bypass tunnel from the 17th hour onward is almost constant and stable.

As shown in the discharge of sediment of Figure 9c, the sediment pocket corresponding to the area of diversion weir and third sediment trapping weir as the initial condition is in operation from the state of empty. Therefore, while the capacity still remains in the sediment pocket, sediment is filled in the empty part. For this reason, the discharge of sediment gradually rose until bed level reached the full state near TP 614 m.

On the other hand, as shown in the sedimentation distribution ratio in Figure 9d, until the 12 hour (the initial bed level is low and the bypass discharge amount is almost equal to the inflow amount), the diversion ratio of the sediment temporarily becomes larger than 1, and the diversion ratio of water is lower than the diversion ratio of sediment. This is because the sediment eroded in the river channel in addition to the sediment inflow from the upstream is discharged from the inlet of the bypass tunnel. After that, after 17 hours when sediment on the front of diversion weir increased to reach the crest height, the split ratio of water and sediment is stable at about 0.85.

Note that the bed material for 2004 set in this analysis has a large proportion of medium gravels having a representative grain diameter of 8.6 mm. For this reason, the sediment transported in the bed load state tends to accumulate in the bypass tunnel, and the sedimentation split ratio becomes higher than the river containing many fine grains. Considering the above, it is necessary to study the influence of the grain size distribution in more detail.

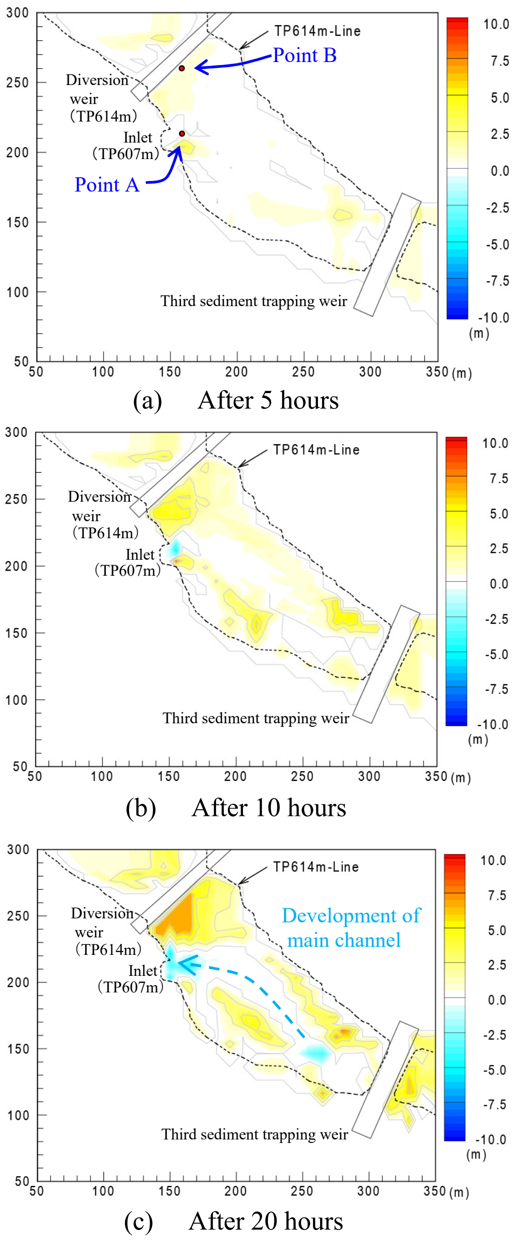


Figure 8: Planar distribution of bed height changes from the beginning

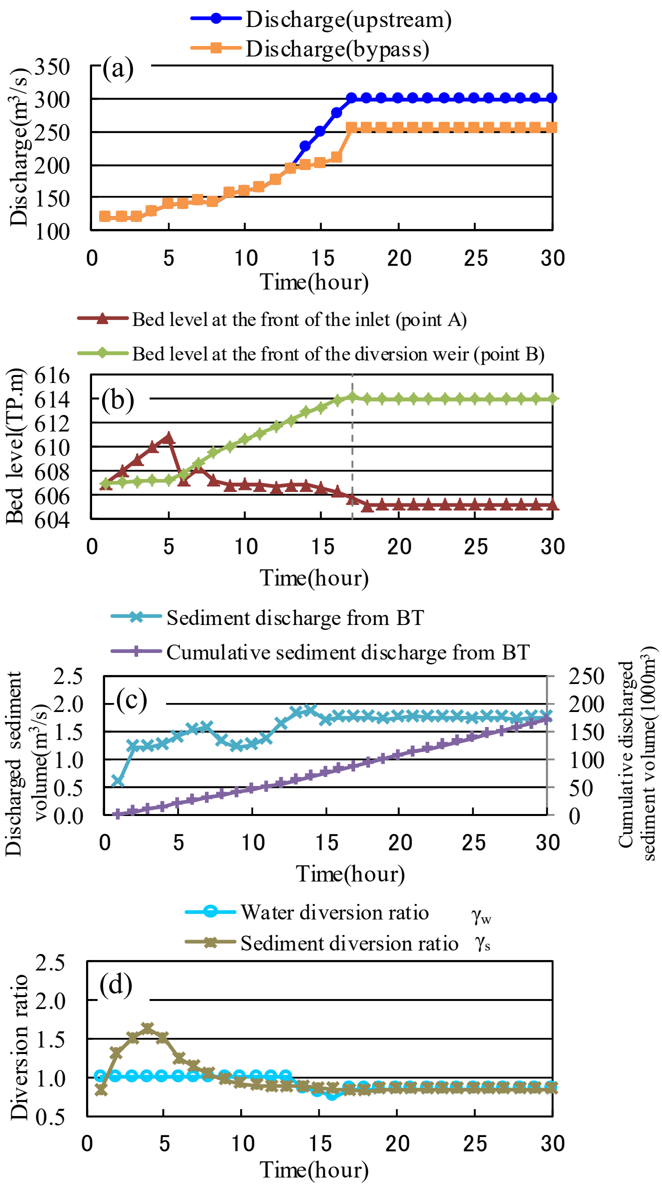


Figure 9: Time series Time series in (a) discharge,(b) river bed height, (c) discharged sediment volume, (d) diversion ratio of water and sediment

4 Conclusion and future tasks

A simulation using a three-dimensional sediment transport model was performed on the area around the inlet of Koshibu Dam's diversion weir and the bypass tunnel. From the results, findings were obtained about time series changes in flow, bedlevel, sediment discharge and diversion ratio around the bypass inlet at the time of flooding. The conclusion and future tasks is shown below.

4.1 Conclusion

1) The structure of the flow around the bypass facility

Flows in the surface and bottom layers during the flood were shown, and in the vicinity of the bypass inlet, very complex flow with a strong three dimensional nature accompanied by a helical flow is generated from third sediment trapping weir toward the inlet was shown.

2) The bed level of the front of the bypass tunnel inlet from the start to the end of the flood, the time series of the discharge sediment volume and the sedimentation distribution ratio

During the rise of the flood, sediment is trapped in the area from third sediment trapping weir to the bypass tunnel, so that sediment discharge from the bypass tunnel is unstable and there is a high possibility of sedimentation also on the front of the tunnel inlet. After that, when the water passage is formed by sedimentation advancing from diversion weir to third sediment trapping weir, the sediment discharge on the front of the bypass becomes close to the dynamic equilibrium and the sediment discharge stabilizes.

3) The diversion of water and sediment

The diversion ratio of the sediment becomes the maximum from 0 to 5 hours, then declines and becomes the same as the water diversion ratio. The diversion ratio of water is almost 1.0 because almost all of the inflow amount is guided to the bypass tunnel at the time of flow increase corresponding to the initial stage of the flood. When the inflow exceeds the flood control start discharge, the flow diverges to the downstream side of the weir, the water diversion ratio decreases to about 0.85.

4) The planar distribution of sediment

Sedimentation proceeds from the diversion weir to the third sediment trapping weir area except for the main stream of the flow leading to the bypass tunnel. Although it was not carried out in this study, sedimentary sediments other than the main stream may dry out and remain undischarged from the bypass tunnel during the decline of the flood.

4.2 Future tasks

In the sediment bypass facility, water and sediment from the upstream flow into the sediment pocket area flooded by the downstream diversion weir. For this reason, as the shear stress decreases when the state of the influent water changes from the river state to the flooding state, accumulation tends to occur from the boundary point of the flooded area. The above sediment is introduced and discharged to the bypass tunnel inlet at the decay of the flood. However, if discharge and water level reduction are not carried out so that the flow directly affects the sediment area, the sediment area will remain dry. This sedimentation/sediment discharge process is similar to the sediment inflow, deposition and discharge process on the front of spillway gate in Flood Mitigation dam indicated by Sumi *et al.* (2013).

In order to discharge sediment more smoothly by eliminating biased sediment from the beginning to the middle of the flood, the following ingenuity is required to concentrate sediment on main channel as shown in Figure 10.

- Sediment placement to main channel
- Construction of guide wall (like groin)

As in this research, to utilize a three-dimensional model is important from the viewpoint of predicting the spatial flow and sediment transport around the hydraulic structure and examining effective sediment control measures.

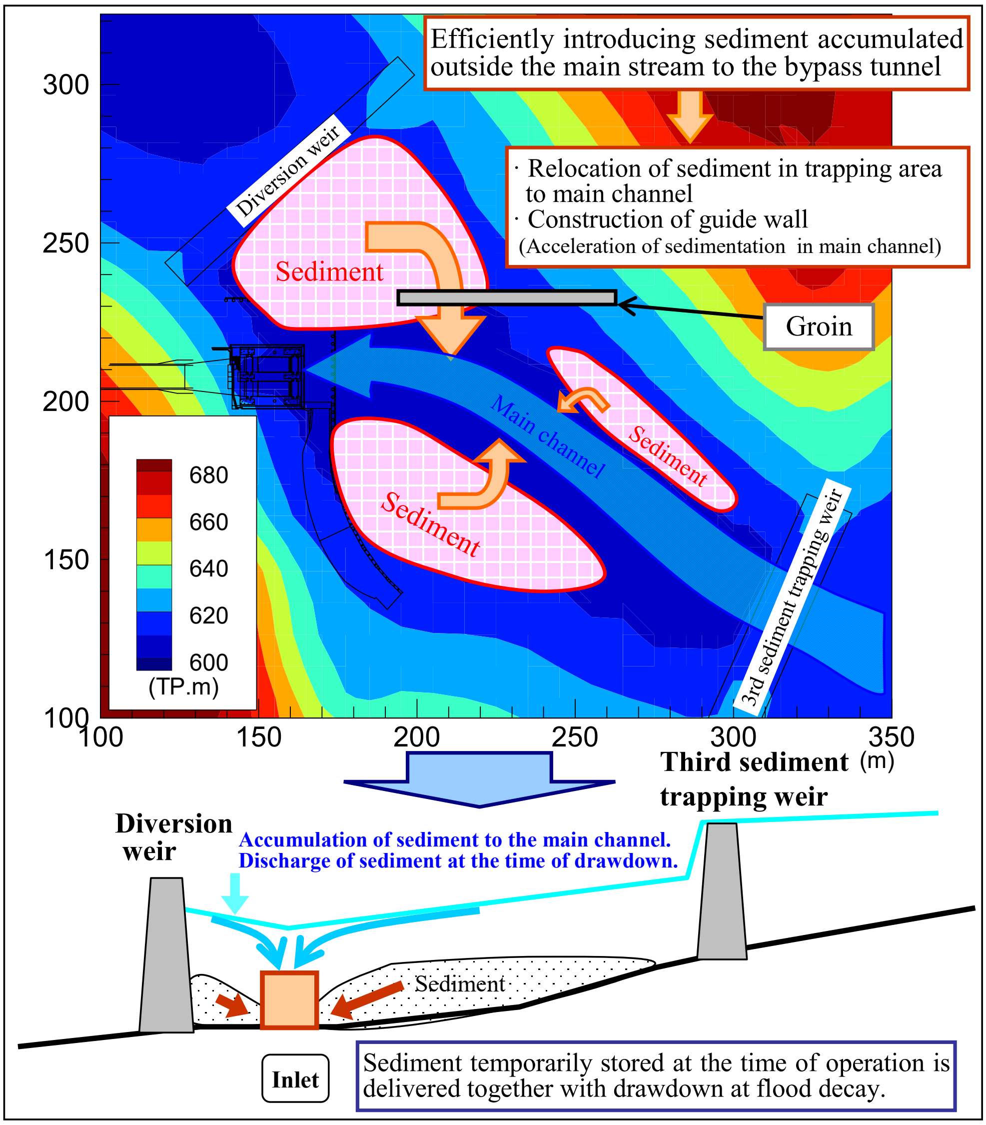


Figure 10: Proposal of sediment discharge method during flood decay period

Acknowledgement

The authors would like to address their sincere thanks to Ministry of Land, Infrastructure and Transport Chubu Regional Development Bureau Tenryu River Dam Integrated Management Office for providing valuable data about Koshibu Dam.

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