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Quasi-three dimensional numerical and scale-model studies on flood propagation and water storage in a dam reservoir

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ABSTRACT: The flood management in dam reservoirs has been performed by the estimation of inflow discharge using the assumption that a water level observed near the dam body holds everywhere in the reservoirs. However, we are not sure whether the water level in dam reservoirs rise horizontally or not during a flood because propagation characteristics of flood water level and discharge hydrographs are different. For efficient and floods and sediment management in dam reservoirs, it is important to clarify the mechanism of flood propagation and three-dimensional flow structures. Hydraulic model test was carried out in order to investigate the characteristics of reservoir storage and flow mechanism in dam reservoirs. Moreover, the quasi-three dimensional flood flow analysis method considering main stream layer and non-equilibrium vortex layer was developed to understand dynamic characteristics of flood flows in dam reservoirs and applied to the hydraulic model tests. From the analysis result, characteristics of flood flow dynamics and flood propagation in dam reservoirs were clarified.

1 INTRODUCTION

The flood management in dam reservoirs is important for the improvement of the safety level control in downstream rivers of the dam. Figure 1 presents the dam reservoir flow during a large flood. The inflow discharges to dam reservoirs have been evaluated by using rate of storage volume dS/dt from the H-V relation assuming the horizontal rise of reservoir water level and outflow discharges estimated by reservoir water elevation near the dam body. This provides a simple estimation method for the outflow and inflow discharges in dam reservoirs. Assuming the horizontal rise of reservoir water level means that the flood flow propagates with very large velocity within the reservoir. However, floods in dam reservoirs flow down transforming a water-level and discharge due to three dimensional reservoir flows. But, the present reservoir management conducted by assuming the horizontal rise of water levels has not considered flood propagation mechanism and flow dynamics of flood water in reservoirs.

The reservoir water levels were observed in order to understand the mechanism of translatory waves during floods in Wheeler dam reservoir in America (Wilkinson et al. 1944). In this study, It was shown that the water surface profiles in reservoirs were generally horizontal. The hydraulic model test and

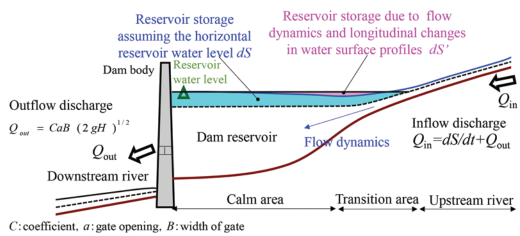

Figure 1. The dam reservoir flows during a flood.

analysis have been performed in order to understand characteristics of the flood propagation in a simple reservoir model channel with the uniform bed-gradient and width (Yano et al. 1965). Their study clarified three typical flow areas such as river area, transition area and calm area as shown in Figure 1 and provided the fundamental information about the flood propagations in a dam reservoir, but it was not clear the dynamics of flood flow in dam reservoirs. The one-dimensional flow analysis model was applied to the system of reservoirs and the network of tributaries (Garcia-navarro et al. 1993). They investigated the applicability of the model. The effects of the gate operation in small hydropower dams on flood propagation and water storages were clarified using unsteady one-dimensional flow analysis using observed water-level data

(Takemura et al. 2010). The accuracy of inflow and outflow discharge hydrographs were investigated by two-dimensional unsteady flow analysis using observed temporal changes in water surface profiles in the Kusaki Dam reservoir in Japan (Tsukamoto et al. 2014). Their results suggested that the unsteady two-dimensional flow analysis in dam reservoirs could not explain sufficiently the dynamics of flood flows because of three dimensional features of reservoir flows.

For efficient and safe management in dam reservoirs, it is necessary to verify the estimation accuracy of inflow and outflow discharge hydrographs and establish a proper analysis model for explaining three-dimensional flow features such as vertical and horizontal velocity distributions and transformation of water level and discharge. To predict the bottom velocity is very important for estimation of the sediment movement in the reservoir. For these purpose, we measure characteristics of flood flows in dam reservoir model by using large-scale hydraulic model test and analyze observed flow data by newly developed quasi-three dimensional numerical model.

Generation mechanism of three-dimensional flows in dam reservoirs was considered by introducing non-equilibrium vortex layer near the bed and clarified the three-dimensional flow dynamics and flood propagation mechanism in dam reservoirs.

2 SCALE-MODEL EXPERIMENT

It is hard to measure flood flow structures in large reservoir such as water levels, flood velocity and discharges over time in detail. The large-scale model test was carried out to investigate the flow dynamics in dam reservoirs. Figure 2 shows the plan form and longitudinal distributions of the average and the lowest bed elevations of the reservoir model. The model scale is 1/75 of the Kusaki Dam in Japan and the total length is about 60 m. Table 1 shows the conditions adopted in the hydraulic model test. Inflow discharge hydrograph is the 2013 flood discharge of the Kusaki Dam. The peak discharge of the 2013 flood was 1,000 m^3/s, but it was extended to 1,300 m^3/s (converted about 26.6 l/s in scale model) because the flow velocity of 1,000 m^3/s flood was too small to be measured in the hydraulic model. The initial reservoir water elevation is set to 0.74 m of the flood season control level. The outflow discharge hydrograph is given according to the operation rules of the Kusaki dam. The items measured are water levels, inflow and outflow discharges, and flow velocity distributions.

Table 1. Conditions used in hydraulic model test.

Model scale 1/75		Field	Model
Discharge	2013 flood	1,000 m^3/s	20.5 l/s
	Extension	1,300 m^3/s	26.7 l/s
Roughness	River	0.050 m$^{-1/3}$s	0.024 m$^{-1/3}$s
Coefficient	Reservoir	0.025 m$^{-1/3}$s	0.012 m$^{-1/3}$s
Model size	Total length	4,500 m	60 m
	Width (Reservoir)	300 m	4 m
	Width (River)	50 m	0.67 m
Experiment time		11 hr	1.27 hr

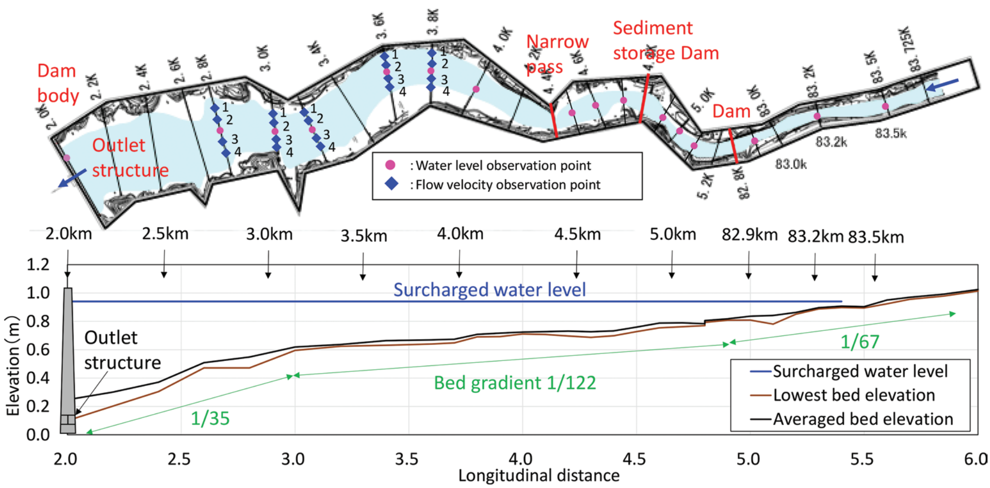

Figure 2. Plan form of the experimental channel and longitudinal distributions of the average and lowest bed elevation.

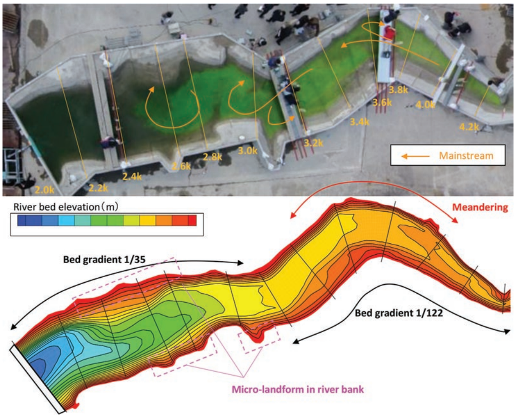

Figure 3. Diagram of the flow regime and bed elevation contour in the hydraulic model test.

Figure 3 shows the diagram of the flow regime visualized by the dyestuff and river bed elevation contour in the hydraulic model test. This diagram visualizes the flow after 18 minutes from beginning of the test. Flood flows entering from the upstream river formed multiple large horizontal eddies at the right bank of around 3.6 km point. In the downstream section from 3.2 km point, the velocity was decreased and nearly stagnant since the cross-sectional area was increasing with the downstream section in dam reservoirs. Horizontal eddies were affected each other by the increase in water depth and river width and shape of micro-landform in river bank (see Figure 3). Thus, the flood flow had three-dimensional characteristics by vertical and cross sectional geographical changes in the reservoir.

3 QUASI-THREE DIMENSIONAL NUMERICAL CALCULATION IN DAM RESERVOIRS

3.1 *Necessity of three-dimensional flood flow analysis in dam reservoirs*

Generally, dam reservoirs have the characteristic shapes of cross sectional areas since the water depth and width become larger in the downstream direction. So, flood flows in reservoirs change not only horizontally but vertically and vary water level and discharge hydrographs. It is important to analyze three-dimensional flows in dam reservoirs with complex three-dimensional shape for proper dam reservoir management. Therefore, the quasi-three-dimensional flood-flow analysis model is developed for the estimation of complex flow fields.

3.2 *Framework of the dam reservoir flow analysis model*

The quasi-three-dimensional flow analysis method (the Bottom Velocity Computation (BVC method)) was developed by Uchida & Fukuoka (2011, 2013). This method can estimate three-dimensional horizontal and vertical velocity distributions using observed temporal changes in flood water surface profiles in various rivers.

Figure 4 shows the framework of dam reservoir flow analysis model. This model consists of a main stream layer and a vortex layer. The former is a layer of flood flows with large momentum. The BVC method is applied for this layer of dam reservoirs.

The latter is a thin vortex layer on bed surface where the streamwise velocity near the reservoir bed is non-equilibrium. This is caused by longitudinal change in the flow with steep slope and large depth in transition area. The continuity and momentum equations in the vortex layer are developed and the whole flow area is examined considering the exchange of mass, momentum and vorticity between main stream layer and vortex layer.

3.3 *Governing equations*

The governing equations of the BVC method are given by Uchida et al. (2014) and applied to the main stream layer of reservoirs. In this chapter, the analysis method of flows in the vortex layer is mainly explained.

The continuity equation and the equation of motion in the vortex layer are given as follows:

$$w_{\sigma b} = -\frac{\partial \delta z_b u_{vi}}{\partial x_i} \tag{1}$$

$$\frac{\partial u_{vi}}{\partial t} + u_{vk}\frac{\partial u_{vi}}{\partial x_k} = -\frac{\partial (dp_b + \rho g z_s)}{\rho \partial x_i} + \frac{\tau_{bi}}{\rho \delta z_b} - \frac{\tau_{0i}}{\rho \delta z_b} \tag{2}$$

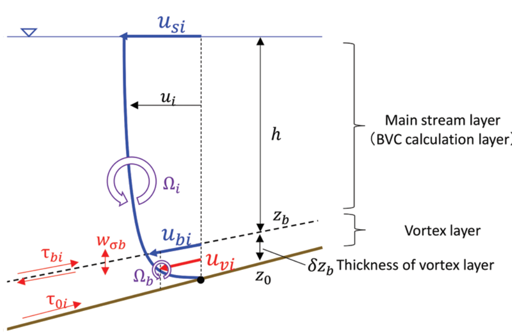

Figure 4. Dam reservoir flow analysis model.

where, $k = 1,2,3$, $w_{\sigma b}$: velocity normal to the surface of vortex layer, δz_b: the thickness of vortex layer, u_{vi}: i direction velocity in the vortex layer, dp_b: pressure deviation from hydrostatic pressure distribution at the bottom, z_s: water level, τ_{bi}, τ_{0i}: shear stress acting on the upper boundary and bottom of the vortex layer, respectively.

The shear stress in the equation (2) for the vortex layers is given by using the eddy viscosity coefficient as follows:

$$\frac{\tau_{bi}}{\rho} = \left(\nu_t \frac{\partial u_i}{\partial z} \right)_b = \nu_{tb} \cdot A_b \frac{(u_{bi} - u_{vi})}{h} \tag{3}$$

$$A_b = \frac{1}{\alpha(c_b - c_v)} \tag{4}$$

The coefficients c_b and c_v are expressed by equation (5) by the logarithmic velocity distribution.

$$c_b = \frac{1}{\kappa} \ln\left(\frac{z_b}{k_s}\right) + A_r, \quad c_v = \frac{1}{\kappa} \ln\left(\frac{\delta z_b / 2 + \delta z_0}{k_s}\right) + A_r \tag{5}$$

The eddy viscosity coefficient at the bottom of the vortex layer is expressed by equation (6).

$$\nu_{tb} = \alpha_b \delta u_b h, \quad \delta u_b^{\,2} = (u_{bi} - u_{vi})(u_{bi} - u_{vi}) \tag{6}$$

where, ν_{tb}: eddy viscosity coefficient, u_{bi}: i direction bottom velocity, h: water depth, z_b: bed level, $\alpha = \kappa/6$, $\kappa = 0.41$, $A_r = 8.5$. The bottom eddy viscosity coefficient ν_{tb} is presented in the previous papers (Uchida & Fukuoka, 2011, 2013):

$$\nu_{tb} = \frac{\alpha \kappa \omega_b h^2}{2 \ln(z_s / z_b)} \tag{7}$$

We use the average value of equation (6) and (7) for ν_{tb} in this model.

The non-equilibrium bottom vorticity is given by equations (8) and (9) which are derived from the equilibrium vorticity in the production term of the vorticity equation in the vorticity layer.

$$\omega_{bej} = 2\varepsilon_{ij3} A_\omega \frac{u_{bi} - u_{vi}}{h} \tag{8}$$

$$A_\omega = \frac{1}{\kappa(c_b - c_r)} \ln\left(\frac{z_s}{z_b}\right) \tag{9}$$

where, ω_{bei}: equilibrium vorticity on the bottom.

3.4 *Analysis condition*

We applied the quasi-three dimensional reservoir flow analysis model consisting of the main stream layer and vortex layer to the results of hydraulic model test. The analysis was performed from 2.0 km to 83.725 km shown in Figure 1. The computational mesh size is set to $dx = dy = 5$ m in the upstream river, and $dx = dy = 20$ m in reservoir areas. The upstream boundary condition is given by the observed inflow discharge hydrograph and downstream boundary condition by the observed reservoir water level hydrograph. Figure 5 shows the method determining the downstream boundary condition. The outflow discharge hydrograph was set by adjusting the gate opening so as to coincide calculated water levels near the dam body with observed discharge hydrograph. We assumed that the vorticity fluxes were discharged out by the height of gate open out of vorticity fluxes in meshes in front of the dam body. Moreover, the dynamic pressure and the static pressure are considered on the dam body. The roughness coefficients are determined so that calculated temporal changes in water surface profiles may agree with observed one during the flood. As a result, temporal roughness coefficients were set to n = 0.053 to 0.087 (n = 0.026 to 0.042 in scale model) for transition area and the upstream river, respectively, n = 0.025 (n = 0.012 in scale model) for the calm area.

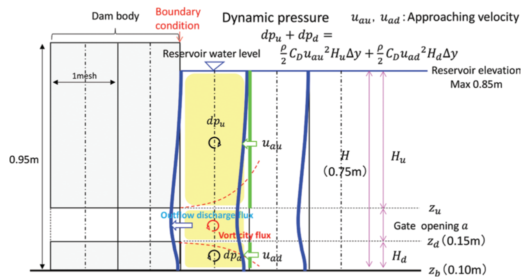

Figure 5. Downstream boundary conditions in dam reservoir.

3.5 *Calculation results*

Figure 6 shows the comparison between observed and calculated water surface profiles during the flood. The velocity of the flood flows is reduced and become nearly stagnant by the dam body, since the inflow discharge is small as compared with a volume of the reservoir. Longitudinal water surface profiles in the calm area are generally horizontal in rising and falling water stages. In the transition area at 4.0 km to 4.4 km section, longitudinal changes in water surface profiles occurrs in discharge rising stage (experiment time 20 minutes to 32 minutes). At 4.4 km to 5.0 km section, calculated water surface profiles cannot explain the observed ones, since the vorticities due to flow separation generated in

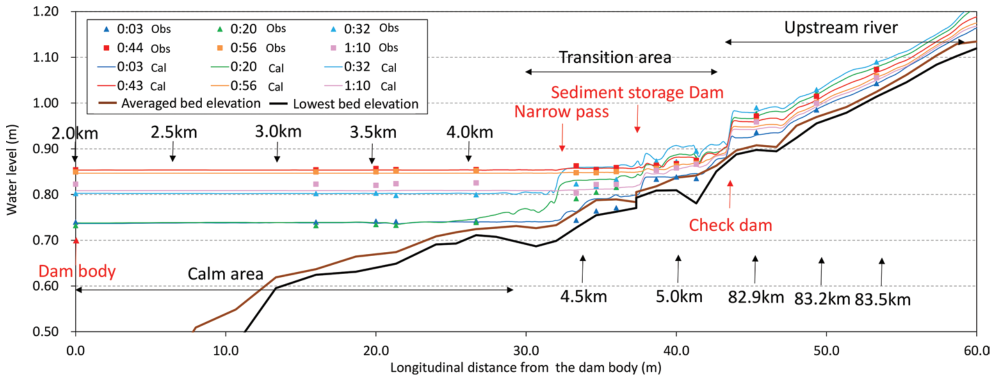

Figure 6. Comparison between observed and calculated water surface profiles.

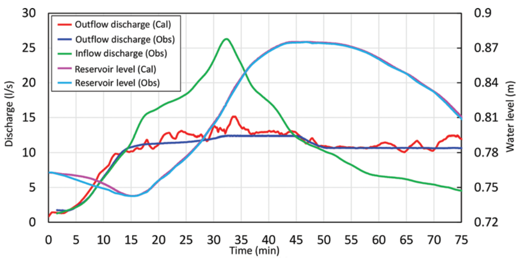

Figure 7. Comparison between observed and calculated outflow discharge and reservoir elevation.

narrow pass are not described enough in this model. In the upstream river, temporal longitudinal water surface profiles are made mainly depending on river bed-gradient. Calculated water surface profiles are found to reproduce mostly the observed ones in the reservoir.

Figure 7 shows the temporal changes in observed and calculated outflow discharges and reservoir water levels in the calm area. The inflow discharge hydrograph at the upstream boundary condition is described for reference. The observed outflow discharges is calculated by outflow discharge formula based on gate opening and reservoir water level. Although the calculated outflow discharge is a little larger than observed one around the time of peak discharge, the calculated results reproduce well observed ones. Both observed and calculated water levels in the dam reservoir go up horizontally in totality.

Figure 8 shows the comparison between observed and calculated horizontal velocities at the water surface and the bottom. In discharge rising stage, the water depth is small and flow velocities are large in reservoirs. The flood flows enter into the reservoir with large inertial force from the upstream river area. The area around 4.0 km is the

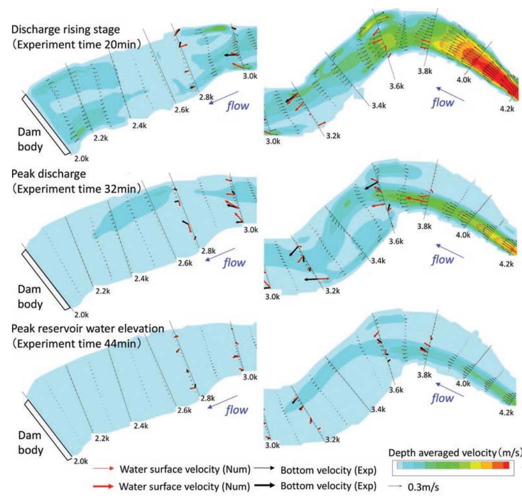

Figure 8. Comparison between observed and calculated horizontal velocity.

occurrence area of water storage *dS'* (see Figure 1 and the section of 4.0 km to 4.4 km in Figure 6), which causes local changes in water surface and resulting change in flow dynamics of the reservoir. Horizontal and vertical mixing happens by large velocity difference between water surface and bottom in this area.

The flow which enters into the calm area from the transition area is curred to the right at around 3.6 km point, and is divided into flows of the downstream and upstream. Multiple horizontal eddies are formed and their occurrence points depend on the reservoir water level and flood discharge scale. The inflow discharges enter into the calm area with small velocity, reservoir water levels go up generally horizontally. At the time of peak reservoir water level, longitudinal water surface profiles tend

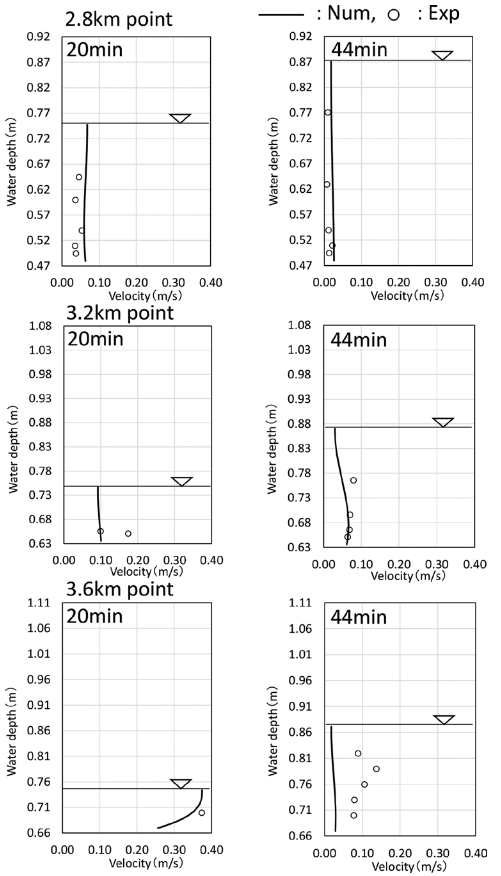

Figure 9. Comparison between observed and calculated vertical distributions of streamwise velocity.

to be horizontal by the 5.0 km point. After then, dynamic flow movement in the reservoir occurrs again when the outflow discharge is greater than inflow discharge and reservoir water level goes down. Calculated horizontal velocity explains observed one fairly well in dam reservoirs.

Figure 9 presents observed and calculated vertical distributions of streamwise velocity. The reservoir width and depth around 3.6 km point are smaller, calculated and observed vertical distributions of velocity are similar to those of rivers. In 3.2 km point, calculated vertical velocity distributions generally reproduce observed ones except for around bottom. Velocities at 2.8 km are smaller than those of the upstream area.

3.6 *The applicability of the dam reservoir flood analysis model*

In order to clarify the applicability of the dam reservoir flood analysis model, we applied the developed model and depth averaged 2D calculation model to large-scale hydraulic model test.

Figure 10 shows the horizontal velocity at the water surface and the bottom by using the dam reservoir flood analysis model and 2D calculation model in discharge rising stage. The calculated result of flow dynamics by the new model can reproduce the observed one. However, the calculated result of flow dynamics by the 2D calculation model cannot explain the observed one around 2.8 km point.

Figure 11 shows the difference of bottom vorticity between equilibrium and non-equilibrium flow. The non-equilibrium bottom vorticity was estimated by the difference of velocity between bottom and vortex layer as shown in equation (8). The equilibrium bottom vorticity was estimated by the velocity assuming the logarithmic distribution

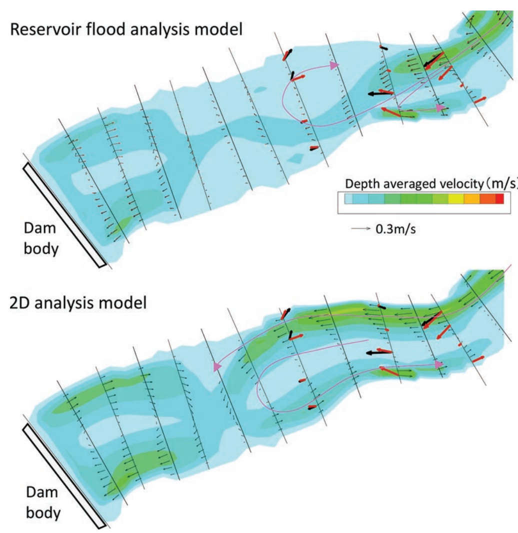

Figure 10. Horizontal velocity at the water surface and the bottom.

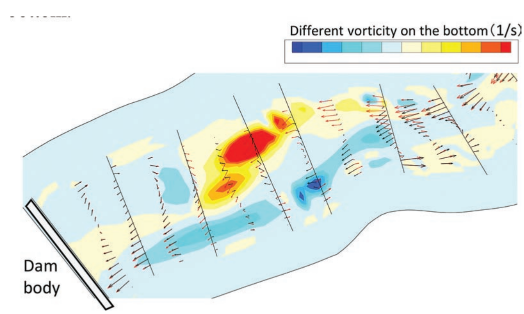

Figure 11. Difference of bottom vorticity between equilibrium and non-equilibrium flow.

low in vortex layer. Around 2.8 km point, non-equilibrium flow was caused because the difference of bottom vorticity between equilibrium and non-equilibrium is large. Thus, non-equilibrium flow changes in the velocity distributions temporally and spatially, and the three-dimensional flows were formed in dam reservoirs.

These results demonstrate that the quasi-three dimensional reservoir flow analysis model can explain characteristics of rather small velocity field in dam reservoirs with three-dimensional shape, and provides a prediction tool for sediment movement in reservoirs.

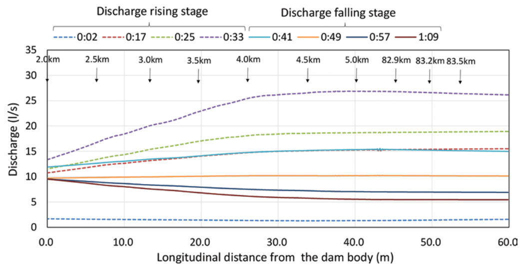

Figure 13. Longitudinal distributions of calculated flood discharge with time.

4 FLOOD PROPAGETION IN DAM RESERVOIRS

Figure 12 shows calculated longitudinal change in water level and discharge hydrographs. Discharge hydrograph is the value averaged for 1 minute in each cross section. The propagation mechanism of water level and discharge is greatly different from each other. While the peak of water level and discharge occurs at nearly same time in the upstream river, the occurrence time of peak water level is 11 minutes behind the time of peak discharge in the calm area. In the upstream river, the discharge hydrograph is hardly transformed in shape. In the calm area, the peak discharge is decreased clearly with distance.

Figure 13 shows the longitudinal distributions of calculated flood discharge. The discharges in discharge rising stage (dashed line in Figure 13) reduce remarkably in the downstream section of 4.0 km point which is the boundary of the calm area and transition area. The rate of storage water volume dS/dt is evaluated by the difference of inflow discharges Q_{in} and outflow discharges Q_{out} or temporal changes in water surface elevation in the target area.

$$\frac{dS}{dt} = Q_{in} - Q_{out} = \int_L \frac{\partial A}{\partial t} dx \tag{10}$$

where, S : storage water volume, A: cross sectional area of flood flow, L: length in the target section.

As shown in equation (10), the longitudinal difference of flood discharges is equal to the storage water volume. The shape of discharge hydrographs changes in the longitudinal direction since the flood flow is stored in the calm area and transition area. Moreover, in the discharge falling stage (solid line in Figure 13), storage water volume is reduced gradually since inflow discharge into dam reservoirs is smaller than outflow one from the dam gate. As shown in Figure 12, water level hydrograph greatly transforms in shape in the transition area, and becomes the same shape in the calm area. This is because the inflow discharge in this model test is small enough as compared with the reservoir capacity and the reservoir water levels go up almost horizontally in mid scale floods. Thus, the difference from the horizontal water level is not so large to transform the shape of discharge hydrograph. This means that current estimation method assuming the horizontal rise of reservoir water level is fairly accurate for the estimation of the inflow discharge hydrograph of mid scale floods.

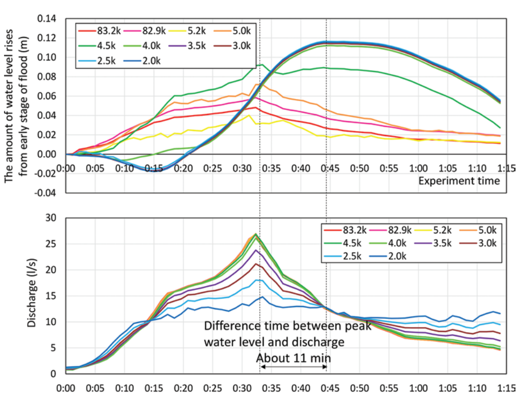

Figure 12. Longitudinal change in water level and discharge hydrographs.

5 DYNAMICS OF FLOOD FLOWS IN A RESERVOIR WHERE LARGE FLOODS INFLOW

When larger floods flow into a dam reservoir, it is imagined that flows in the transition and calm areas are different from mid scale floods. The quasi-three dimensional numerical analysis was conducted about the flow and storage in the reser-

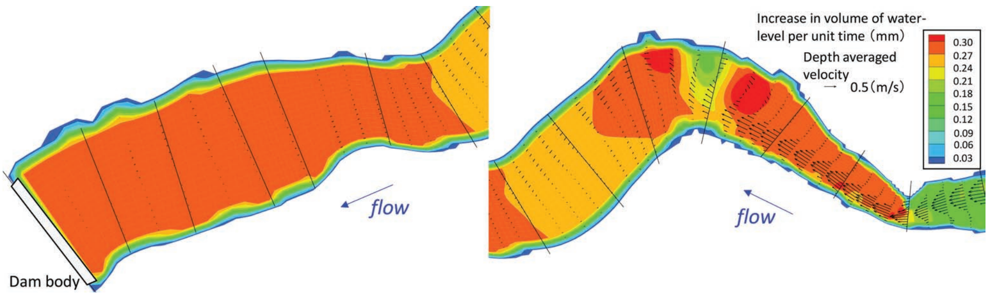

Figure 14. Depth averaged velocity and increment water-level per unit time.

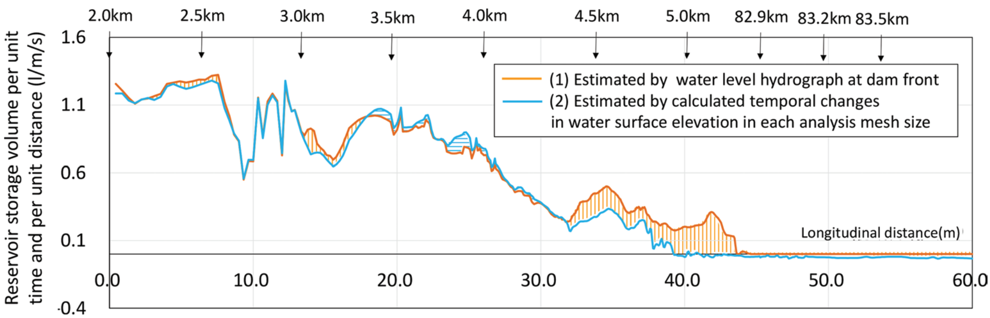

Figure 15. Longitudinal distribution of reservoir storage volume per unit time and per unit distance.

voir during the large-scale flood. Figure 14 shows the increase in water-level elevations per unit time at the peak discharge. The peak discharge of large-scale flood was extended to 2,200 m^3/s (discharge probability about 1/200). At the time of peak discharge, horizontal eddies were created around 3.5 km to 4.0 km points. Then, the local water level changes in this area.

Figure 15 shows the longitudinal distribution of reservoir storage volume per unit time and unit distance at the time of peak discharge. Similar figures can be drawn in each time. Figure 16 shows the rate of storage volume during large-scale flood flow. The reservoir storage volume estimated by the water level hydrograph at the dam front is compared with one calculated by temporal water surface elevations and velocity in each analysis mesh size. The storage volume estimated by assuming horizontal rise of water level used in current dam reservoir management is larger than the storage volume considering local depth and flow velocity distributions during floods. In the downstream end of the calm area, the water surface elevation nearly equals to the energy head, because the outflow discharges is small enough and the kinematic energy is sufficiently small. Therefore, the water level at this point is regarded as the highest within the reservoir. Therefore, the storage volume estimated by the present method may be overestimated a little. It can be interpreted as giving the clearance to the capacity of reservoir storages in the present dam reservoir management during a flood. It suggests that the inflow discharges may be estimated larger than actual one into dam reservoirs.

To obtain accurate inflow discharge hydrographs and understand three-dimensional flow dynamics in dam reservoirs are essential in order to perform efficient and safe dam reservoir management against the large-scale flood and to mitigate sedimentation problems in reservoirs. It is also important to establish the flood observation systems in dam reservoir and upstream and downstream rivers during floods in order to assess properly the flow dynamics by dam reservoir flow analysis.

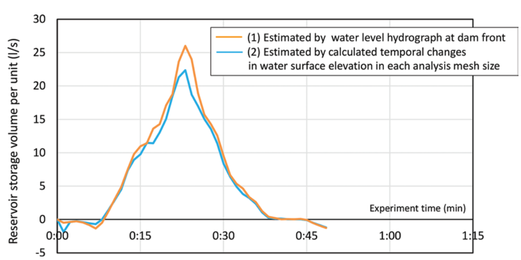

Figure 16. Rate of storage volume during large-scale flood flow.

6 CONCLUSIONS

In this paper, we developed the dam reservoir flow analysis model and checked the validity of this model by applying to large-scale hydraulic model test. Main conclusions are drawn as follows.

1. The hydraulic model test were carried out and the flood propagation and flow mechanism in the dam reservoir were investigated in detail.
2. The dam reservoir flow analysis model was developed considering observed temporal changes in water surface profiles. We applied this model to the hydraulic model test and clarified the mechanism of flood propagation and flow dynamics in dam reservoir.
3. This paper proved that to obtain inflow discharge hydrographs with a high accuracy and to clarify flow dynamics in dam reservoirs as well as understanding of the occurrence mechanism of the flood retarding volume were essential for the reliable dam reservoir management.
4. The developed model presents detailed velocity distributions near reservoir beds. This model gives a useful tool for mitigating reservoir sedimentation problems.

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