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Experimental study on effective sediment channel with reservoir topography and morphology

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ABSTRACT: Measures to exclude the sedimentation in dam reservoirs are important for the sustainable maintenance and operation of dam reservoirs. There is sediment flushing and pass-through method for measures for reservoir sedimentation. This method is to lower reservoir water level during flooding, to increase tractive force, to accelerate erosion of sediment, to form sediment channel, and to pass sediment through spillway or sediment release gate. This method is economical measure because of utilizing the stream power during flooding. On the other hand, sediment channel formed in the reservoir has a great change in shape of meander and water passages depending on the plan shape of reservoir. Flushing efficiency also greatly differs. For this reason, in order to conduct flushing smoothly sediment in reservoir during flood period and passing effectively through reservoir, a hydraulic study on the sediment channel formed in reservoir is important.

In this paper, we report results of consideration about sediment channel to improve the efficiency of sediment flushing and pass-through during flooding. We investigate about characteristics concerning the sediment channels naturally formed in reservoir and artificially constructed beforehand by excavating and dredging in dry season through the mathematical and the hydraulic scale modelling experiments.

RÉSUMÉ: Les méthodes visant à empêcher la sédimentation dans les réservoirs des barrages sont importantes pour l'entretien et l'exploitation durable de ceux-ci. Il existe une méthode de vidange des sédiments pour empêcher la sédimentation. Cette méthode consiste à abaisser le niveau d'eau du réservoir pendant les crues afin d'augmenter les forces d'entraînement, d'accélérer l'érosion des sédiments, de former un chenal à travers les sédiments et de faire transiter les sédiments par l'évacuateur ou la grille de vidange des sédiments. Cette méthode est une mesure économique en raison de l'utilisation de la puissance du courant pendant les crues. Par ailleurs, le chenal formé à travers les sédiments dans le réservoir est caractérisé par une variété de méandres et de passages pour l'eau en fonction de la topographie du réservoir. L'efficacité de la vidange est aussi très variable. Pour cette raison, une étude hydraulique du chenal formé à travers les sédiments dans le réservoir est importante pour réaliser la vidange des sédiments pendant les périodes de crues et pour les faire transiter à travers le réservoir.

Dans cet article, les résultats de considérations au sujet des chenaux à travers les sédiments pour améliorer l'efficacité de la vidange et du transit des sédiments pendant les crues sont rapportés. Les caractéristiques des chenaux naturellement formés dans le réservoir et artificiellement construits au préalable par excavation et dragage pendant la saison sèche sont étudiées à l'aide d'expériences de modélisation mathématique et hydraulique.

1 INTRODUCTION

Reservoir sedimentation control measures are important for sustainable operation and maintenance of dam reservoirs. There are two commonly used methods for achieving that goal: the method of mechanically removing accumulated sediment from the reservoir by excavation and dredging carried out during times of normal flow, and the method of releasing sediment through scour gates, sand bypasses or spillways by making use of the tractive force of flowing water in times of flood (Onda & Sumi 2017). The latter method is more economical than the former because the latter makes use of the force of flooding water. Another important consideration is the fact that bedforms change over time depending on reservoir and sediment deposition characteristics, flood magnitude and sediment load characteristics so as to affect sediment release rates significantly. It is very important, therefore, to gain knowledge about reservoir geometry requirements for effective discharge and removal of flood flows from upstream and sediment accumulated in the reservoir.

In this study, a numerical analysis and a hydraulic model experiment were conducted with the aim of identifying reservoir geometry requirements that need to be met in order to increase the sediment discharge capacity of a flow channel in times of flood by excavating and dredging the channel during times of normal flow according to the geometric characteristics of an existing dam reservoir. This paper reports the findings thus obtained.

2 CHARACTERISTICS OF THE DAM RESERVOIR CONSIDERED

2.1 *Outline of Senbiri Dam*

Senbiri Dam is a combination of concrete gravity and earthfill dam. The crest height and width of the concrete section is 11.7 m and 103 m and the crest height and length of the earthfill section is 11.2 m and 260 m. The dam, built on the Toshibetsu River in the Tokachi River system, is located in Honbetsu, a town in the county of Nakagawa, Hokkaido. Table 1 summarizes the outline of Senbiri Dam, and Figure 1 shows its location.

2.2 *Flood due to 2016 typhoon*

Figure 2 shows a general view of the Senbiri Dam following the flood caused by the 2016 typhoon. The flooding damage inflicted on Ashoro, which locates by the Toshibetu River. The Toshibetsu River Basin Liaison Council was set up to discuss disaster prevention and mitigation measures to be taken in connection with the river. Participating in the discussions of the council, J-Power also proposed a number of disaster prevention/mitigation measures to the organizations concerned with the river basin, and one of those measures, namely, the removal of the sandbars and riparian woods in the reservoir, is currently being carried out.

Table 1. Profile of Senbiri Dam

Dam type	Concrete gravity and earthfill dam
Dam height	Concrete section : 11.7m Earthfill section : 11.2m
Dam length	Concrete section : 103m Earthfill section : 260m
Reservoir capacity	3,100,000m³
Effective depth	0.70m
Water level	H.W.L 80.9m L.W.L 80.2m
Spillway gate	4 roller gates
Design flood discharge	2000m³/s
Turbine discharge	90m³/s
Maximum output	25,000kW

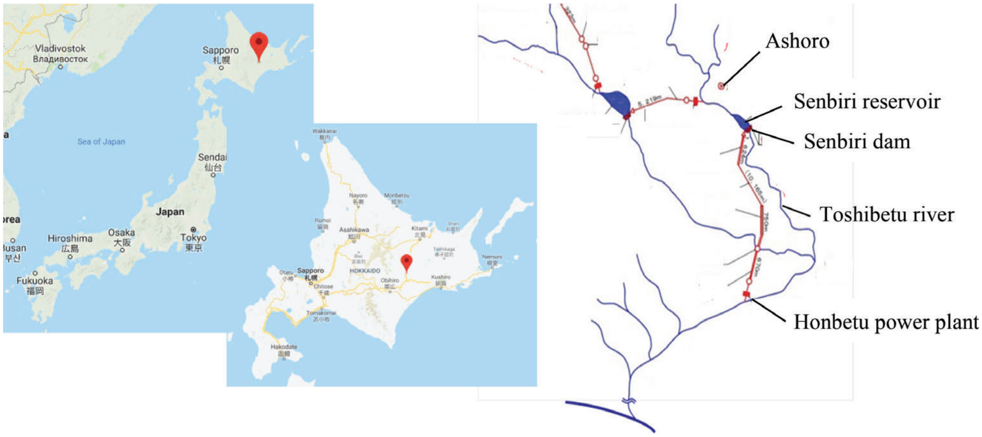

Figure 1. Location of Senbiri dam

Figure 2. Whole view of Senbiri dam after the flood in 2016

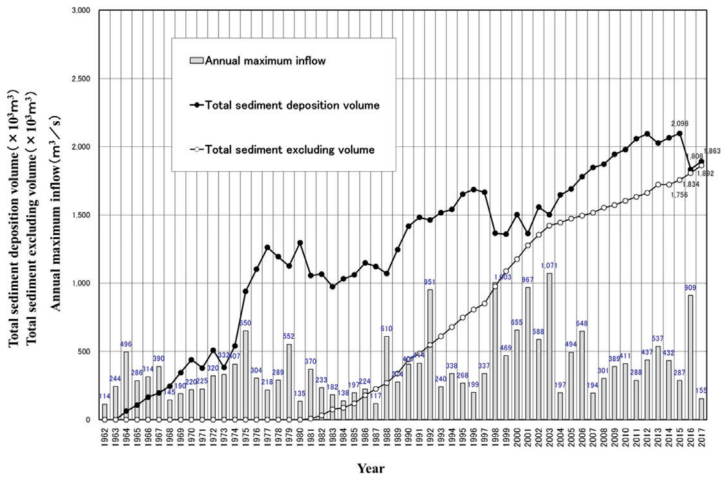

Figure 3. Annual change of the sediment deposition volume at Senbiri reservoir

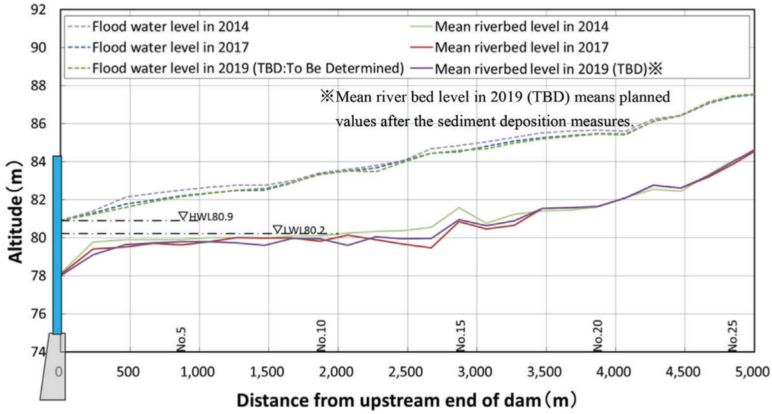

Figure 4. Flood water level and mean riverbed level at Senbiri dam upstream

The next step is to plan and carry out excavation and dredging, taking into account the results of the numerical analysis and hydraulic model experiment reported in this paper, so that the reservoir can be configured so as to facilitate the discharge of flood flows.

2.3 *Sedimentation and morphological condition at Senbiri reservoir*

Figure 3 shows the annual change of the sediment deposition volume at Senbiri reservoir. The sedimentation and exclusion at the reservoir is increasing. Figure 4 shows the annual change of the mean bed level at the reservoir. The bed level is situation of dynamic stability bed level. The sediment deposition in Senbiri reservoir is mainly fine sediment and the grain size is between 0.1mm to 2mm as D50.

3 ANALYSIS OF FLOW CONDITION

A three-dimensional flow condition analysis under fixed-bed conditions was performed for the present topography case(Case-1) and three bedform improvement cases. Case-2 is the right-bank channel case. Case-3 is the straight-channel case. Case-4 is the left-bank channel case. The analysis involved computations associated with friction velocity related to flow regime, velocity and sediment transport from the point of view of tractive force for sediment load.

3.1 *Analysis conditions*

The analysis domain was defined, within a 1.8 km × 1.5 km area, so as to be parallel with the dam axis as shown in Figure 5. The upstream end of the domain was defined to be located at Measurement Line No. 12 about 2.3 km upstream from the dam axis. The mesh sizes used for analysis were Δx = 3.0 m to 17.0 m, Δy = 1.8 m to 12.8 m and Δz = 1.0 m to 2.5 m. Table 2 shows the analysis conditions. The upstream boundary condition was given as the discharge (velocity) condition, and the downstream was given as the water level of dam. The simulation was gradually started from zero to design flood discharge with the soft start method. The water level at the upstream end was determined through backwater analysis, and the water level at the downstream of dam was assumed in Case 1 to be EL. 80.90 m (design flood level). In Cases 2 to 4, conditions were defined, assuming the use of lowered-water-level operation utilizing the free-flow condition, so that the water level was kept at EL. 79.91 m (free overflow level). For the purposes of the analysis, the FLOW-3D software developed by Flow Science, Inc. (USA) was used. The simulation time is about 0.8day by the workstation (64bit dual processor) for each cases.

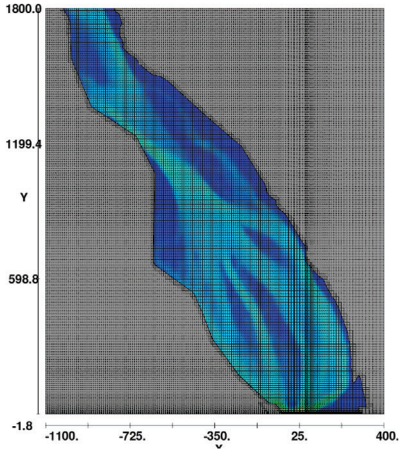

Figure 5. Numerical analysis mesh map

Table 2. Calculation conditions

Case	Bedform	Flood
Case-1	Present topography	2000m³/s
Case-2	Right bank channel case	(Design flood discharge)
Case-3	Straight channel case	
Case-4	Left bank channel case	

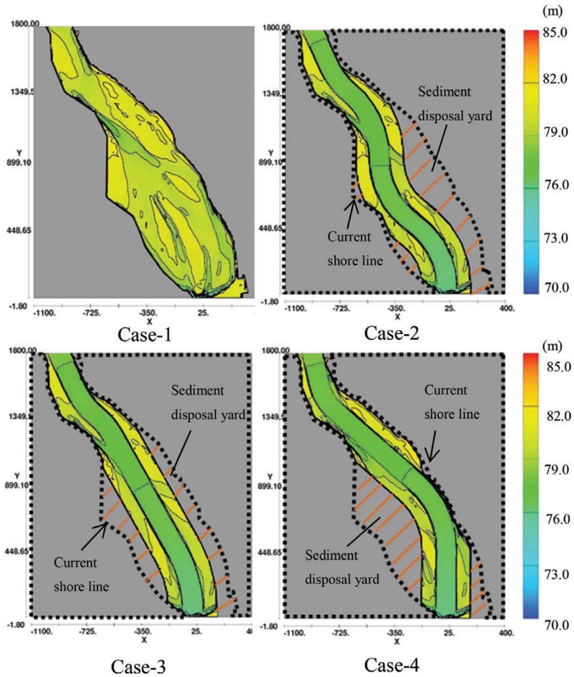

Figure 6. River bed height contour maps

4 FLOW REGIME ANALYSIS RESULTS

4.1 *Distribution in plain view of flow velocity*

Figure 7 shows the distribution in plain view of flow velocity in the surface layer (EL. 80.5 m) in each case. In the present topography case (Case 1), the channel downstream of the reservoir is wide and divided into subchannels and formed on reticulated streams by sediment deposits. Flow velocity, therefore, decreases in the lower half of the reservoir. In the right-bank case (Case 2), flow runs on the high-flow channel at places because of strongly curved sections for each side. Consequently, flow velocity changes at many locations. In the straight-channel case (Case 3), flow converges toward the mid-channel zone so that a uniform flow with relatively small amounts of fluctuations in velocity results. In the left-bank case (Case 4), flow convergence occurs more clearly than in Case 3, and the flow is stable.

4.2 *Cross-sectional distribution of flow velocity*

Figure 8 shows the cross-sectional flow velocity vectors in the near-gate regions and the resultant flow velocity contours in each case. The cross sections are seen to downstream. In the present topography case, flow with low velocity occurs throughout the reservoir. In the straight-channel case and the right-bank case, flows that move toward the left-bank side on the flood plane and run on the left flood plane are formed. It suggests that these flows may cause

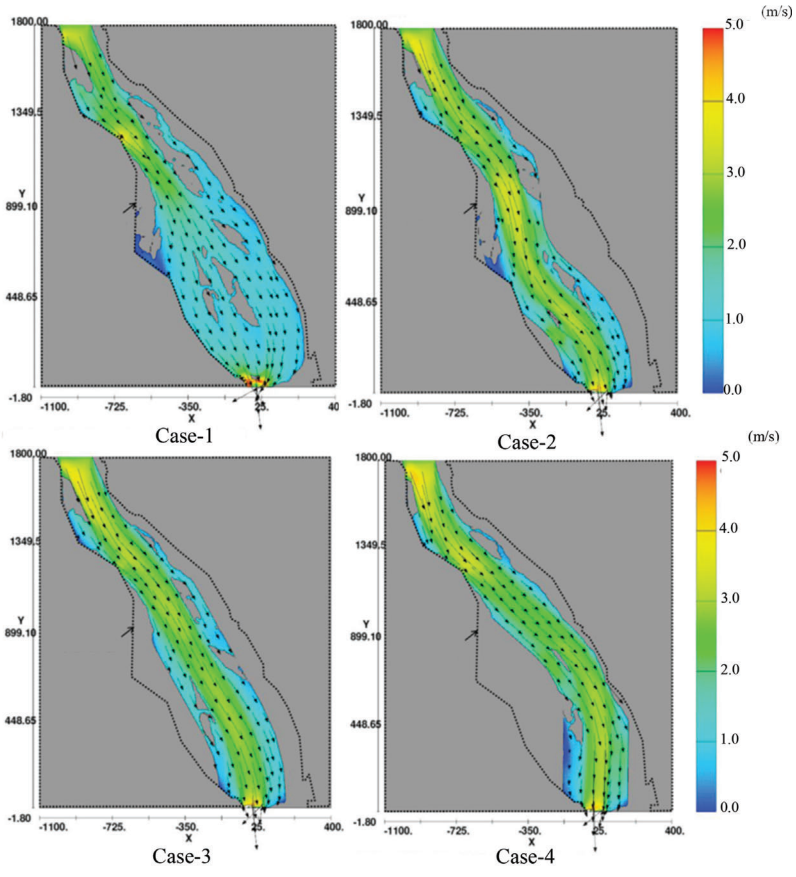

Figure 7. Surface flow velocity maps

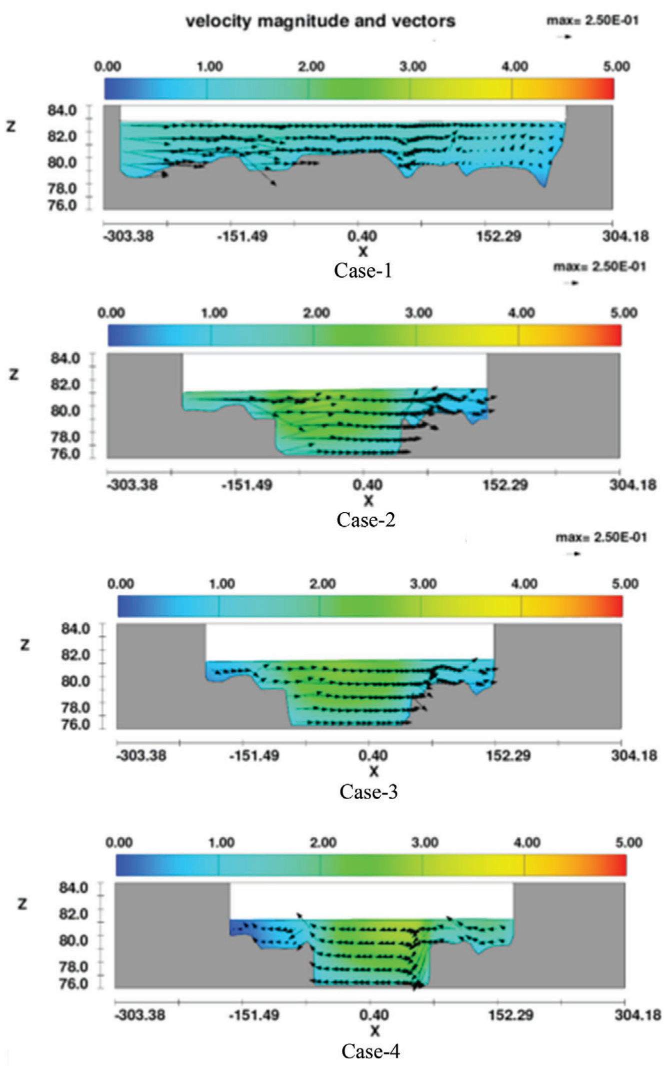

Figure 8. Cross-sectional flow velocity maps near spillway gates at the measurement line No.2

erosion at right-bank and sediment deposition on the left-bank side of the channel. In the left-bank case, flows that move toward the mid-channel zone are formed, indicating that these flows may cause the sediment deposited on the left-bank side to be retransported toward the mid-channel zone and then transported downstream.

4.3 *Distribution of bottom friction velocity*

Figure 9 shows the bottom friction velocity distribution in each case. In the present topography case, it can be inferred that sediment transport within the reservoir is likely to occur in a nonuniform manner so that a complex bedform results under the influence of sediment deposition and erosion. In the other three bedform improvement cases, sediment transport is likely to be accelerated in comparison with the present topography case because friction velocity in the channel is more or less uniform. Since the bottom friction velocity in the bedform improvement cases ranges from about 0.1 m/s to 0.2 m/s, it is thought likely, according to

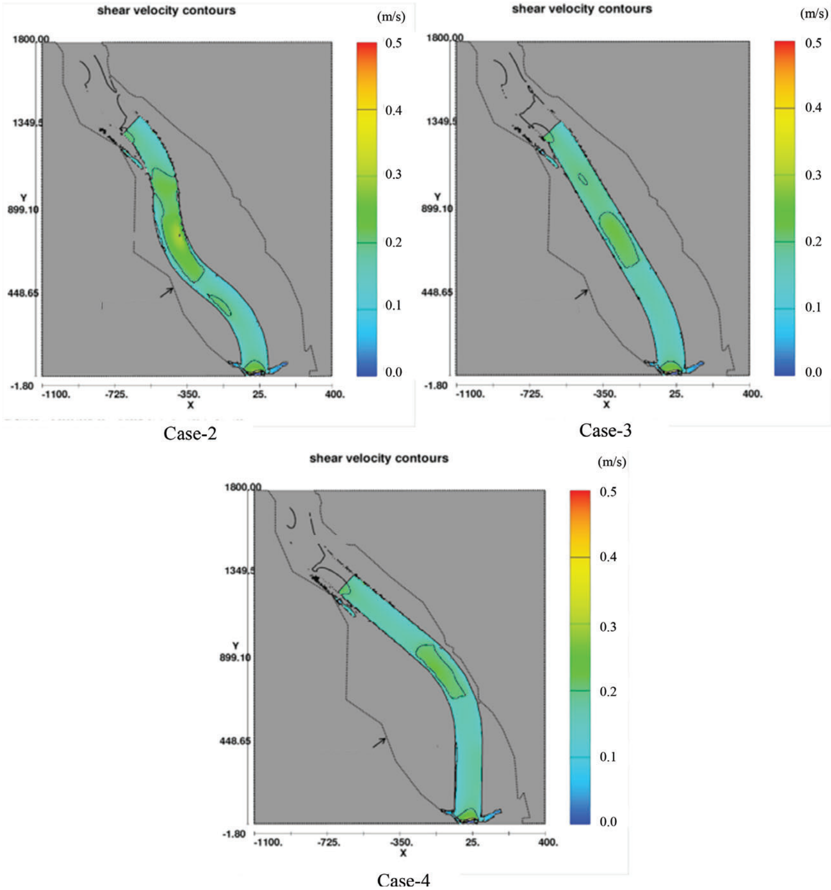

Figure 9. Bottom friction velocity maps

Iwagaki's formula, that sediment particles ranging in size from 12 to 50 mm will be transported downstream as bedload or suspended load (JSCE 1999).

5 HYDRAULIC SCALE MODEL EXPERIMENT

In the hydraulic scale model experiment, flow regimes and pre- and post-experiment riverbed conditions were compared between the present topography case and the three bedform improvement cases from the viewpoint of channel sustainability.

5.1 *Model and apparatus*

In the hydraulic model experiment, a distorted model made with a horizontal scale of 1/100 and a vertical scale of 1/50 was applied. The modeling was made according to the Froude similarity law for flow. The sediment material in the model will be too small and be clay material and cohesive material, because Senbiri reservoir is between 0.1mm to 2mm as D50. Therefore the sediment material in the model was also distorted by using the lighter weight material (Mesaraito, D50=0.7mm, dry density 1.3g/cm^3). Figure 10 shows a general view of the model. The structure of the model container is steel-framed, plywood-lined and waterproofed. The model bank protection was formed with crushed stone and mortar. The channel bed was

Figure 10. General view of hydraulic model

formed with light-gauge steel members. The model spillways and gates were fabricated with polyvinyl chloride. The model domain is a 5.5-km-long section upstream of the dam. Note that care needs to be taken in evaluating sediment movement results because not only geometric scale of the model but also scale of weight of sediment material was distorted (Suga et al 1990). Main measurement items are listed in Table 3.

5.2 *Experiment and study procedures*

The experiment was conducted by the following procedure:

Step 1: Experiment to simulate the present topography (discharge 2000 m^3/s)
Step 2: Experiment for bedform improvement cases (discharge 2000 m^3/s, 3 cases)

The average riverbed elevations determined from the 2017 land surveying results were used as initial conditions. In the experiment simulating the present topography, a design flood discharge of 2000 m^3/s was let to flow down for a long period of time, and the accuracy of simulation was evaluated by comparison with the land surveying results and other data such as aerial photographs. The equilibrium condition of riverbed was formed after the experimental time was 2 days (in the proto model) continuous of design flood discharge peak. In the experiment on the three bedform improvement alternatives, the upstream channel section was used

Table 3. Measurement items

Measurement items	Measuring instruments
Water level	Water gauge, Point gauge
Discharge	Electromagnetic flowmeter
Flow regime	Video camera, Camera
Riverbed condition	3D Laser scanner

in the simulation experiment, and the downstream channel section was formed according to each plan. Measurements were taken for flow regime and riverbed conditions, and the results were compared and evaluated.

6 EXPERIMENT RESULTS

6.1 *Riverbed conditions before and after experiment*

Figures 11 to 14 show photographs taken in each case before and after the experiment. Figure 15 shows the measurement results obtained with a three-dimensional laser scanner (RIEGL VZ-2000).

The photograph showing the present topography case taken after the experiment (Figure 11) shows channel formation on both the right-bank and left-bank sides. The photograph also shows sandbar formation at the center of the reservoir. From these results, it can be said that the present bedform is simulated with fairly good accuracy. As shown in Figure 12, in the right-bank case, considerable erosion and sediment deposition can be seen in

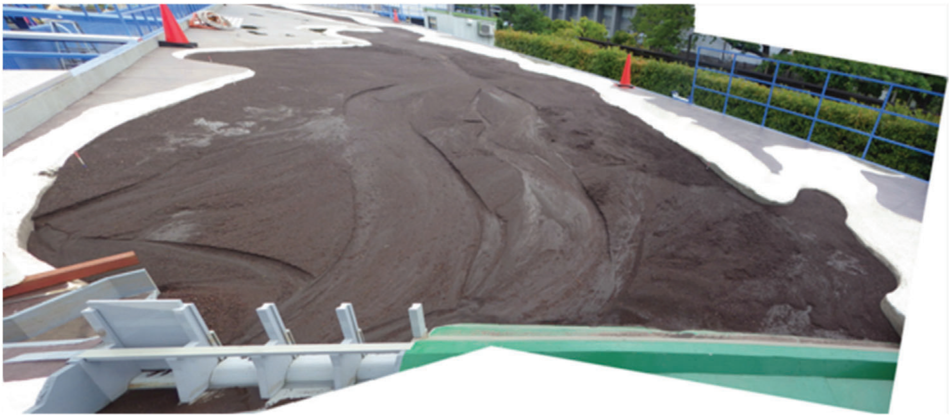

Figure 11. Riverbed after the flood (Case-1)

Figure 12. Riverbed before and after the flood (Case-2)

the high-flow and low-flow channels. From this, it can be said that there are considerable differences between the pre-experiment bedform and the post-experiment bedform. As shown in Figure 13, in the straight-channel case, the differences between the pre-experiment bedform and the post-experiment bedform are smaller than in the right-bank case, indicating that the flood flowed down smoothly without depositing sediment. As shown in Figure 14, in the left-bank case, more erosion and sediment deposition occurred than in the straight-channel case, and there are considerable differences between the pre-experiment bedform and the post-experiment bedform.

Figure 15 shows the riverbed fluctuation with colored deposition and erosion areas after flood. According to Figure 15, in the right-bank case, the sediment deposition rate tends to be high in the low-flow channel in the lower half of the reservoir. Erosion can also be seen along the banks in that region. In the straight-channel case, the sediment deposition rate is lower than in the right-bank case, and the bank erosion rate is also relatively low. In the left-bank case, the sediment deposition rate is high in the low-flow channel, and the erosion rate tends to be high in the bank zones and in the high-flow channel. The deposition was found in Case 2 and Case 3, and erosion was found in Case 4. The hydraulic model experiment showed that Left bank channel bedform, Case 4 flushed and passed through the reservoir during flood

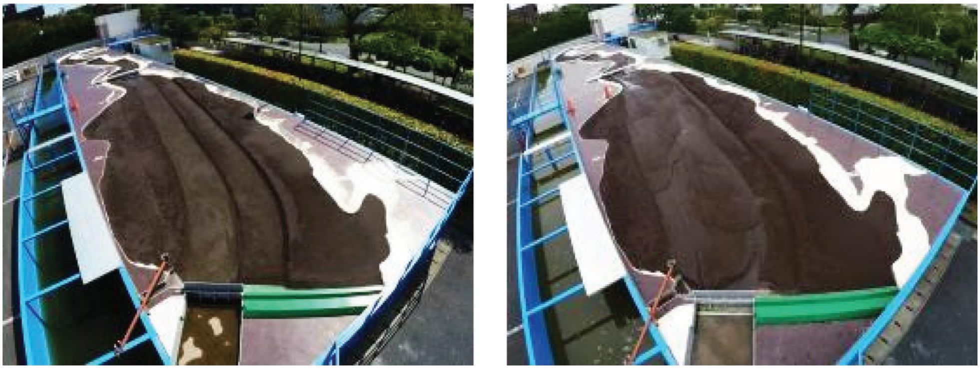

Figure 13. Riverbed before and after the flood (Case-3)

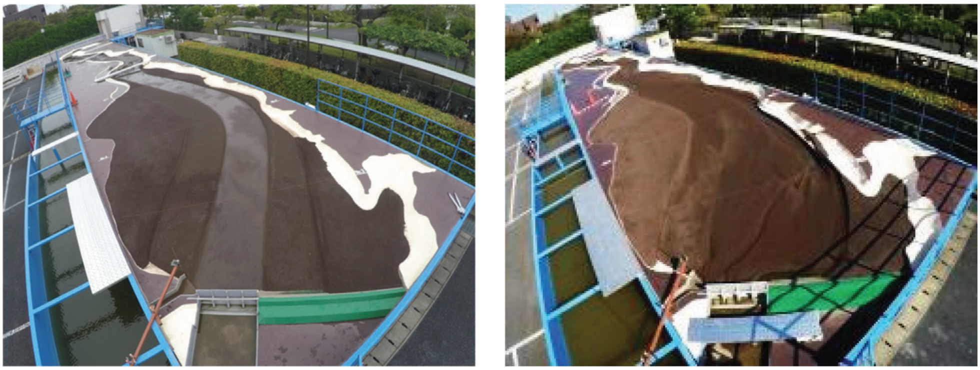

Figure 14. Riverbed before and after the flood (Case-4)

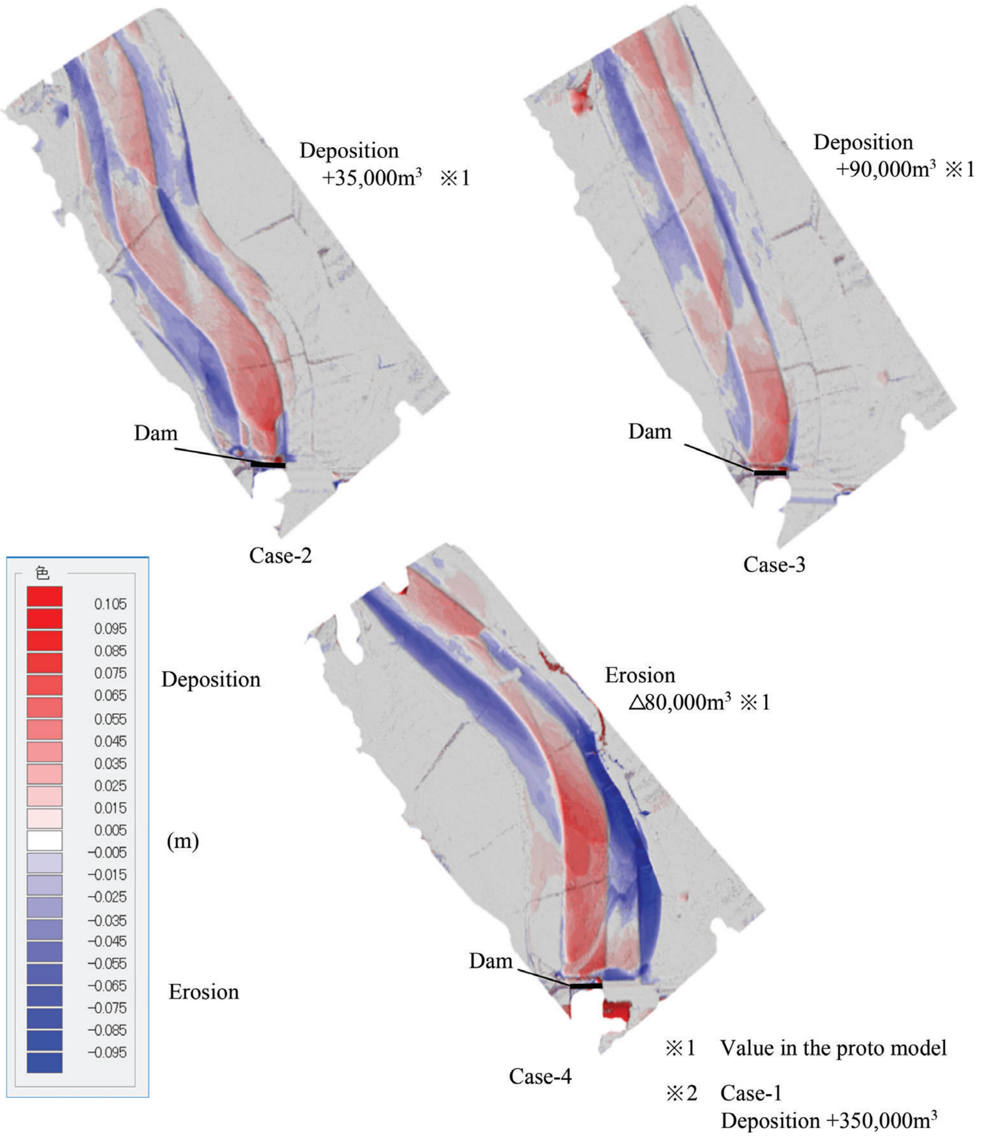

Figure 15. Riverbed fluctuation after the flood

period. This channel formation has the much closer tendency of original channel form without the dam (Sloff et al 2004).

7 CONCLUSIONS

In this study, a numerical analysis and a hydraulic model experiment were conducted to gain hydraulic knowledge needed to identify effective reservoir configurations that help increase the capacity to discharge sediment-laden floods at the Senbiri Dam. Main conclusions drawn from this study are as follows:

(1) The numerical analysis gives the idea for sediment movement in the reservoir through the horizontal and cross sectional flow velocity, and bottom friction velocity. It gives the idea of precise 3-dimentional flow structures in the reservoir for the initial condition of reservoir. Furthermore it is difficult to measure 3-dimentional flow in the hydraulic model experiment, but it gives clearly the process and result of sediment movement in the reservoir. They will interpolate to understand the flow and sediment phenomena well.
(2) The numerical analysis under the fixed-bed conditions showed that in times of sediment-laden flow, a better flow regime can be attained in the following order: left-bank case > straight-channel case > right-bank case.
(3) The hydraulic model experiment showed that the most effective configuration in maintaining channel geometry and creating a better flow regime in times of sediment-laden flow was the straight-channel case followed by the left-bank case and then the right-bank case. But the left-bank case showed the sediment flushing from the reservoir area, and it was the best case from the point of sediment flushing volume.
(4) The present bedform allows sediment deposition in the reservoir because of in-channel obstacles such as sandbars and flow velocity fluctuations. Because of complex patterns of sediment deposition, the present bedform cannot be expected to contribute to smooth discharge of flood flows. It will carry more sedimentation without measures.
(5) Flushing efficiency also greatly differs for the geometry of sediment channel. The suitable geometry of channel is close to the original and natural channel form without the dam in order to conduct flushing and passing sediment through the reservoir.
(6) Finally the numerical analysis and hydraulic model experiment showed for managing of sedimentation in reservoirs that there is to exist the suitable shape of artificial sediment channel which smoothly flush the sediment and pass effectively through the reservoir during flood period.

The experiment in this study was conducted without sediment supply. As a next step, therefore, the authors intend to make further evaluation through experimentation taking account of sediment inflow.

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