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Study on Flushing Mechanism of Dam Reservoir Sedimentation and Recovery of Riffle-Pool in Downstream Reach by a Flushing Bypass Tunnel

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ABSTRACT:
In the Asahi River, riffles and pools had been scaled down in the downstream reach of Asahi Dam due to sediment deposition in Asahi Dam reservoir. To improve this environmental problem, a flushing sediment tunnel was constructed so as to bypass Asahi Dam reservoir. In this study, first, the authors demonstrated the recovery of riffles and pools and the grain size distribution in the downstream reach by using the data of cross-sectional surveying, air photographs and field investigation. Next, authors' two-dimensional model was applied to a series of flood events in the Asahi River. As a result, the flushing mechanism of Asahi Dam reservoir sedimentation, the recovery process of riffles and pools and the change in grain size distribution in the downstream reach were clarified by the model.

Keywords: Flushing Sediment Bypass Tunnel, Riffle and Pool, Numerical Model, Sediment Transport, Grain Size Distribution

1. INTRODUCTION

Sandbars, riffles and pools characterized in the meandering channel were seen in the Asahi River of the Shingu River system, Nara Prefecture. However, in association with Asahi Dam constructed in 1978, some problems had occurred such as occurrence of the long-term turbid water, sediment deposition in the dam reservoir and scale-down of riffles and pools in the downstream reach of Asahi Dam. Moreover, since granitic white stones yielded from the upstream of Asahi Dam had not been transported to the downstream, white sandbars which characterizes the Asahi River had been hardly seen in the downstream reach. To improve these environmental problems, a flushing sediment tunnel was constructed so as to bypass Asahi Dam reservoir in 1998. Sediments including white stones have been transported effectively through the bypass tunnel to the downstream of the dam, and so riffles and pools in the downstream reach have gradually come to the condition before the dam construction. To develop a numerical model explaining flood flow and sediment transport through the bypass tunnel is important for the design of structures for flushing sediment from other dam reservoir where sediment deposition is serious.
The Asahi River is a stony-bed river with a wide range of grain size distribution from boulder to sand. Thus, the recovery of riffles-pools and grain size distribution in the downstream of the dam must be reproduced by a numerical model which describes proper sediment transport and riverbed variation in the stony-bed rivers. Osada and Fukuoka (2010, 2011) have developed a new two-dimensional model for estimation of riverbed variation by considering sediment transport mechanism and bed surface unevenness in the stony-bed river. Availability of this model was verified with the results of the field experiments carried out in the Jyoganji River. It was clarified that the model is capable of explaining sediment transport and grain size distribution in stony-bed rivers.

In this study, first, the authors demonstrated the recovery of riffles and pools by using the data of cross-sectional surveying, air photographs and field investigation in the Asahi River. Next, authors' two-dimensional model is applied to a series of flood events in the Asahi River. Calculated results such as flood flows, sediment transport, riverbed variation and grain size distribution as well as recovery process of riffles and pools are verified by respective observed data.

2. RECOVERY OF RIFFUL AND POOL IN THE DOWNSTREAM REACH OF ASAHI DAM

2.1. Outline of the Asahi River and the Flushing Bypass Tunnel

Figure 1 shows the Asahi River basin and the flushing bypass tunnel of Asahi Dam. Asahi dam has been

Figure 1. (Left) Asahi River Basin (Right) Plan View of the Flushing Bypass Tunnel

Figure 2. (Left) Entrance Viewed from Upstream (Right) Exit of Bypass Tunnel

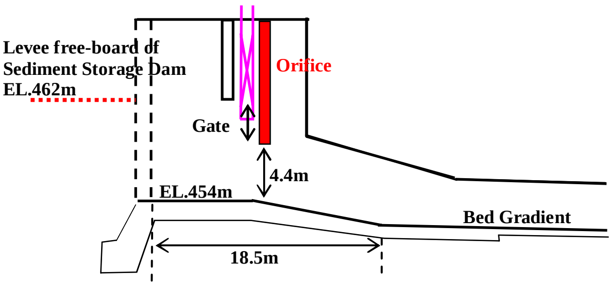
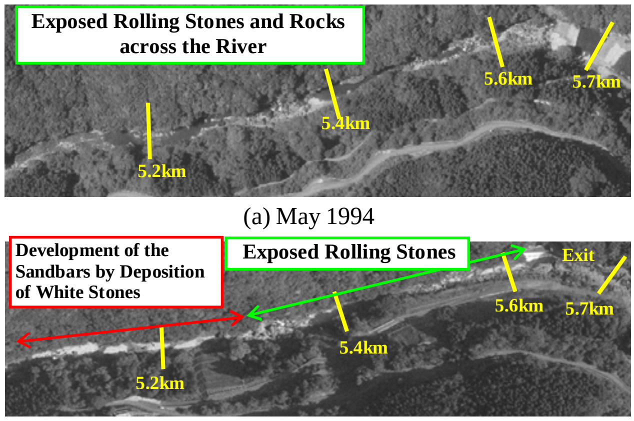


Figure 3. Structure of the Entrance

operated from 1978 as the lower reservoir of the pumped-storage power generation dam located at 6.0km section in the Asahi River. The flushing bypass tunnel was constructed in 1998 to mitigate the long-term turbid water, to reduce the sediment deposition in the reservoir and to recover the riffles and pools in the downstream reach. The flushing bypass tunnel is a 2,350m long, 3.8m wide and 1:35 bed gradient. Figure 2 shows the entrance and exit of the flushing bypass tunnel. At the entrance, a sediment storage dam was constructed in order to prevent sediment flowing into the reservoir. Figure 3 shows an entrance structure. An orifice has been constructed at the entrance. When the discharge from upstream is greater than 120m^3/s, orifice flow occurs and prevent the clogging by the sediment deposition in the flushing bypass tunnel.

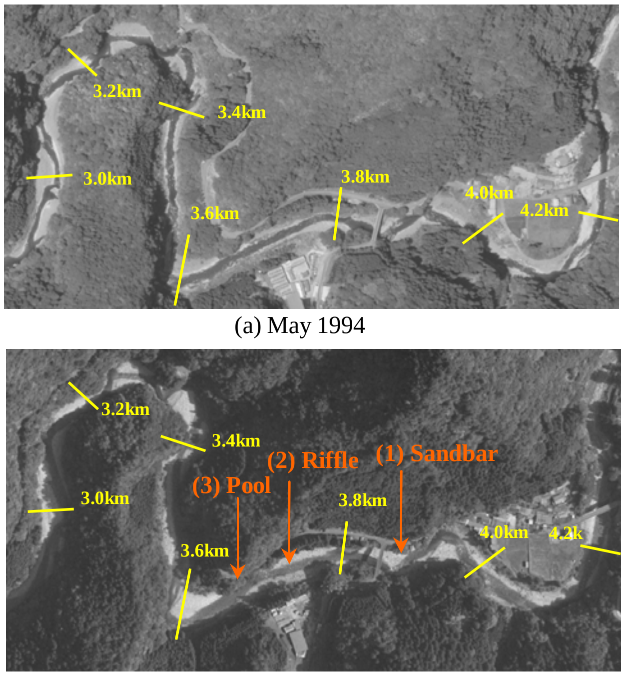
In the upstream of the entrance, the bed gradient was 1:45 before the dam construction. However, since the sediment deposition into the dam reservoir had occurred after the dam construction, bed gradient had come to be low gradient, approximately 1:75. In the downstream reach from just downstream of Asahi Dam to 5.0km section, the bed gradient is steep slope (1:36), and the bed gradient downstream of 5.0km section is 1:100 on the average.



(a) May 1994

(b) May 2004

Figure 4. River Situation Just Downstream of the Dam



(a) May 1994

(b) May 2004

Figure 5. River Situation from 3.0km to 4.5km

2.2. Change of Channel Condition Due to Sediment Flushing in the Downstream Reach

Figures 4 and 5 show air photographs of the downstream reach taken before and after the construction of the flushing bypass tunnel (May 1994, May 2004). Figure 4 shows the channel situation just downstream of Asahi Dam. In 1994, the riverbed are visible to gray, and white

(a) White Stones deposited on Sandbar ((1) in Fig. 5)

(b) Riffle ((2) in Fig. 5)

(c) Pool ((3) in Fig. 5)

Figure 6. Close-up View of Sandbar, Riffle and Pool

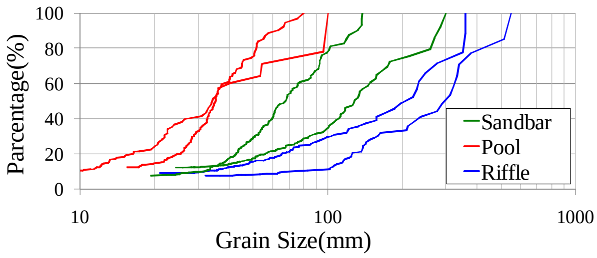


Figure 7. Grain Size Distributions of Sandbar, Riffle and Pool

stones are not seen on the riverbed, since many rolling stones and rocks of the sedimentary rock which are substratum in this reach are exposed. In 2004, many rolling stones and rocks are seen in the upstream reach of 5.3km section, on the other hand, white stones discharged through the flushing bypass tunnel had deposited, and alternate bars had developed downstream of 5.3km section. Figure 5 shows the channel situation from 3.0km to 4.5km section. In 1994, flow channel looks like a straight line all over the reach, and riffles and pools are rarely seen. In this reach, rolling stones are smaller in size than that just downstream of the dam, and riverbeds are visible to gray in colour. It is considered that riverbed materials were composed of the sedimentary rocks. In 2004, deposition of white stones are seen on sandbars. Riffles and pools are recovered by the development of sandbars. Figure 6(a)~(c) are close-up views of sandbar, riffle and pool shown in Fig. 5(b), May 2011. Figure 7 shows the grain size distributions on the bed surface measured at sandbars, riffles and pools in May 2011. In Fig. 6(a), black stones seen in the right part are the sedimentary rock, and white stones deposit on the black stones. Since the riffle has usually high flow velocity, white stones (less than 150mm) are rarely seen and bed materials on the surface are composed large black stones of the sedimentary rock. Pools are located at the front of projected rock and outer bank of meandering channel as in Fig. 6(c). White stones are seen on the bed surface of pools, and the bed material

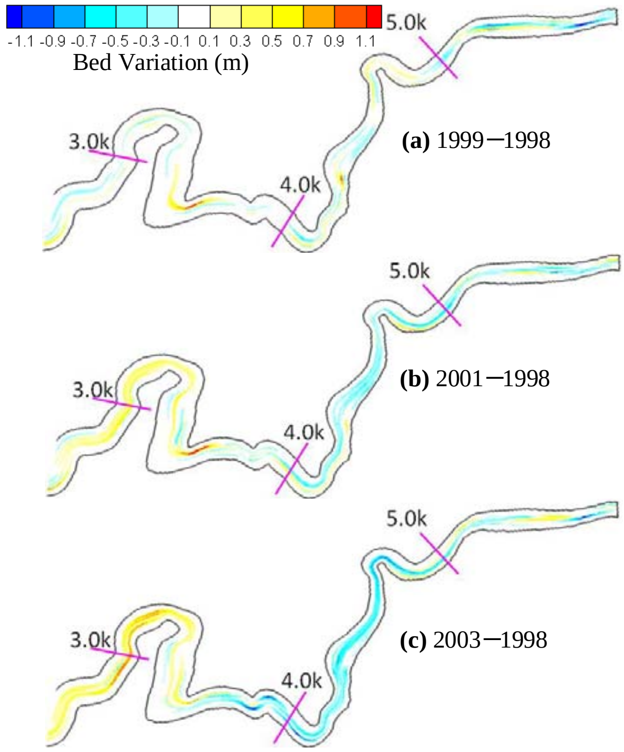


Figure 8. Riverbed Variation in the Downstream of the Dam (Based on 1998)

size are smaller than that of sandbars and riffles. From the result of the field investigation, bed materials at riffles have been composed of coarse sediments of the sedimentary rock, and white stones are not easily deposited there. In contrast, white stones are easily remained in pools.

Figure 8 shows riverbed variation from bed elevation measured in 1998. Figure 8(c) corresponds to the situation of Fig. 4(b) and Fig. 5(b) taken May 2004. Flood peak discharges beyond 250m^3/s in 2001 and 2003 seem to cause larger riverbed variation and riverbed degrades from 3.8km to 5.0km and aggrades downstream of 3.8km.

3. NUMERICAL MODEL AND ANALYSIS CONDITION

The authors investigate effects of the bypass tunnel and how riverbed and grain size distribution recovered by using the numerical model. The numerical model combined unsteady two-dimensional flood flow analysis with two-dimensional riverbed variation analysis for stony-bed rivers has been developed by Osada and Fukuoka (2010, 2011). This model is constructed by focusing on sediment transport mechanism and bed surface unevenness in stony bed rivers. The detail of the model was explained in the Osada and Fukuoka's paper (2010).

The analysis was performed from the junction with the Kumano River to 2km upstream of the entrance as shown in Fig. 1(Right). Cross-sectional forms observed in 1998 were used to the initial form for the computation. The numerical model was applied to floods occurred from 1999 to 2003. Water level and discharge have been measured at observation stations upstream and downstream of the dam. Discharges from the flushing bypass tunnel and gates of the dam have also been observed. The upstream boundary condition was given by observed discharge hydrographs, and the downstream boundary condition given the uniform flow depth because water level had not been observed near the downstream end. Figure 9 shows computational grids at the area of the entrance and exit. To take into account the shape of the entrance and exit, the computational grid was developed more in detail than that of other area. The resistance of the orifice constructed at the entrance was given by the drag force so as to minimize difference between observed and calculated discharge hydrographs through the bypass tunnel. Figure 10 shows the grain size distribution observed upstream and downstream of the dam. Initial grain size distribution used for calculation was determined based on observed data as shown in Fig. 10. Equilibrium sediment transport was given as the upstream boundary condition.

4. RESULT OF ANALYSIS AND CONSIDERATION

Figure 11 shows calculated and observed hydrographs of upstream flood discharge and flow and sediment discharge through the flushing bypass tunnel from 1999 to 2003. Figure 11 also shows total discharge hydrograph from the bypass tunnel and the gates of Asahi Dam. The result of the analysis shows that large amount of sediments was discharged through the bypass tunnel not in the orifice flow period but recession period when flood discharge is less than 70m^3/s. This phenomenon was also demonstrated by Harada et al. (1998) by the laboratory bypass tunnel experiment. Figure 12 shows riverbed variation in the upstream of the entrance during the second flood in 2001. Figure 13 shows longitudinal water level and riverbed elevation profiles upstream of the entrance each time ((A)~(D)) shown in Fig. 11. Time in Fig. 13(B) displays as orifice flow. The water level upstream of the entrance was nearly constant and stones and gravel were not transported near the entrance but deposited in the sediment storage reservoir. At the time (C), water surface slope varied to the steep slope, and sediment deposited upstream entrance was transported to the entrance. Riverbed elevation profile at that time is shown in Fig. 12(b). In the time between (C) and (D), the water surface profile just upstream of the entrance was steep, then, large amount of stones and gravel deposited

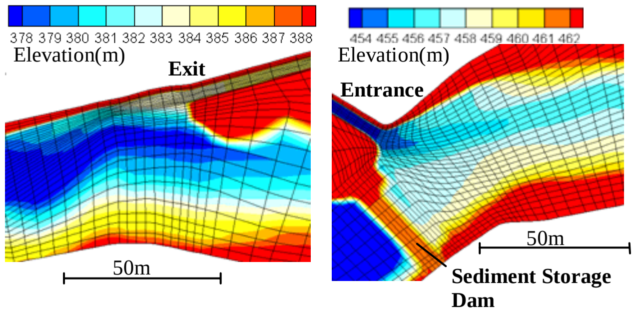


Figure 9. Computational Grid (Left)Exit (Right)Entrance

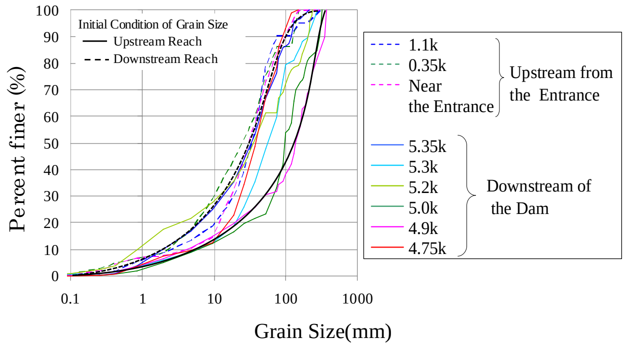


Figure 10. Grain Size Distribution Used for Calculation

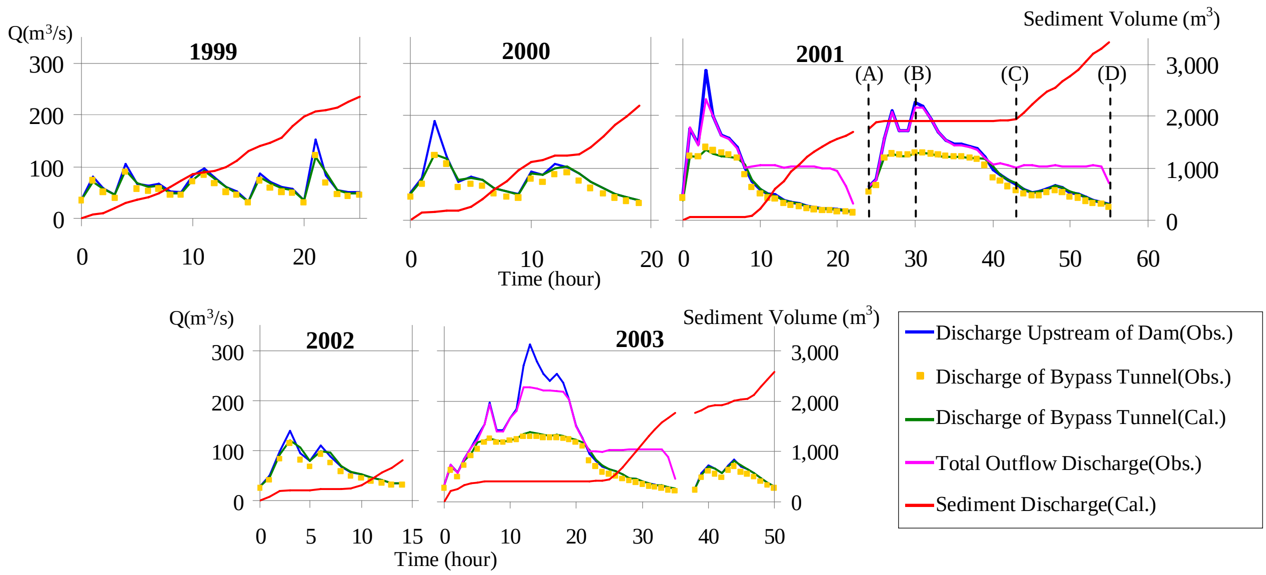
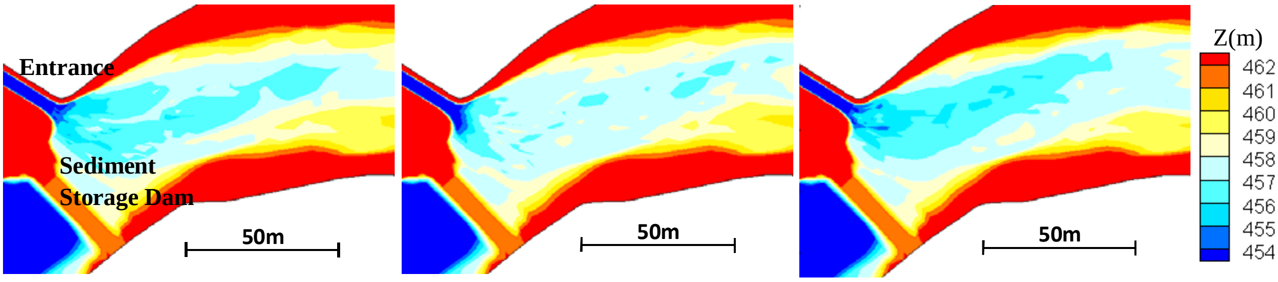


Figure 11. The Relationship between Flood Discharge Hydrograph and Sediment Discharge Volume



(a) Bigining of Second Flood in 2001 (**Figure 11.** (A))
(b) After 19 Hours, Second Flood in 2001 (**Figure 11.** (C))
(c) After 32 Hours, Second Flood in 2001 (**Figure 11.** (D))

Figure 12. Time Variation of the Bed Elevation Upstream of the Entrance (Second Flood in 2001)

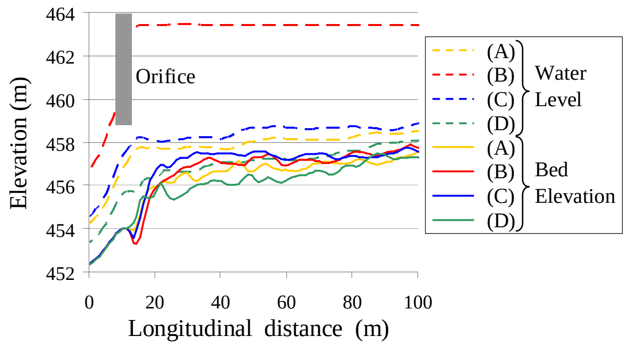


Figure 13. Variation of Water Level, Bed Elevation , Second Flood in 2001 ((A)-(D) correspond to the times indicated in Fig. 11.**)**

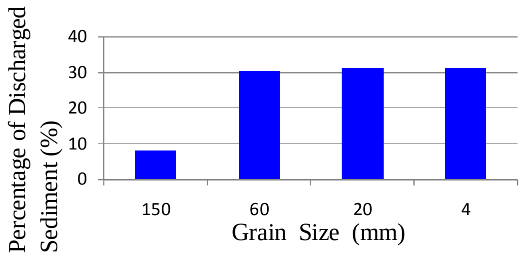


Figure14. Percentage of Each Grain Size in Discharged Sediments

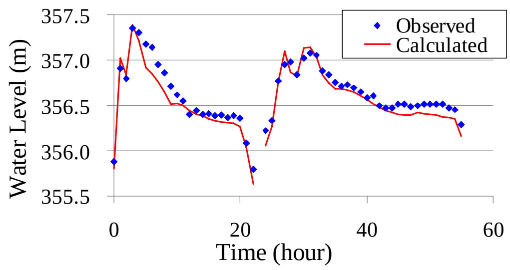


Figure 15. Water Level Hydrographs at the Downstream Observation Stations (4.3km) in 2001

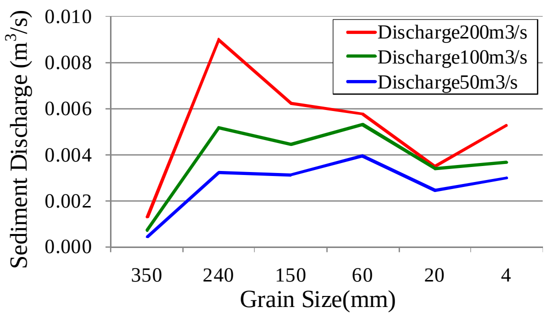


Figure 16. Sediment Discharge of Each Grain Size Associated with change in Flow Conditions

was discharged from the bypass tunnel. Then, bed elevation profiles varied from Fig. 12(b) to Fig. 12(c). The riverbed elevation profile upstream of the entrance was almost the same before and after the floods. It demonstrates that the flushing bypass tunnel displays a good performance. Figure 14 shows the percentage of each grain size in discharged sediments. The stone-class material of 150mm of 8%, and the other grain sizes of 30% were contained in them. These percentages are almost the same as the grain size distribution of initial condition upstream of the dam, thus each grain size group upstream of the dam were properly transported in the downstream river.

Figure 15 shows the comparison with observed and calculated water level hydrographs at 4.3km section. Although the calculated water level hydrographs were estimated slightly low as compared to the observed data in the recession period of the floods, calculated results were able to reproduce the observed data. Figure 16 shows sediment discharge of each grain size group in different flow conditions. These data are the calculated results averaged from 3.0km to 4.0km sections. When the discharge is 200m^3/s, stone-class materials (d > 75mm) are actively transported in comparison with gravel-class materials, and large stones such as rolling stones (d=240mm, 340mm) can also be transported. When the peak discharge was larger than 200m^3/s, outflow discharge is limited by 100m^3/s to regulate the water level in the reservoir as shown in Fig. 11. Sediment transport rate in 100m^3/s was less than that in 200m^3/s. However, the grain size group from 240mm to 60mm were actively transported as shown in Fig. 16. White stone materials (d < 150mm) can be transported enough by 100m^3/s. In case of 50m^3/s, 60mm gravel-class group was mainly transported.

Figure 17 shows calculated riverbed variation corresponding to observed one shown in Fig. 8. The calculated results reproduce the processes of shifting of deposition area to the downstream and development of bed scouring from 4km to 5km, but calculated

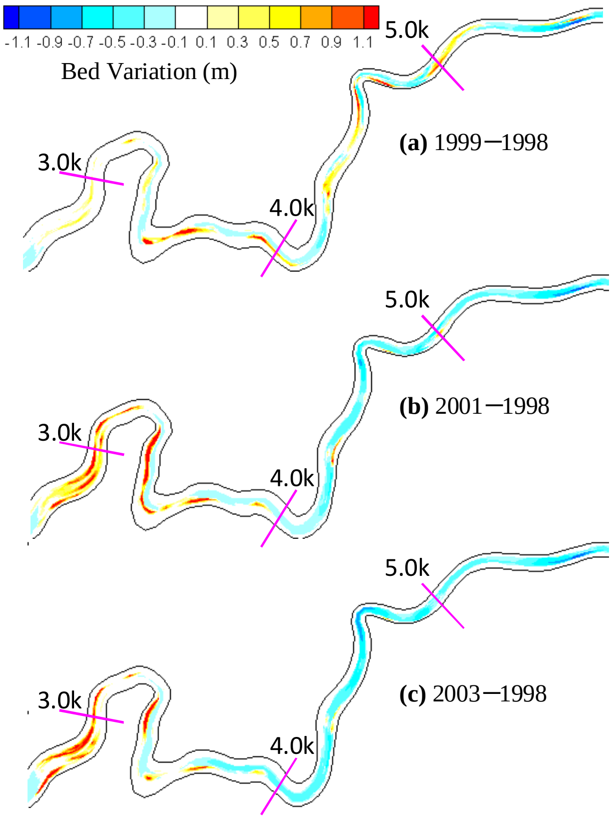


Figure 17. Calculated Riverbed Variation in the Downstream of the Dam

sedimentation distribution in the downstream from 3.6km differs from observed result. Figure 8 shows that sediment from upstream deposited in this reach, but calculated sediments deposited intensively in the inner bank side of meander reaches. There are a lot of rock projections and narrow sections in this reach, while the numerical model is not considered enough these influences on sediment transport.

Figure 18 shows the distribution height of the sediment deposition discharged through the flushing bypass tunnel from 1999 to 2003. Figure 19 shows distribution of calculated mean grain diameter after 2003 floods. Since the initial condition of mean grain diameter was 160mm, the blue colours indicate grain size reduction and red colours armouring. Flushing sediments deposited mainly around 5.0km and in the downstream reach of 3.6km. Figure 5(b) shows that a large amount of depositing white stones is found in the downstream reach of 3.6km. The discharged sediment through the bypass tunnel until 2003 had been mainly deposited in this reach. It is considered that the sediments tend to deposit around 5.0km because river bed slope changes around this reach. Although sandbars by the deposition of white stones around 5.2km had been formed, the calculation could not describe it. The calculated result of mean grain diameter distribution downstream of 3.6km except for few points demonstrates grain size reduction due to deposition of white stones. On the other hand, white stones are hardly seen in riffles (e.g. around 4.2km and 3.7km) as shown by red circles in Fig. 18. Since white stone was not also

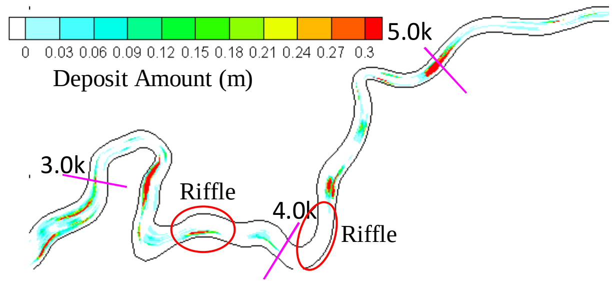


Figure 18. Distribution height of Sediment Deposition, 1999~2003

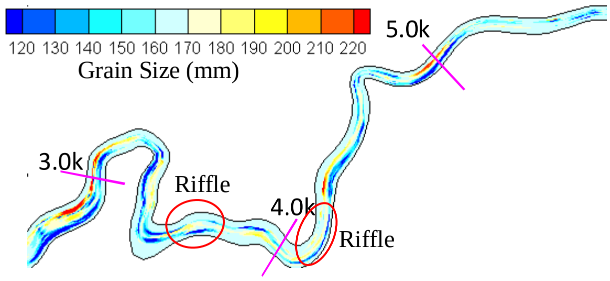


Figure 19. Distribution of Calculated Mean Grain Diameter, 2003

seen in the actual riffles in Fig. 6(b), calculated results seem to reproduce bed conditions.

As above, it was clarified that the numerical model is capable of explaining quantity and quality of sediment flushed by the bypass tunnel, development of sandbar and recovery of riffles and pools in the downstream reach in the Asahi River.

5. CONCLUSION

To elucidate mechanism of sediment flushing by bypass tunnel of Asahi Dam, development of riffles and pools and change in grain size distribution downstream of the dam were studied by using the field investigation data and the numerical model. The numerical model gave a good explanation for the mechanism of sediment flushing by the bypass tunnel and the processes of recovery of riffles and pools and change in grain size distribution by deposition of white stones in the downstream reach.

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