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Geomorphic response of rivers below dams by sediment replenishment technique

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ABSTRACT: Sedimentation problems on regulated rivers are considerably different from natural rivers. An effective means of reservoir sediment management is to excavate deposited sediments within reservoir and transport to the river downstream of a dam. The flood is designed to erode the placed sediment at the banks of Nunome River, in an effort to restore the lower reach of the river to a more natural ecosystem. Since 2004, six attempts of sediment replenishment to rebuilding vital sediment sand bars below Nunome dam are in progressing. Monitoring measurements pre- and post- replenishment show the effect of improvements in riverbed formation, grain size distribution, and erosion processes. Actual field experiments are presented and compared with scaled laboratory experiments, with the objective of identifying parameters and process of sediment replenishment characteristics. The paper investigates the influence of sediment replenishment below Nunome Dam on changes of river bed. Appropriate sediment materials, which are excavated and treated from the upper part of the Nunome reservoir, and supplied to downstream rivers contributes to rebuilt sand bars, mitigate the armouring of river bed, and management of reservoir sedimentation. With the field experiments, the processes are directly visible and a wealth of valuable data is obtained, and will be used for numerical modeling in future application.

Keywords: Dam impacts, Reservoir sediment replenishment, Sediment management, River restoration, Revitalization of regulated rivers, Sediment feeding, Geomorphic response

1 INTRODUCTION

1.1 *Dam Impacts*

Dams greatly influence flow and sediment discharge regimes and can have significant impacts on downstream reaches below dam. Bed load sediment management is required to preserve the capabilities of water resources facilities and to conserve the environment in rivers downstream of the reservoir. The sediment deficit produces a large variety of physical, ecological and environmental effects. To mitigate that coarse sediments, by grain diameter, with specific grain size distributions artificially replenished to satisfy the river bed load capacity (sediment replenishment). Figure 1 classifies the impacts of sediment deficit below dams to three groups; morphological, hydrological, and ecological effects. Sediment deficit is not only an environmental issue but also a socio-economic problem, for instance due to loss of reservoir capacity (Fan and Springer, 1993).

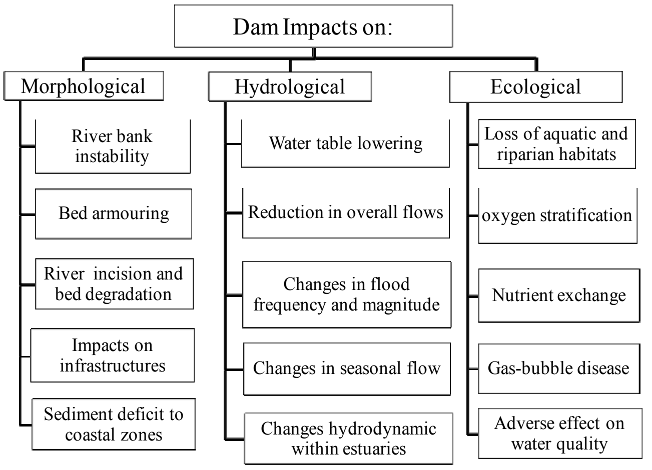

Figure 1. Possible impacts due to lack of sediment transport in the downstream reach below dams

In addition, dams alter the downstream flow regime of rivers (Williams and Wolman, 1984), which controls many physical and ecological aspects of river form and processes, including sediment transport and nutrient exchange (Poff et al., 1997). Morphological effects on the river channel (e.g., Kondolf and Matthews, 1993; Shields et al., 2000) that includes riverbed incision, riverbank instability, upstream erosion in tributaries, damage to bridges, embankments and levees (e.g., Kondolf, 1997), and changes in channel width (e.g., Wilcock et al., 1996). Hydrological effects caused by dams include changes in flood frequency and magnitude, reduction in overall flows, changes in seasonal flows, and altered timing of releases (Ligon et al., 1995).

1.2 *Sediment Replenishment Projects in Japan*

Large Japanese rivers are often trained to a large extent, to maintain services such as navigation, hydropower generation and flood defense. Okano et al., (2004) summarized sediment replenishment projects in Japanese Rivers, such as Tenryu, Otakine, Abukuma, Ara, Oi, Naka, Kuzuryu, Yodo, Kanna, and Tone, have been conducted by Ministry of Land, Infrastructure and Transport (MLIT). Kantoush et al. (2010) investigated the morphological evolution and corresponding flow field during replenishment experiments in Uda River, Japan. Sediment treatment system is applied by Sumi et al. (2009), to produce appropriate grain sized material with less turbidity. Seto et al. (2009), analyzed sediment replenishment effects on the downstream river of Yahagi dam.

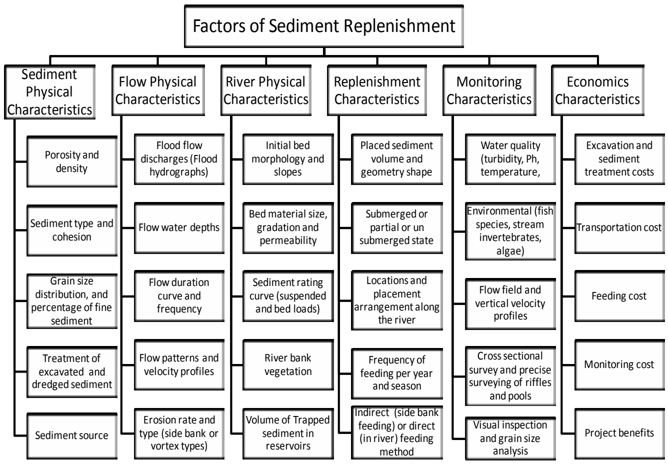

Figure 2. Main groups of sediment replenishment characteristics and managing factors

Sediment transport and associated channel bed mobility are recognized as key processes for creating and maintaining physical habitats, aquatic and riparian ecosystems. In Japan, sediment replenishment projects are undertaking with different configurations and characteristics of sediment and discharges. Figure 2 summarizes factors that influence the sediment replenishment research. These factors are classified in six groups as shown in Figure 2. Several significant gaps in the scientific understanding of these processes remain, particularly concerning how riverbed deposition and geometry are influenced by variability in water and sediment release. Sediment replenishment scenarios may, induce undesirable morphological and ecological consequences as well as significant channel adjustments that can result in failure of the restoration project itself. That is, it is necessary to better understand reversibility, direction and time scale of changes, and the sustainability of a replenishment intervention before it is implemented.

1.3 *Objectives*

The study focuses on the design criteria for sediment replenishment project in Japan to improve river bed conditions. The investigations are based on field and laboratory experiments. The objectives of this paper are: (a) to make a general review of impacts of dam on downstream reach; (b) to discuss the role of different factors influencing the sediment replenishment research; (c) to illustrate and analyze the sediment replenishment through a regulated fluvial system during actual field tests.

2 FIELD EXPERIMENTS FOR SEDIMENT REPLENISHMENT IN NUNOME RIVER

2.1 *Test Procedure and Replenishing Concept*

In Japan, it is common practice to remove accumulated coarse sediment by excavation and dredging, and to make effective use of the removed sediment. Sediment replenishment method is one of new measures of sediment management. In this method, trapped sediment is periodically excavated and then transported to be placed temporarily downstream of the dam. In a manner decided according to the sediment transport capacity of the channel and the environmental conditions. Therefore, the sediment is returned to the channel downstream in the natural flooding processes. The procedure of the experiments consists of four steps: (1) extracting mechanically the accumulated sediment at check dam; (2) transporting it by truck to downstream river; (3) placing the sediment with specific geometry (Figure 3), and (4) monitoring flow, sediment, and environmental parameters.

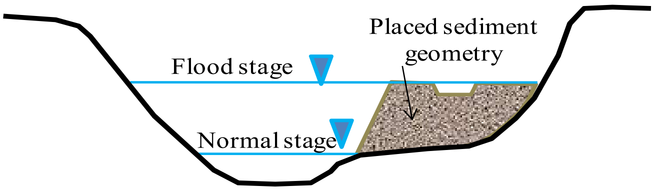

Figure 3. Concept of sediment replenishment and placed sediment geometry on the bank of Nunome River

The replenished sediment is placed at such an elevation; in order to reduce the turbidity during normal flow period. The top of the sediment is adjusted so that the sediment is completely submerged during flood at several times a year and all sediment is eventually transported downstream (Figure 3). Concrete means are being explored, taking into consideration the particle sizes of sediment, such as the scale of flood suitable for the safe implementation, and appropriate ways to place sediment.

2.2 *The Study Area*

Yodo River (Yodo-gawa) system is 75 km in length, located in the central part of Japan, is the seventh largest river basin in Japan with a catchment area of 8,240 km^2. Flowing south out of Lake Biwa first as the Seta River, and then the Uji River, it merges with the Kizu and Katsura Rivers near the border between Kyoto and Osaka Prefectures. There are five completed dams in the Kizu River System, Nunome, Shourenji, Hinachi, Takayama, and Murou dams. Nunome dam is a gravity dam for flood control and water supply, completed on 1994, 16 years ago.

2.3 *Cumulative Sediment in Kizu River Upstream Reservoirs*

Dam reservoirs are normally designed to have a capacity to store 100 years, worth of sediment in the deepest parts close to the dams. Sediment accumulation in the Kizu River upstream group dams up to the end of fiscal 2006 are shown in Table 1. The table shows that sedimentation in all five dams has progressed faster than that of the original plan. In Japan, the planned sedimentation capacity is set by the sedimentation of 100 years. Sedimentation of Nunome dam has already reached 12 to 18% of planned sedimentation. Regarding annual fluctuation of sediment load of Nunome dam, maximum annual sedimentation in a single year is 230,000 m^3.

Table 1. Sedimentation rate of Kizu River upstream dams

Name of Dam	Elapsed time (Years)	Planned sedimentation capacity in 100 years (MCM)*	Actual sedimentation in 2006 (MCM)*	Sedimentation rate (%)
Nunome	16	1.9	0.243	12.8
Shorenji	36	3.4	1.484	43.6
Murou	32	2.6	1.12	43.1
Hinachi	9	2.4	0.41	17.1
Takayama	37	7.6	3.648	48.1

* MCM is Million Cubic Meter

2.4 *Case Study of Nunome Dam Actual Sediment Replenishment Tests*

Since 2004, six experiments of sediment replenishment projects with different sediment volumes are undertaken below Nunome dam. Tracking the history and performance of these projects is helping to understand the evolution of sandbars. Table 2 summarizes the replenishment history, flushing flow and sediments characteristics. The volume of placed sediment is limited to several hundreds of cubic meters each time. To implement this method, consideration has to be given to environmental problems in the lower river basins, to the occurrence of turbid water, and to safety risks due to sediment deposition in the channel. The data in Table 2 indicates that there is a need to increase the amount of the supplied sediments in Nunome River every year.

Table 2. History of the sediment replenishment tests downstream of Nunome dam

Year	Setting sediment period	Flood period	Volume of remained sediment (m^3)	Volume of placed sediment (m^3)	Volume of eroded sediment (m^3)
2004	28-9-2004	29-9-2004	0	190	190
2005	9-8-2005	4, 5-10-2005	0	540	80
2006	NA	19, 21-7-2006	460	0	370
2007	9-8-2007	23, 29-8-2007	90	720	810
2008	27-6-2008	8-7-2008	0	100	35
	7-8-2008	5, 19 -9-2008	0*	100	100
	12-11-2008	NA	0	500	0
2009	NA	2-8-2009	500	0	500
	2-10-2009	7,8-10-2009	0	500	500

* The remained 65 m^3 sediment is removed. NA: No placed sediment or No flood occurred

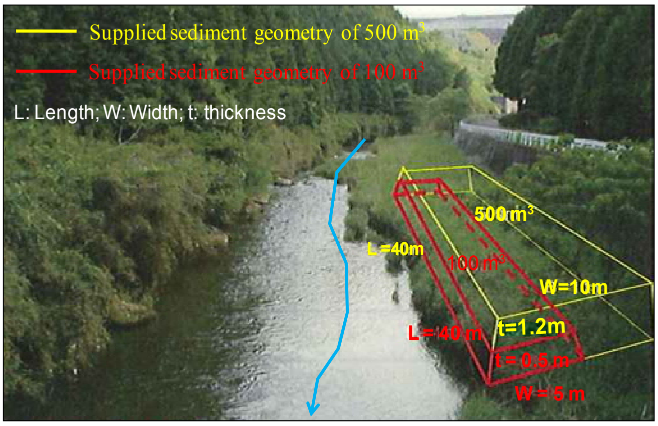

Figure 4. Dimensions and shapes of two different sediment geometries placed on the left bank of Nunome River

The increasing amount of the placed sediment should be proportional to the bed load transport capacity of the river. Furthermore, the period and the discharge of artificial flow flushing should be suitable for the sediment transport capacity. The natural flood duration for Nunome dam in 2008 is approximately 10 hours during one day only. Neither the flushing discharge nor the flushing period is able to transport all the placed sediment volume. Figure 4 shows two geometries with the same length of 40 m and two reduced widths of 10 and 5 m, and geometry thicknesses of 1.2 and 0.6 m, which have rectangular shape in the plan view.

2.5 *Experimental conditions*

The test site is placed by the Japan Water Agency (JWA) on the left side bank of Nunome River (Figure 5). The sediment is located in the downstream reach at 300 m from the Nunome dam. Planning, design, implementation and long-term monitoring of tests are guided by JWA. Figure 5 shows the location map of the placed sediment and reservoir shape. Check dam is a small dam constructed at the upstream end of the reservoir. It has low trap efficiency for suspended sediments and traps primarily sand and gravel sediment. In general, reservoir deposits are attractive sources of aggregates to the extent that they are sorted by size. Designers of replenishments projects are faced with the challenges of estimating the sediment deficit volume and determine sediment grain size distribution. Sand can be obtained from the deposition upstream of check dam.

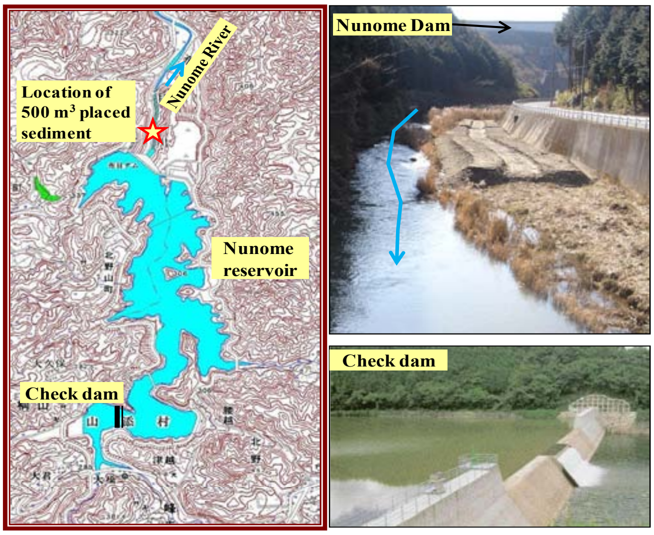

Figure 5. Location map of Nunome reservoir, dam, and placed sediment. Photos of geometry and check dam

The deposited sediments usually require more processing and often require longer transportation. The supplied sediment is composed of sand and gravel with grain size of 19 mm or less. There are a lot of medium gravel with size of 10 mm and medium sand size of about 0.25 mm. The placed sediment median grain size d_{50} is 0.38 mm as shown in Figure 6.

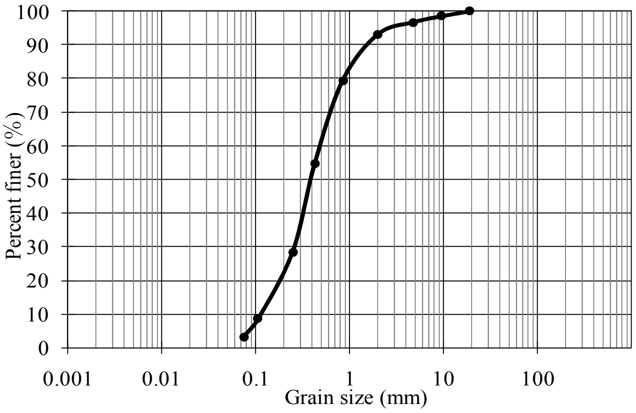

Figure 6. Grain size distribution of placed sediment

Figure 7 shows the monthly inflow and outflow discharges of Nunome reservoir in 2009, with the reservoir storage capacity. The reservoir has the highest flow discharges during July and October. There are two monitoring phases; (1) before flood, (2) after flood. The sediments are placed during the normal flow stage where the water level is low. Then waiting the coming flood to erode and transport the sediment. During one day in 2008 flood the dam gate is opened from 8:00 with discharge of 1.34 m^3/s and gradually increases till reach to the peak discharge around 12:00 with 15.36 m^3/s. The peak discharge remains two hours then a gradually decrease till recover the normal flow stage by the end of the day at 18:00.

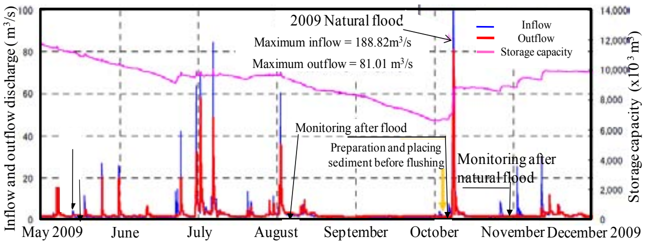

Figure 7: Flow duration curves before and after flood at the Nunome dam gauging station for the study year 2009.

The duration of the peak flow during flood should be longer to effectively erode and transport sediment. During 2008, field test of 100 and 500 m^3 are supplied in a successive periods. The sediments volume of 100 m^3 is completely eroded to further downstream. However, the volume of 500 m^3 is not eroded because no flood occurred. The remained volume of 500 m^3 is transported after the natural flood of 2009 (see Figure 8).

2.6 *Results of Replenishment DS of Nunome Dam*

The evolving of bed topography and grain size distribution is monitored, along with water surface, velocities and rate of sediment transport at the downstream end of the Nunome River. Figure 8 shows the remained sediment of 2008 and during the heavy rain with peak discharge of 81 m^3/s. When the discharge exceeds 8m^3/s, the erosion starts and about 40 m^3 of sediments are transported. Figure 8 shows the photos of field tests phases. All of the remained sediments are removed, and then new dredge sediments are placed.

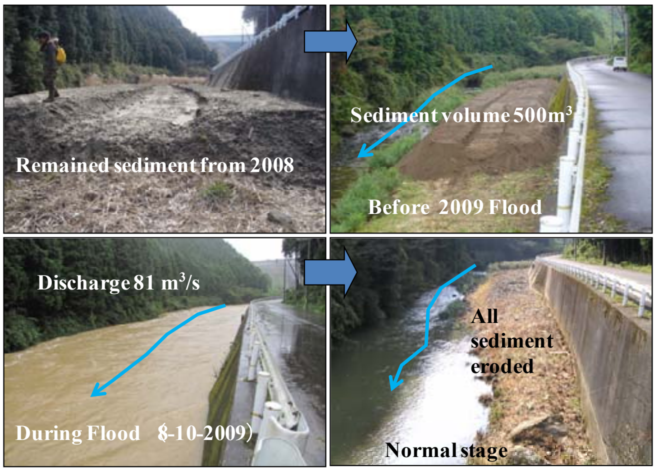

Figure 8. Evolution of sediment replenishment experiment

To understand the process of erosion and deposition of the placed sediment during flood, series of pictures are taken at different time and discharges are shown in Figure 9. The erosion at the base of the placed sediment causes the sand mass of placed sediment bank to slide downward and deposit. Deposited sand mass is then eroded due to water flow. Deposition occurs when the bottom shear stress is less than the critical shear stress. Only sediment with sufficient shear strengths to withstand the highly disruptive shear stresses in the near bed region is deposited and adheres to the bed. The erosion region developed from a straight bank line into the alcove shaped as seen in Figure 9 (b). At the peak discharge the water level increased at 11h50 produces a greater erosion area and the water submerges the placed sediment as shown in Figure 9(c).

The peak discharge is lasted for two hours and permits a deeper cut in the inner side bank. With peak flow, the eroded volumes increased in the range of 45 percent. Reduction of flood discharge reduces the erosion rate, therefore 50 m^3 of the placed sediment remains as shown in Figure 9(d).

By using satellite imagery and aerial photos a map of Nunome River in 2009 is constructed for 1 km below the dam. The river channel, island, point bars, and vegetation area are identified and distinguished by color as shown in Figure 10. The downstream reach of the dam, first 150 m from dam, experienced the greatest change in channel structure and loss of bars and islands.

The surface flow area in the first reach is greater than the bars and vegetation areas. Between fourth and seventh cross sections, 300 m from dam, reach exhibits variable patterns of channel change and intermediate in loss of island and vegetation. The reach after cross section 7, has a small sand bars, islands, and riparian vegetations. The replenishment processes are efficient to restore the bed load transport and the associated habited by coupling reintroduction with floodplain habitat restoration.

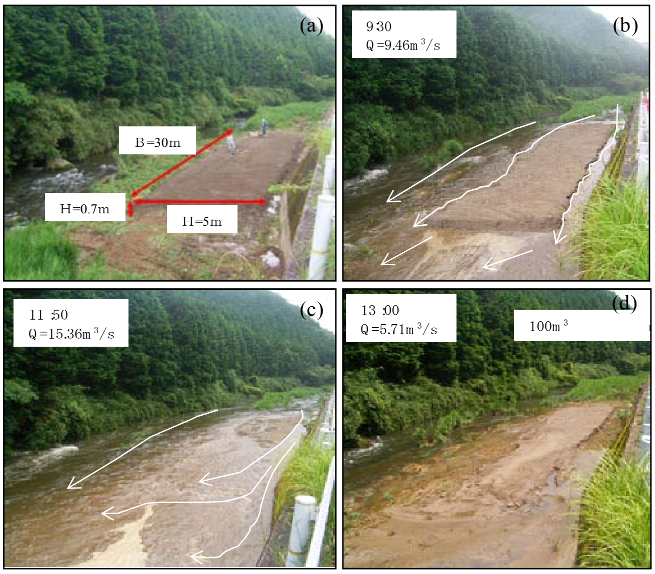

Figure 9. Evolution of sediment replenishment experiment

In Figure 10 along the Nunome River, several cross sections are identified to survey after replenishment. Newly depositions over sand bars and in the river channel are shown in Figure 10. Moreover, a completely new sand bar is formed after 600 m from dam. With the field experiments the processes are directly visible, and will be used for validation of numerical models.

The effects of sediment replenishment are investigated for cross section bed deposition, flow velocity, grain size distribution, water quality and organisms. Eleven monitoring points are shown in Figure 11. The distribution of river bed materials are analyzed by visually determining the sizes of river bed material in quadrate of 1 to 2 m in dimensions and preparing a two dimensional map, which enabled changes in distribution before and after sediment replenishment to be compared.

Figure 11 shows bed material size in three different monitoring times and 10 observation points along the river. By comparing Figure 11(a) and 11(b), a significant riverbed changes can be identified from cross sectional surveys, and visual inspections such as at section No. 1 and No. 11. After 600 m from the dam the survey at point No. 1 shows that the rate of gravel of less than 50 cm increased after natural flood, grace to the replenishment. Similar sediment grain sizes are found at point No 11 after 8200 m from dam point. Before sediment replenishment in point No 1 and No 11, the material is coarser gravel than in the middle points No 4 and No 19 (Figure 11(a)). After flood, the fine material content of the channel deposits strongly increased. The sediment deposition in point No 1 and No 11 after replenishment consist of a nearly continuous layer of fine sand, but no change occurs from No 2 to No 9 (Figure 11(b)). But after second flood where another placed sediment conducted, the bed material is transported and much of the coarsest sediment is supplied to point No 1, and No 11 (Figure 11 (c)).

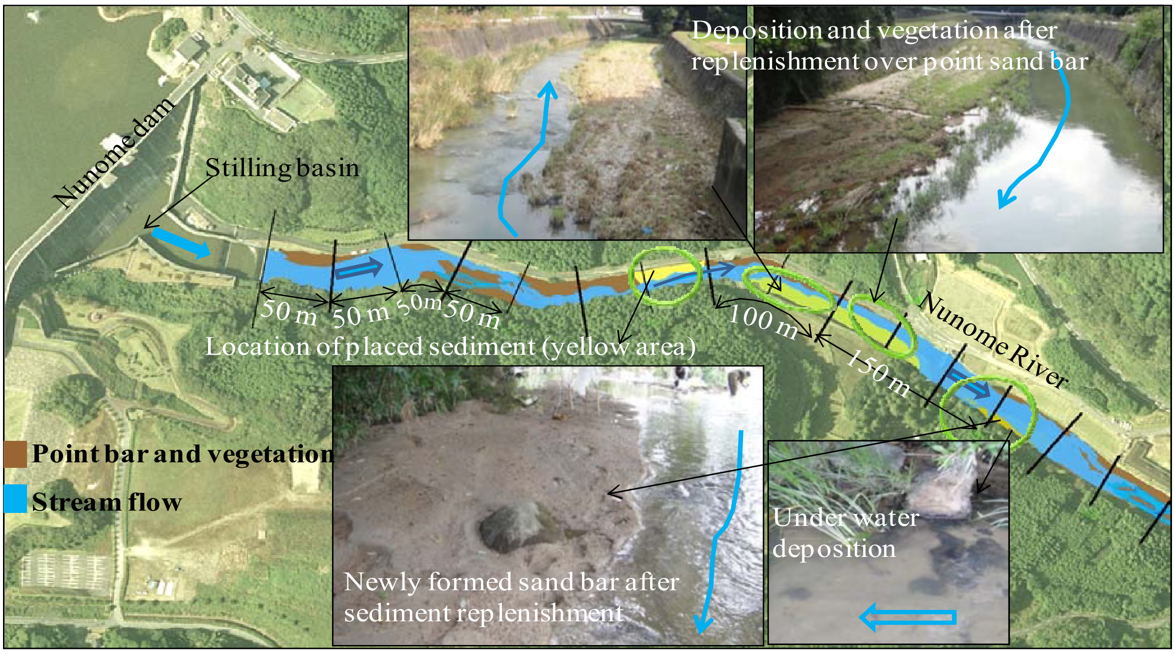

Figure 10. Aerial photographs of Nunome dam with the downstream reach of Nunome River. Morphological changes and the self forming sand bar due to sediment replenishment below the dam (14-10-2009)

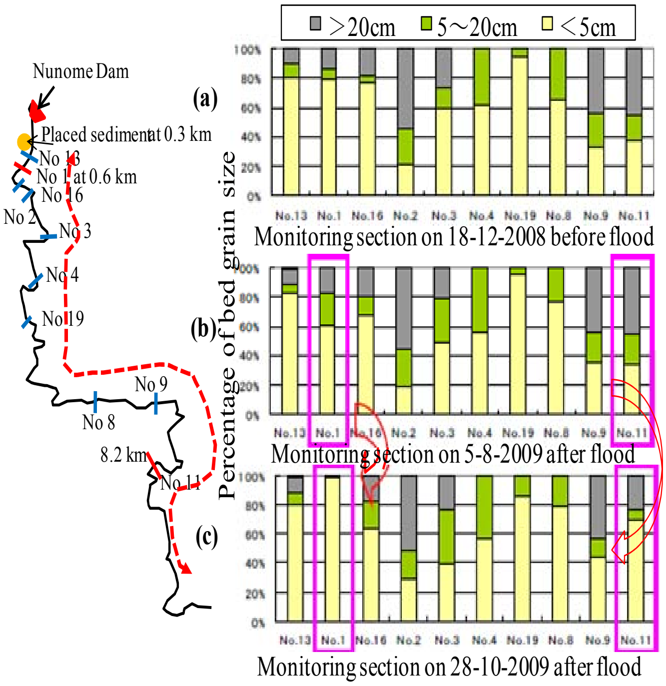

Figure 11. Variations of river bed material size at 10 cross sections along the Nunome River

3 PHYSICAL MODEL TESTS

It is difficult to compare and examine the processes of different sediment types in the field tests, due to the differences in discharge condition and measuring limitation during flood. Therefore, a series of laboratory tests are conducted with six sediment grain sizes and heights. The primary aim of laboratory tests is investigating the nature of the relationship between sediment grain size and erosion processes. The placed sediment erosion is in general a very complex problem because it involves multi-processes such as bank surface erosion, bank toe erosion and bank material mechanic failure, etc. Each of these processes is related to several parameters: sediment size distribution, sediment cohesion, slope, homogeneity, consolidation, soil moisture and ground water level, as well as sediment height.

3.1 *Experimental Facility and Conditions*

An extensive series of laboratory tests are carried out in large flume facility at the Ujigawa Open Laboratory of the Kyoto University. A schematic view of the experimental setup is shown in Figure 12. The facility measures a length of over 20 m, a width of 1 m and a depth of 0.3 m (Figure 12(c)). The channel slope is adjusted to 1/250 (Figure 12(a)). Rectangular sediment geometry has a fixed length and width of 1.0 and 0.3 m, respectively (Figure 12(b)). Several sediment heights t of 5, 7.5, 10, 12.5, and 15 cm are investigated (Figure 12(c)).

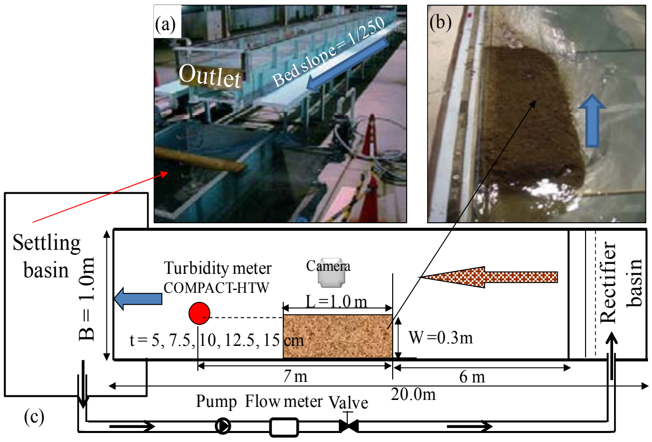

Figure 12. Laboratory setup and sediment geometry, (a) general view of flume, (b) placed sediment geometry, (c) plane view of the experimental installation circuit.

The sediment geometry is placed over a fixed bed which located at 6.0 m from the inlet of flume. In each of the tests the flow rate of Q = 20 *l/s* remained constant. Near the downstream end, a turbidity meter is installed for suspended sediment concentration measurements (see Figure 12(a)). The erosion mechanism is recorded at successive instants by video camera which is fixed perpendicular on the flume covering the plane sediment area (Figure 12(c)). The sediments grain characteristics used in the tests are based on those of the Nunome River (Figure 13).

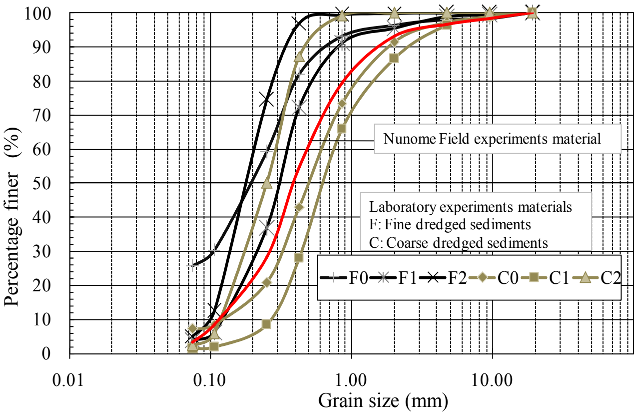

Figure 13. Sediment size distribution of laboratory tests and actual material for Nunome field tests

Two groups of fine (F) and coarse (C) sediments by grain diameter are used, the size distributions of which are seen in Figure 13. Each group contains different treatments to change the sediment cohesion.

3.2 *Experimental Results*

In order to explain the mechanism of the erosion features; time sequence investigations for fine and coarse materials with constant sediment height of 10 cm were conducted. The pictures of erosion evolution are described in Figures 14 and 15, every 8 minutes for coarse C0 and fine sediment F0 group. Figures depict the erosion process of different materials. The erosion process is a combination of lateral erosion of the placed sediment toe, and mass failure of the sediment. Erosion of the placed sediment toe by hydraulic forces is a common mechanism of bank over steepening, leading to collapse of the upper part of the bank.

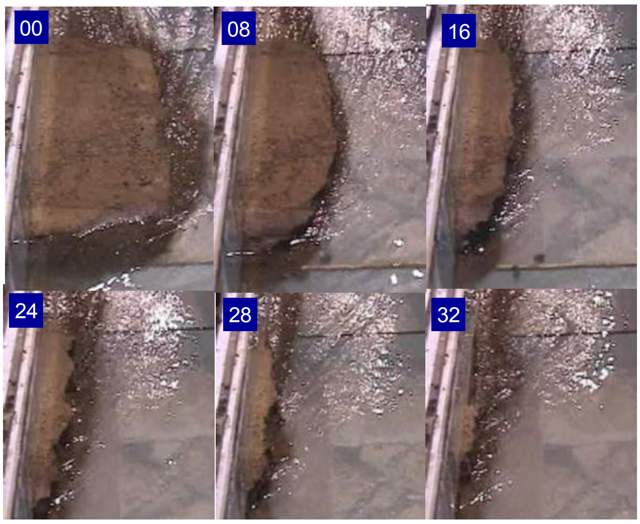

Figure 14. Time series of erosion sequences of C0

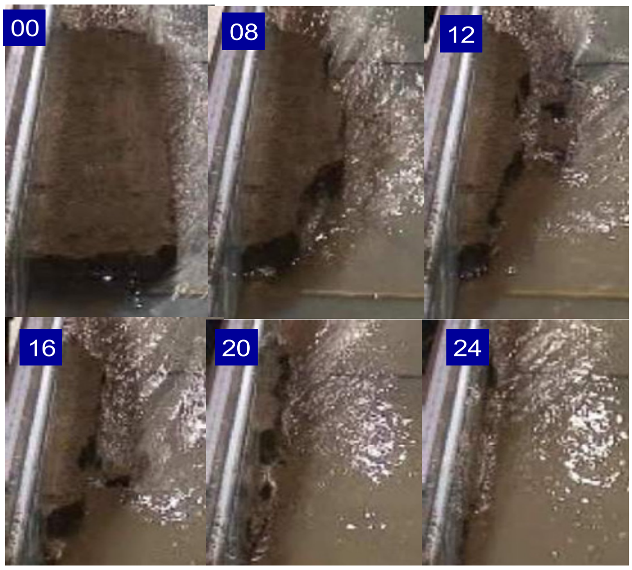

Figure 15. Time series of erosion sequences for sediment F0

This typically occurs in sediment having a composite grain size, particularly if noncohesive materials comprise the geometry toe. Larger shear stresses exerted by the flow at the base of the geometry and the greater erodibility of noncohesive sediment material leads to undercutting and the formation of cantilevers. Once the stability criterion is exceeded, a sediment mass failure would occur. The failed material deposits first on the bed near the placed sediment toes and then is eroded away by the flow. Cohesive material is generally more resistant to surface erosion because its low permeability. As water flows along the eroded sediment, secondary currents remove the noncohesive material at the toe creating a cantilever overhang of cohesive material. At the toe of the geometry, where shear stress exceeds critical shear stress, particles are detached from the bank by the flowing water.

This oversteepens the bank, causing noncohesive particles higher up on the bank to fall off in thin, vertical slices. When the cohesive silt layer is undercut, the cantilever overhang collapses into the eroded pocket. This loose, fallen material is then transported downstream, resulting in a repositioned bank line or bank retreat.

According to real-time observation and film analysis, the following were found; (1) The eroding speed of C2 > F2 > C1 > F1 > F0 > C0., (2) a lump of sediment is eroded and the erosion rate increased rapidly, (3) C1 and C2, rate of bed load transport is governing the total eroding speed, (4) C0 rate of mass failure is governing the total eroding speed (5) C1, C2, F1, and F2 have about 30° steepens of the bank. Figure 16 shows the time variation of erosion depth for different sediment materials. The erosion of a material proceeds rapidly for the first 8 minutes, and after that the erosion rate decreases gradually according to the sediment type (see Figure 16). This may be due to some extent to the decrease of shear stress as the erosion depth grows larger. For the sediment type F0 that contain large amount of clay, there is a sudden drop in the erosion rate as shown in Figure 16. The erodibility of sediment type F2 and C1 is almost same behavior, with different transport rate. The erosion rates comparison are C2 > C1 > F2 > F1 > F0 > C0.

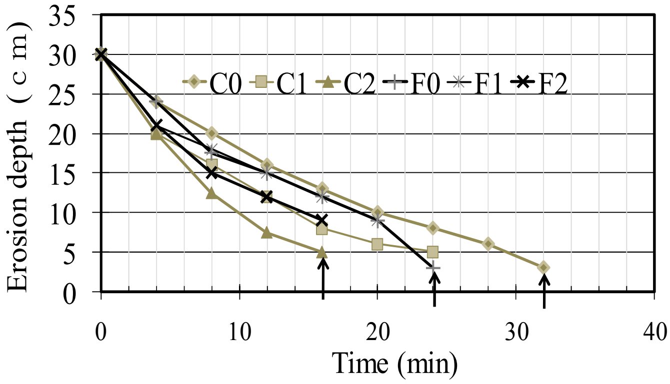

Figure 16. Time variation of erosion depth for six materials

4 CONCLUSIONS

The first results of ongoing research on the artificial sediment replenishment downstream dams are presented. Furthermore, several series of systematic experiments are conducted to investigate the erosional characteristics of original and treated materials. The effect of the sediment grain size and clay content on the erosion rate is evaluated. By replenishing sand at different locations of the Nunome River within the downstream reaches, the replenishment may direct future supplements for a more widespread dispersal of suitable sand for fish spawning.

In order to prepare the downstream sediment replenishment technique to the practical use, it is also essential to share information with the people concerned in the same river basin, such as fishery workers associations and environmental groups, and endeavor to make the method socially acceptable. Sediment replenishment for the purpose of keeping a dam functional needs to be performed semi-permanently. If the downstream replenishment technique is to be used as a means of reservoir sedimentation control, cost reduction is also an important consideration.

Regarding the continuation of this research project, the major goal is to find out which sediment geometry, volume, and feeding frequency leads to environmental and physical improvements below dams. This requires long duration tests combined with numerical modeling techniques.

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