RESERVOIR SEDIMENT MANAGEMENT MEASURES AND NECESSARY INSTRUMENTATION TECHNOLOGIES TO SUPPORT THEM

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Abstract

Reservoir sediment management approaches are largely classified into the following techniques: 1) to reduce sediment transported into reservoirs, 2) to bypass inflowing sediment and 3) to remove sediment accumulated in reservoirs. When the sediment management measures are selected, it is necessary to consider those environmental influences in the river from both positive and negative point of views. In order to evaluate these influences, it is also important to develop appropriate sediment transport monitoring techniques. In this paper, state of the art of reservoir sediment management measures in Japan and some advanced support monitoring techniques such as suspended sediment concentration measurement and morphological change surveys in rivers and reservoirs are discussed.

Keywords: Reservoir sediment management, sediment routing system, sediment flushing, environmental impact assessment, SMDP, 3D-laser scanner

1. Introduction

The sediment yields of the Japanese rivers are high in comparison with other countries due to the topographical, geological and hydrological conditions. This has consequently caused sedimentation problems to many reservoirs constructed for water resource development or flood control purposes. Under such circumstances, studies on estimation of sediment volume and countermeasures for sedimentation have been conducted for a long time.

Currently, the reservoir sedimentation management in Japan is embarking on new stages from two points of view. One is, in contrast to the emergent and local conventional countermeasures such as dredging and excavation, the active promotion of introduction of sediment flushing using sediment flushing outlets and sediment bypass systems, which aim at radically reducing the sediment inflowing and deposition. Unazuki dam and Dashidaira dam on the Kurobe River, and Miwa dam on the Tenryu River and Asahi dam on the Shingu River are advanced examples of using sediment flushing and sediment bypass techniques, which are placed as permanent measures for sedimentation at dams. The other is, considering a sediment movement zone from mountains through coastal areas, the initiation of a comprehensive approach to recover a sound sediment transport in the sediment routing system.

However, these advanced techniques for sediment management aiming at long life of dams have only been applied to a limited number, and therefore continuous study is required. It is also important to solve the social issues, such as consensus building on the need for sediment management throughout the basin people, establishment both of legal system and cost allocation system. Especially, when the sediment management measures are selected, it is necessary to consider those environmental influences in the river from both positive and negative point of views. In that case, development of the technique that minimizes the negative influences such as the water quality change caused by the sediment discharge and maximizes the positive influences such as the recovery of the sediment routing system is demanded. In order to evaluate these influences, it is important to develop appropriate sediment transport monitoring techniques.

In this paper, state of the art of reservoir sediment management measures in Japan and some advanced support monitoring techniques such as suspended sediment concentration measurement and morphological change surveys in rivers and reservoirs are discussed.

2. Reservoir Sediment Management in Japan

2.1 Present State of Sedimentation Problems

In Japan, all dams having a storage capacity over 1 million m^3 have been obliged to report sediment condition to the authority every year since 1980s. As of 2003, from 922 dams accounting for approximately 1/3 of 2,730 dams over 15 meters in height in Japan, annual changes in sedimentation volume and the shape of accumulated sediment were reported. It is probably only Japan that established such a nationwide survey system, and such accumulated data is regarded as considerably valuable records on a global basis.

Fig. 1 shows the "Sediment yield potential map of Japan" that is made by GIS using the reservoir sedimentation records and existing geographical features and geological data (Okano et al., 2004). Fig. 2 shows the relationship between reservoir sedimentation rate and years after dam completion (Sumi, 2003). Here, the sedimentation rate is calculated using sedimentation volume to gross storage capacity.

Concerning the dams constructed before World War II and used for more than 50 years, sedimentation proceeded in the range from 60 to beyond 80 % in some hydroelectric reservoirs. Likewise, for the dams constructed approximately between 1950 and 1960, or from the postwar years of recovery through the high economic growth period, and used for more than 30 years, sedimentation rates beyond 40 % are found in many cases. The influence of sedimentation in those hydroelectric reservoirs depends on the type of power generation.

Following this period, meanwhile, a large number of multi-purpose dams gradually came to be constructed. This type of dams does not have high sedimentation rates compared to the hydroelectric type, though, the rates of 20 to beyond 40 % are found in some dams. Since maintaining storage capacity is directly linked to maintaining the function of dams such as flood control, the influence of sedimentation in the multi-purpose reservoir becomes large.

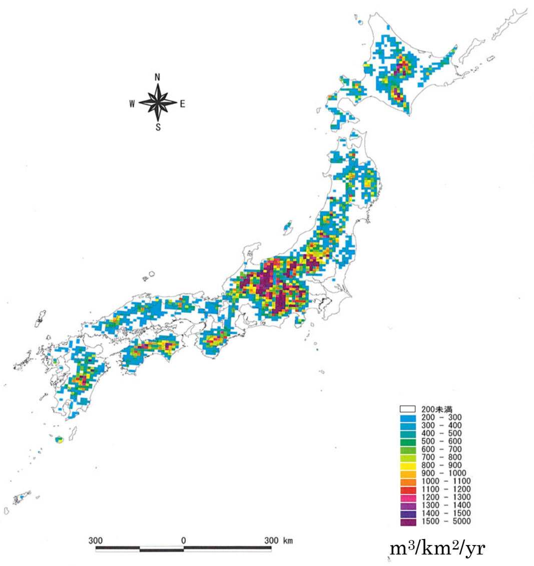

Fig. 1 Sediment yield potential map of Japan

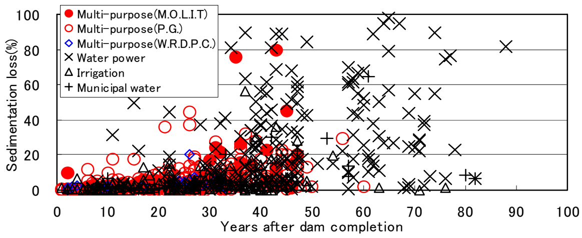

Fig. 2 Relationship between reservoir sedimentation rate and years after dam completion

(Note: M.O.L.I.T.: Ministry of land, infrastructure and transport, P.G.: Prefecture government, W.R.D.P.C.: Water resources development public corporation)

Here, an average annual capacity loss rate for all dams is 0.24 %/year and it is very high up to 0.42 %/year in Chubu region along the Tectonic Lines where a large amount of sediment is produced in the catchment.

Nowadays, new concept of sediment management is also discussed. The amount of sediment supplied from rivers to coasts was radically reduced with construction of erosion control dams or storage dams in mountain areas and acceleration of the aggregate excavation from riverbed after World War II. As a result, various problems rose up including riverbed degradation at downstream channel, oversimplification of river channel, and retreat of shoreline due to the decrease in sediment supply to the coast.

Following a recommendation by River Council of Japan in 1997, comprehensive sediment management in order to recover a sound sediment transport

Table 1 Sediment replenishment dams in Japan

Name of dam	Name of river	Drain-age area (km^2)	Location	Year	Purpose	Sediment used for replenishment (Particle size)	Transportation distance (km)	Volume used for replenishment ($\times 10^3 m^3$/cycle)	Average annual rate of reservoir sedimentation ($\times 10^3 m^3$/Year)
Akiha	Tenryu River, Tenryu River System	4,490	Shizuoka Pref	'99～'05	Prevention of riverbed degradation and coastal erosion	Sediment accumulated in reservoir (Gravel 67%、Sand 29%)	Akiha 3 Funagira 23	18～20	430
Miharu	Otakine River, Abukuma River System	226	Fukushima Pref.	'99～'05	(1) Prevention of downstream riverbed degradation (2) Prevention of increase in coarse grain content	Sediment accumulated in front reservoir (Sand 60%、Silt 28%)	4	1～2	149
Futase	Ara River, Ara River System	260	Saitama Pref.	'99, '01～'05	(1) Improvement of habitat of fish (sculpin)	Sediment accumulated at check dam (Gravel ,boulder)	15	3～8.8	101
Naga-shima*1	Oi River, Oi River System	958*2	Shizuoka Pref	'00～'01	(1) Acquisition of basic data for annual sediment replenishment planning for Nagashima Dam (2) Determination of influence on downstream river environment	Sediment accumulated just upstream of an embankment dam downstream of the dam (Average particle diameter 31mm)	1*3	20～25	400
Urayama	Urayama River, Ara River System	51	Saitama Pref.	'00,'02, '03	(1) Improvement of habitat of fish (2)Prevention of increase in coarse grain content	Sediment accumulated in reservoir (－)	4	1～14	144
Hachisu	Hachisu River, Kushida River System	80	Mie Pref.	'02～05	(1) Improvement of habitat of *ayu* (sweet fish) (2) Prevention of riverbed degradation	Sediment accumulated in reservoir (－)	5	0.3	29
Nibutani	Saru River, Saru River System	1,215	Hokkaido	'02～04	(1) Disposal of sediment accumulated at check dam (2) Improvement of downstream river environment	Sediment accumulated at check dam (－)	11 20	1～5.8	764
Shimo-kubo	Kanna River, Tone River System	322	Gunma Pref.	'03～05	(1) Conservation of landscapes of Sanbaseki Ravine downstream of the dam (prevention of armoring)	Sediment accumulated in reservoir (Gravel)	5	1	240
Nunome	Nunome River Yodo River System	75	Nara Pref.	'05	(1) Disposal of sediment accumulated at check dam (2) Improvement of downstream river environment	Sediment accumulated at check dam (Gravel 20%、Sand 60%)	1	0.3	12
Hitokura	Ina River Yodo River System	115	Hyogo Pref.	'02～05	(1) Prevention of increase in coarse grain content (2) Improvement of habitat of *ayu* (sweet fish)	Sediment from downstream river (Gravel)	-	0.19-0.6	30

*1: Sediment accumulated at *Shiogo Weir* downstream of Nagashima Dam is used.
*2:The size of a catchment area at *Shiogo Weir* *3:Distance from *Shiogo Weir* to a temporary place

regarding not only quantity but also quality point of view in the sediment routing system is now being advanced earnestly. To be more precise, the erosion control dams in the upstream region are planned to be converted to slit dams with notches, which are so designed as to pass, not to trap, as much fine sediment carrying less risk of sediment disaster as possible. For storage dams, sediment bypass or sediment flushing outlets are also progressively added in order to reduce sedimentation and accelerate sediment discharge to the downstream and, at the same time, an attempt to return the excavated and dredged sediment to the downstream river has been undertaken. Since the influence of storage dams on the sediment routing system is extremely huge, it is highly meaningful to reduce sediment trap by means of appropriate sediment management.

Based on these circumstances, needs for reservoir sediment management in Japan can be summarized into the following three points:

1) To prevent the siltation of intake facilities and aggradations of upstream river bed, accompanied by the sedimentation process in reservoirs, in order to secure the safety of dam and river channel.
2) To maintain storage function of reservoirs, and realize sustainable water resources management for the next generation.
3) From a perspective on comprehensive sediment management in a sediment routing system, to release sediment from dams.

2.2 Reservoir Sedimentation Management in Japan

Sediment management in reservoirs is largely classified into the three approaches: 1) to reduce sediment inflow to reservoirs, 2) to route sediment inflow so as not to accumulate in reservoirs and 3) to remove sediment accumulated in reservoirs.

(1) Reduction of Sediment Inflow into Reservoirs

There are two techniques to reduce the amount of transported sediment: 1) countermeasure to control

Table 2 Sediment Bypass Tunnels in Japan and Switzerland

Name of Dam	Country	Tunnel Completion	Tunnel Shape	Tunnel Cross Section (B×H(m))	Tunnel Length (m)	General Slope （%）	Design Discharge (m^3/s)	Design Velocity (m/s)	Operation Frequency
Nunobiki	Japan	1908	Hood	2.9×2.9	258	1.3	39		
Asahi	Japan	1998	Hood	3.8×3.8	2,350	2.9	140	11.4	13 times/yr
Miwa	Japan	2005	Horseshoe	2r = 7.8	4,300	1	300	10.8	-
Matsukawa	Japan	U.C.	Hood	5.2×5.2	1,417	4	200	15	-
Koshibu	Japan	Planning	Hood	9.0×8.2	4,000	1.8	500		-
Egshi	Switzerland	1976	Circular	r = 2.8	360	2.6	74	9	10days/yr
Palagnedra	Switzerland	1974	Horseshoe	2r = 6.2	1,800	2	110	9	2～5days/yr
Pfaffensprung	Switzerland	1922	Horseshoe	A = 21.0m^2	280	3	220	10～15	～200days/yr
Rempen	Switzerland	1983	Horseshoe	3.5×3.3	450	4	80	～14	1～5days/yr
Runcahez	Switzerland	1961	Horseshoe	3.8×4.5	572	1.4	110	9	4days/yr

sediment discharge which covers entire basin including the construction of erosion control dams; and 2) countermeasure to forcibly trap sediment by constructing check dams at the end of reservoirs. Although the catchment areas of dams have high forest cover rates, a remarkable amount of sediment is produced in the watershed where landslides frequently occur due to the topographical and geological conditions.

Since an attempt to trap sediment using check dams is found effective for the reservoirs where bed load of relatively coarse grain size accounts for a large percentage of sediment inflow, many dams have proceeded in constructing them recently. In this technique, a low dam is so constructed at the end of reservoir as to deposit transported sediment, and then the deposited sediment is regularly removed. The accumulated sediment can be excavated on land except for flood time, and the removed sediment is utilized effectively as concrete aggregate. As of 2000, the check dams have been constructed at 57 out of the dams under jurisdiction of Ministry of Land, Infrastructure and Transport.

Recently, sediment replenishment tests have been carried out in some dams. Trapped sediments in the sediment check dam upstream of the reservoir are excavated and transported to the downstream of the dam. These sediments are put on the downstream river channel temporarily and washed out by the natural flood flows. Typical cases are descried in Table 1 (Okano et al., 2000a and 2004b). Moreover, there is an example of combining with the environmental flushing flow such as in the Managawa dam and the integrated improvement of the river environment is expected by the flood disturbance and the sediment supply.

(2) Routing of Sediment Inflow into Reservoirs

Another possible approach to sediment management, next to the reduction of sediment inflow itself, is to route sediment inflow so as not to allow it to accumulate in reservoirs. In Japan, the following techniques are adopted: 1) sediment bypass by directly diverting sediment transport flow, and 2) density current venting by using a nature of high-concentration sediment transport flow.

In Japan, it is sediment bypass tunnels that have been studied most exhaustively. Although this technique involves high cost caused by tunnel construction, there are several advantages such that it is also applicable to existing dams; it does not involve drawdown of reservoir level and therefore no storage capacity loss; and it has relatively small impact on environment because sediment is discharged not so rapidly as sediment flushing, which is described later. Nunobiki dam is the first example of the bypass tunnel in Japan. The reservoir to which longevity is estimated to be only 25 years without bypass is prolonged to over 1,000 years (Sumi, Takata and Okano, 2004a). Recently, the bypassing effect is clarified after completion of the Asahi dam, and the planning and construction of the bypass have been advanced also in the Miwa, Matsukawa and Koshibu dams.

The subjects of designing sediment bypass tunnels are to secure the safety of sediment transport flow inside tunnels and to take countermeasures for abrasion damages on the channel bed surface. Among factors that significantly relate to these problems are grain size, tunnel cross-sectional area, channel slope, and design velocity. Table 2 shows some examples of existing sediment bypass tunnels and ones under construction and planning (Vischer et al., 1997, Sumi, Okano and Takata, 2004). It should be understood that design condition becomes increasingly hard if higher velocity and larger grain size will be expected.

Density current venting, on the other hand, is a technique to use a nature of high-concentration sediment transport flow, which runs through relatively deep reservoir with original channel bed of steep slope as a density current with less diffusion, and to discharge it effectively through outlets in timing of reaching dam. In both techniques, the main target is fine-grained sediment such as suspended sediment and wash load. In multiple-purpose dams in Japan that usually have high-pressure bottom outlets for flood control, the effective operation of these facilities during flood season can increase a chance to actively discharge fine-grained sediment.

If sediment concentration in the main river is very high, both a flood control dam which is kept empty except flood times in the main river and a water storage dam in the tributary should be constructed separately in order to reduce total sediment management costs (Sumi, Takata and Okano, 2004b).

(3) Removal of Sediment Accumulated in Reservoirs

This approach is regarded as a last resort in case sediment is accumulated in reservoirs in spite of various efforts being done: 1) mechanically excavating sediment accumulated in the upstream region of reservoirs, 2) dredging sediment accumulated at the middle and downstream regions, and 3) flushing out sediment with tractive force. As for excavation and dredging techniques, it is important that the removed sediment should be treated properly and reused.

On the other hand, sediment flushing is a technique to restore tractive force in a reservoir beyond its critical force by means of drawdown of reservoir level, and flush the deposits through bottom outlets in the dam body with inflow water, mainly in an open channel flow condition, to the downstream of dam. When the amount of sediment inflow is significantly large, man-powered techniques such as excavation and dredging are hard to be adopted because of problems involving transportation and dump site. In such a case, however, sediment flushing can be a permanent measure if conditions are met. Traditionally in Japan, sediment flushing facilities such as flushing sluices and outlets were installed at small-scale hydroelectric dams or weirs for the purpose of discharging sediment deposited in the vicinity of intake. In contrast, at Dashidaira-Unazuki dams in the Kurobe river, where a large amount of sediment is discharged, sediment flushing is implemented in coordination of upstream and downstream dams (coordinated sediment flushing) (Sumi and Kanazawa, 2006).

Sediment flushing is performed at many dams all over the world (Morris and Fan, 1998, White et al., 2000). Sediment flushing is considered as an extremely effective technique for discharging sediment in terms of harnessing tractive force in natural river channel. However, when this technique is introduced, an extensive study is required in the planning stages, considering such conditions as inflow, sediment inflow, storage capacity, grain size distribution and reservoir operation. At the same time, it is also required to consider measures concerning environmental problems under sediment flushing process (Sumi, 2000a, Sumi and Kanazawa, 2006).

Moreover, HSRS (Hydro-suction Sediment Removal System) which can intake and discharge sediment using only the water level differences without the mechanical force is developed in some types in recent years. There are stationary and movable types in the system. In case of the stationary type, establishment of the measures to move sediment to the system neighborhood in the reservoir and, in case of the movable type, securing enough operation time corresponding to the target sediment volume to be discharged during a year and a safe work environment are problems to be solved.

2.3 Promotion strategy of reservoir sedimentation management

The problems to promote such reservoir sedimentation management in future are priority evaluation of reservoirs where sediment management should be introduced and appropriate selection of reservoir sediment management strategies.

The World Bank is advancing RESCON project (Reservoir Conservation Project) (Palmieri, 2003). It

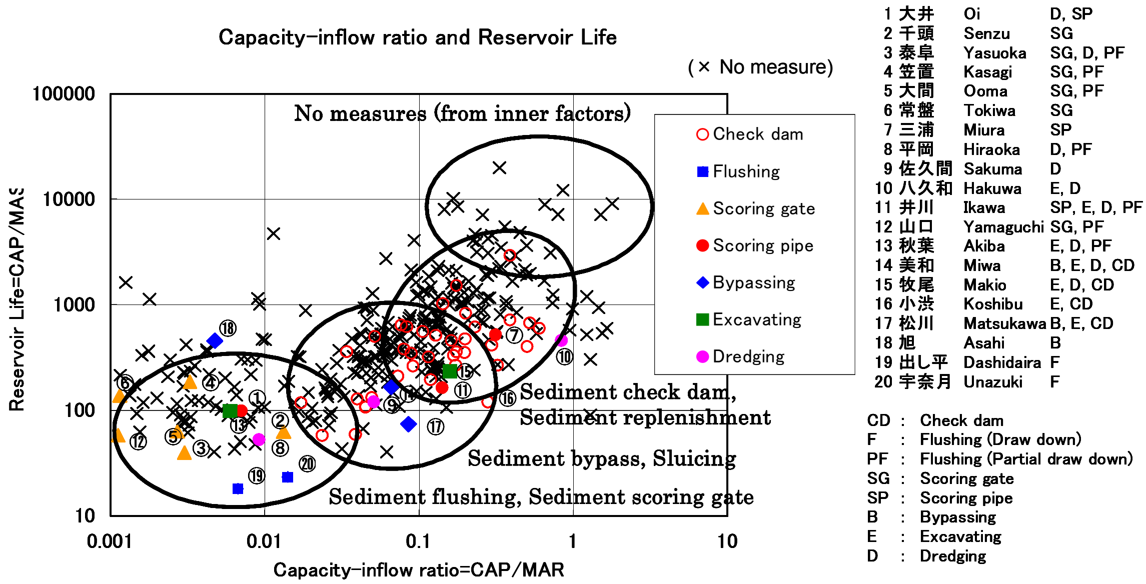

Fig. 3 Representative sediment management dams in Japan

will be thought that reservoir sedimentation problem becomes a key issue while putting the target on the redevelopment project in the future though the World Bank has financed the developing country only to the new construction projects. For instance, when there are several dams in the same water system, estimated each reservoir life when measures are not taken is concretely presented. And, if it is understood that remainder of the life is very short, the feasible sediment management measures considering economy etc. is concretely proposed. It will be thought that such an approach is important also in Japan. Especially, when several dams exist in a water system, it is realistically difficult to introduce the sediment management all together due to the limit of the budget under the present situation. Then, it is necessary to evaluate priority according to some indices.

If the dam whose priority is high is selected, it is necessary to select a concrete sediment management strategy. In Figure 3, dams in the Japanese whole country are plotted by the parameter of the turnover rate of water (CAP/MAR=Total capacity/Mean annual runoff) and sediment (CAP/MAS=Total capacity/Mean annual inflow sediment) (Sumi, 2003). It is thought that the selected sediment management measures are changed by these two parameters. It is understood that measures actually selected have changed in the order of the sediment flushing, the sediment bypass, sediment check dam and excavating, and dredging as CAP/MAR increases (decrease in the turnover rate). This is because of greatly depending on the volume of water to be able to use the sediment management measure that can be selected for the sediment transport (Sumi, 2000b).

We are intensively studying to improve the RESCON model based on actual records in the Kurobe river (Sumi and Iguchi, 2005, Sumi, Takata, Iguchi and Nakanishi, 2005).

3. Monitoring techniques to support sediment management

In order to evaluate environmental influences and effectiveness of sediment management measures such as sediment flushing and sediment bypassing and so on, various types of sediment monitoring techniques should be developed. Here, new measurement techniques for suspended sediment concentration and morphological changes such as sediment erosion and deposition in rivers and reservoirs are introduced.

3.1 Suspended sediment concentration measuring system with differential pressure transmitter

It is important to know quantity of wash load for the integrated sediment management from upstream through downstream river basins. For the purpose of environmental assessment to the aquatic species during sediment discharging by sediment flushing or bypassing, it is also important to observe high turbidity in real time in the river. Generally, both continuous turbidity measuring and bottle sampling are used for suspended-sediment concentration measurement in rivers or reservoirs. Here, we have developed a new suspended sediment concentration measuring system with differential pressure transmitter (hereafter, we call *SMDP*) (Sumi, Morita, Ochi and Komiya, 2001 & 2002).

The *SMDP* has advantages in long-term and high turbidity measurement because differential pressure transmitter is measuring density of water directly. Based on measuring conditions, a submersible type and a water circulating type *SMDP* are available, and both of them have shown good performances through laboratory tests and field experiments at the Miwa and Koshibu dams in the Tenryu river, and Dashidaira and Unazuki dams in the Kurobe river.

The schematic diagram of SMDP is shown in Fig. 4. Two pressure detectors are placed vertically with the interval H=1,000mm and connected by small pipes filled up with water to the differential pressure transmitter mounted at the center of the system. We have developed two different unites to measure water with suspended sediments based on different measuring situations. One is the submersible type and the other is the water circulation type. The submersible type is shown in Fig. 5(a). The main measuring equipment is suspended from a float and submerged in the measuring water directly. Advantages of this type are simple structure and easy maintenance. On the other hand, it is necessary to secure enough water depth

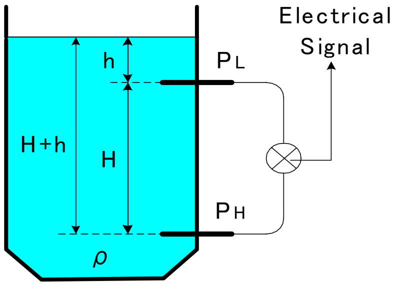

Fig. 4 Schematic diagram of SMDP

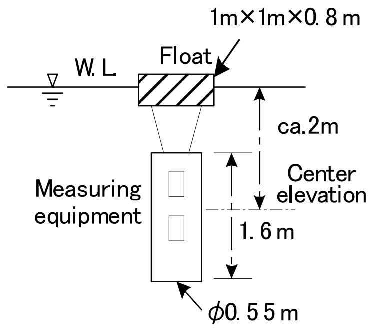

Fig. 5(a) Schematic diagram of the submergible SMDP

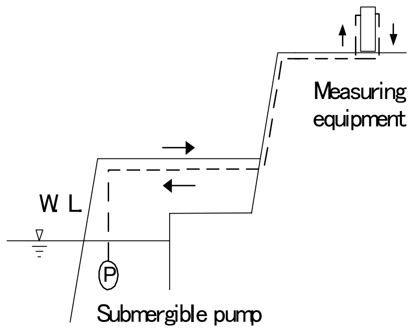

Fig. 5(b) Schematic diagram of the water circulation SMDP

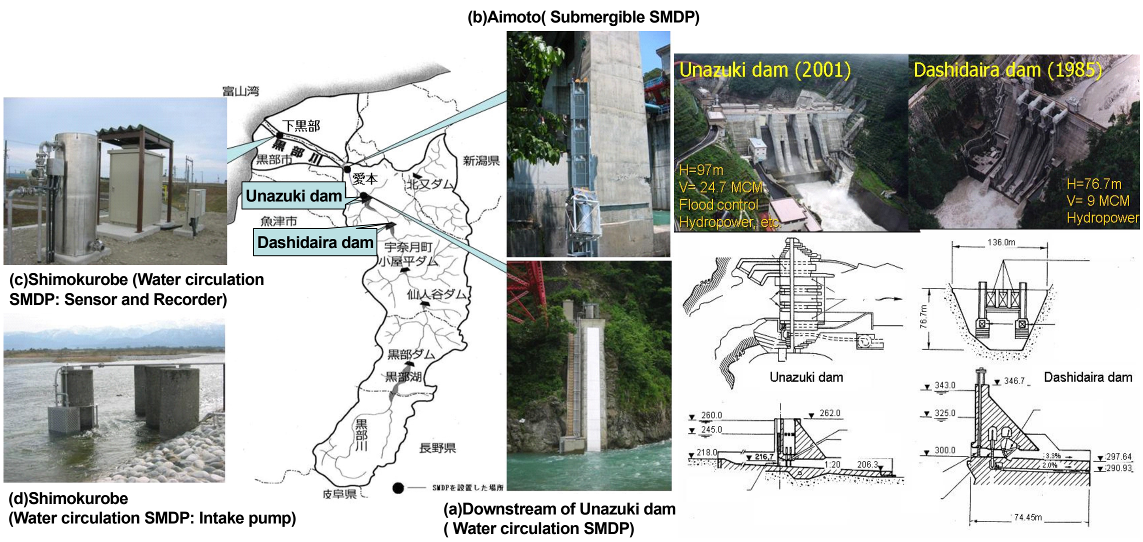

Fig. 6 Sediment flushing gates of Unazuki and Dashidaira dams and SMDP installations in the Kurobe river

over about 2.5～3.0 m for measuring, to keep almost equal velocities between the high and low pressure detectors and to protect the measuring equipment by floating debris such as gravels or driftwoods. We have solved this subject by shielding the equipment with the shell type cylinder. This submergible type is applicable for measuring such as in reservoirs.

On the other hand, adopting the submergible type becomes difficult in the case that the water depth changes largely depend on time like a natural river. Then, we have also developed the water circulation type shown in Fig. 5(b). Here, the main measuring equipment is installed in a water tank that is placed in land and two pipes are connected. One is to intake measuring water from a river and another is to drain from the tank. An intake pipe is connected to a submergible pump in river water.

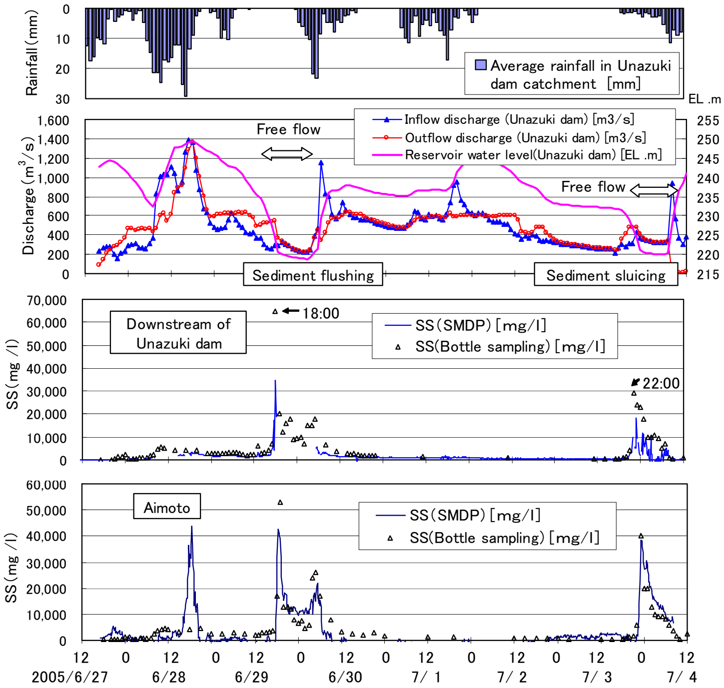

Fig. 7 Suspended sediment concentration measured by SMDP during sediment flushing in the Kurobe River

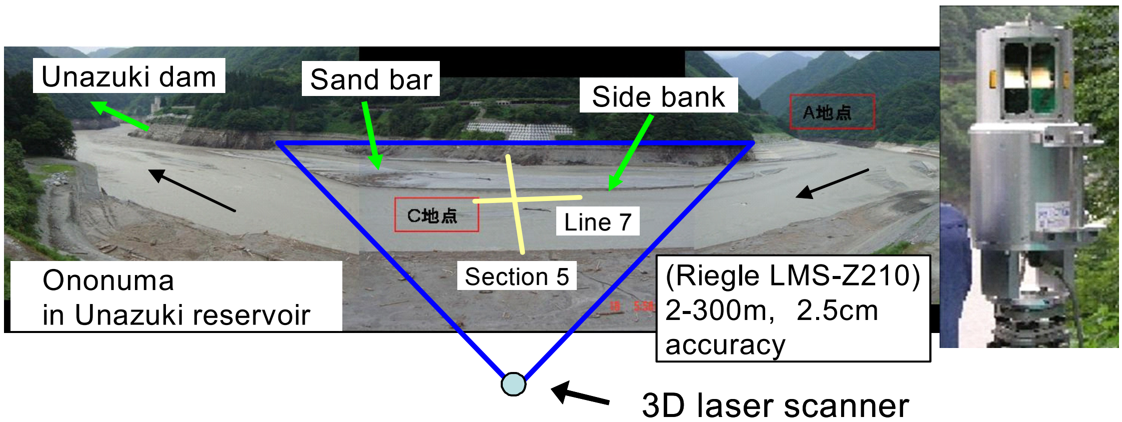

Photo 1 Unazuki reservoir and 3D laser scanner

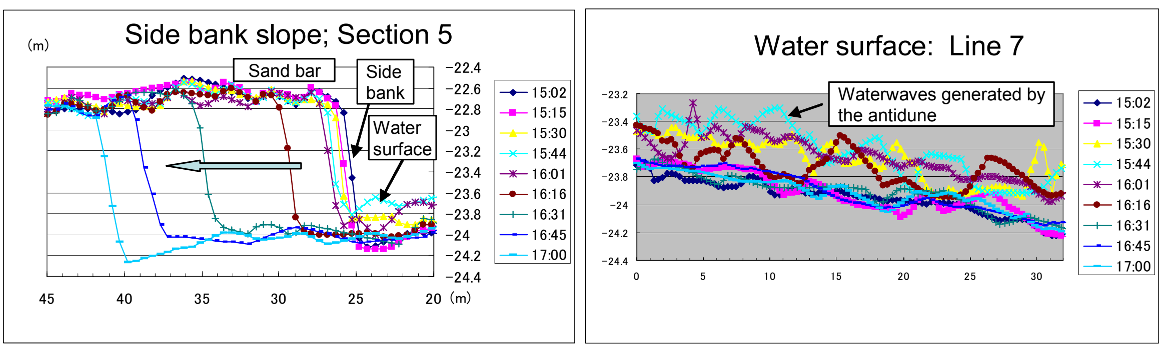

Fig. 8 Process of the side bank erosion and water surface changes in the channel

This type can be applicable to anywhere, if the minimum water depth for intake is secured, and is safer than the submersible type at the time of the flood. On the other hand, pump operation is needed for continuous measurement. The system has the electromagnetic flow meter to measure quantity of water, and the accumulated sediment can be discharged periodically from the valve installed at the bottom of the tank. This water circulation type is applicable for even at the natural rivers and we are doing field experiment in the Kurobe River. Fig. 6 shows SMDP installations in the Kurobe river (Sumi, Baiyinbaoligao and Morita, 2005) and Fig. 7 shows data monitoring results during sediment flushing operations in June-July 2005 (Sumi, Baiyinbaoligao and Morita, 2006). High suspended concentrations were measured up to 40,000mg/l by these systems during free flow flushing. By analyzing these data and bottle sampling results, characteristics of fine sediment discharge during sediment flushing of Unazuki dam have become clear. These results are also useful to assess environmental impacts to aquatic species by the sediment flushing.

3.2 3D laser scanner

In order to evaluate efficiency of the sediment flushing operation from reservoirs or observe morphological changes in river channels during and after sediment management, it is necessary to measure erosion-deposition process of sediment in reservoirs and rivers. Recently, we have conducted field measurements with the 3D laser scanning technology (Sumi, Murasaki, Fujinaga, Nagura and Tamaki, 2004, Sumi Murasaki, Nagura, Tamaki and Imaki, 2005) .

The 3D laser scanner used for the measurement is shown in Photo 1. Side bank erosion process of the sand bar formed in the Unazuki reservoir and water surface profiles near by banks are shown in Fig. 8. By these data, we can estimate that side bank of the height of 1.0-1.2m was eroded with the speed of 7.5m/hr. Slope of water surface is also estimated as 1/75 and water waves generated by the antidune are also observed.

Since the bed morphological change where water and sandbars exist together complexly can be also measured even in a night time, this technique can be used to understand sediment transport in a reservoir and to estimate the sediment volume flushed out by the operation.

4. Conclusions

Reservoir sedimentation management in Japan is entering a new era. Although there are still technical problems to be solved, we believe that the importance of sediment management will increasingly grow. Assessing issues, depending on each case, of dam security, sustainable management of water resources and sediment management in a sediment routing system, an effective sediment management plan should be studied and materialized.

Needless to say, of course, our best endeavors should be exerted to minimize negative environmental influences involved in sediment management. From the above point of view, necessary monitoring techniques to support the sediment management in rivers and reservoirs should be intensively studied and developed. One of new monitoring techniques, suspended sediment concentration measuring system with differential pressure transmitter (*SMDP*) for high turbidity measurements and 3D laser scanner for morphological change surveys are useful to evaluate sediment transport during sediment management.

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