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ANALYSIS OF SEDIMENTATION COUNTERMEASURES IN HYDROPOWER DAMS CONSIDERING PROPERTIES OF RESERVOIR SEDIMENTATION*

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SUMMARY

Sedimentation in hydropower reservoir is one of the most important problems for sustainable power generation. Many our company's dam and reservoirs were installed in post war reconstruction period, then for decades reservoirs have stored much sedimentation inside up to sedimentation ratio about 10% because of high degree of sediment production and river flow regime. We have trying to excavate sedimentation out of reservoirs to avoid aggradations of upstream riverbed and obstacle for intake and outlet functions.

Reprehensive five different type reservoir sediment managements considering sediment properties have been really carried out. In comparatively large Sakuma dam, provisional transporting inside reservoir is main countermeasure, in near future radical management will be required. In comparatively small Futatsuno and Taki dam, current excavating sedimentation volume is enough for maintaining reservoir size for flow sedimentation. So that sediment routing methods as bypassing will be planned in a hurry. In smaller Setoishi and Yambara dam, sediment sluicing or hydro-suction sediment removal systems have been already started as test.

In spite of no quick remedy to countermeasure reservoir sedimentation dramatically, some methods exist that select suitable options for each reservoir

* *Analyse des contre-mesures de sédimentation dans les barrages hydroélectriques tenant compte des propriétés de la sédimentation des réservoirs*

considering with reservoir size, life and basin. Not only the technical feasibility, but also the economic advantages and ecological acceptability should be considered. For sustaining reservoir and hydropower, reservoir sedimentation management will be active and adaptive more and more.

Keywords: Sedimentation, Reservoir, Reservoir Capacity, Reservoir Operation, Dam Operation, Sakuma Dam, Futatsuno Dam, Taki Dam, Setoishi Dam, Yambara Dam.

RÉSUMÉ

La sédimentation des réservoirs hydroélectriques est l'un des problèmes les plus importants pour la production d'électricité durable. Parmi les barrages et réservoirs de notre société, de nombreux ont été installés pendant la période de reconstruction après-guerre, puis pendant des décennies les réservoirs ont stocké des sédiments avec des taux de sédimentation atteignant 10 % en raison du haut degré de production de sédiment des régimes des cours d'eau. Nous avons essayé d'excaver les sédiments hors des réservoirs pour éviter l'exhaussement du lit de la rivière en amont et les obstacles pour les fonctions d'amenée et de fuite.

Cinq différents types de gestion de sédiments dans les réservoirs ont été réellement appliqués suivant les propriétés des sédiments. Pour le barrage de Sakuma, relativement grand, un transport provisoire au sein du réservoir a été la principale mesure, mais très rapidement une gestion plus radicale sera nécessaire. Pour les barrages plutôt petits de Futatsuno et Taki, le volume actuel de sédiments excavé est suffisant pour maintenir la capacité du réservoir face à la sédimentation. Des méthodes de dérivation des sédiments seront prévues dans l'urgence. Pour les barrages plus petits de Setoishi et Yambara, le drainage des sédiments ou des systèmes d'évacuation par hydrosuccion ont déjà été lancés sous forme de tests.

Malgré l'absence de solutions rapides pour réduire fortement la sédimentation dans les réservoirs, des méthodes existent en choisissant des options adaptées à la taille, la durée de vie et le bassin de chaque réservoir. Il faut prendre en compte non seulement la faisabilité technique, mais aussi les avantages économiques et l'acceptabilité écologique. Pour le maintien des réservoirs et de l'hydroélectricité, la gestion de sédimentation des réservoirs va être de plus en plus active et adaptative.

1. INTRODUCTION

Because of active sediment production and much rainfall, dams in Japan have incurred sedimentation problem in these days. As countermeasure against reservoir sedimentation, installation of sedimentation capacity, monitoring sedimentation and local excavation have been selected as ordinary ways for many years. In 1997 River Law in Japan changed, sedimentation control had drastically changed from keeping sediment in mountains for disaster prevention to flowing sediment down the river for environment of river basin. For sustainable power generation, sedimentation management is not only for keeping reservoir capacity and riverbed control, but also for environment of river basin. Regarding these situation, reservoir sedimentation management has been discussed. Hydropower has been changing the role of energy supply, from base energy source to peak energy source. In these days, it has been more important to sustain power generation of existing hydropower plant as a role of regulating power supply using its convenience of easy start and stop generation. Hydropower has more advantageous points, such as producing no greenhouse gas in operation, renewable and domestic. The climate change and extensive disaster make hydropower more important. Therefore, existing hydropower plant has to be maintained for sustainable power generation.

2. RESERVOIR SEDIMENTATION IN HYDROPOWER DAMS

There are 1,887 hydropower stations in Japan, and 737 among them have reservoirs. About 230 are operated as storage reservoirs, and 464 and 43 are operated as regulating and pumped storage ones, respectively [1]. Among them, 44 dams are maintained by our company (Electric Power Development Co., ltd. (EPDC)), many of these dams were completed from 1950's to 1960's. Total gross storage (initial) of our 44 dams is 3.07 G m^3, total sediment volume is 0.28 G m^3, and the ratio of sedimentation is approximately 9%. Presently it does not become the problem as sediment in many dams, but it is taken measures against 14 dams which are about one-third. We have been trying to excavate sedimentation out of reservoirs to avoid aggradations of upstream riverbed and obstacle for intake and outlet functions. Loss of reservoir capacity will affect flood control dam, will not affect hydropower dam so much. Loss of reservoir capacity for hydropower dam does not reduce always a power generation quantity. The purpose for sediment countermeasure in hydropower dam is mainly to reduce the risks of covering with water and disturbing for intake and outlet functions [2]. It is time to change sedimentation management of hydropower reservoir, because of the reasons bellow. There is too much sediment to remove, resulting too much cost for excavation, and no disposal site near reservoir, on the other hand sediment flow is strongly requested in dam downstream river and coastal area. It is not effective to excavate and dispose sediment just considering hydropower generation, appropriate sedimentation management is needed both for power generation and river basin sustainability [3]. In the following, a number of cases from our reservoirs are presented covering different types of sedimentation countermeasures. They give a rough idea on the specific situation and extent of reservoir sedimentation.

3. CASE OF SEDIMENTATION MANAGEMENT

3.1. Sakuma dam

The Sakuma dam reservoir is constructed in 1956 at middle reach of the Tenryu River, which flows southward to the Pacific Ocean between the Central and Southern Japan Alps (Fig. 1). The Tenryu River has a trunk length of 213km and drains a catchment area of 5,090km^2. The Tenryu River basin is characterized by steep topography and by the fragile geology along the Median Tectonic Line, where heavy rainfalls produced and flood flows transport extremely large quantities of sediment. The specification of Sakuma dam is shown in Table 1.

Table 1
Specifications of Sakuma dam

Catchment Area	3,827km^2	Dam	Type	Gravity
Design flood	7,700m^3/s		Height	155.5m
Power plant	Name: Sakuma		Crest length	293.5m
		Reservoir	Initial capacity	327Mm^3
	Max. output: 350MW		Sediment volume (2016)	126Mm^3

Fig. 1
Location of dams
L'emplacement des barrages

As countermeasures to lower the riverbed in its back sand area, it has been dredged and transported inside reservoir (approximately 1.1Mm^3/year), utilized as aggregate (approximately 0.2Mm^3/year), carrying out to disposal area and artificial acceleration of sediment transport (keeping low water level) (Fig. 2). To dredge and transport the sedimentation in the middle area of the dam reservoir to the downstream area limited to not exceeding the effective volume of the downstream area portion. The operation has been underway at the middle area at a target rate of about 1,1M m^3 per year by 7 groups of dredgers (Fig. 3). And 3 Gravel dealers dredge the sedimentation to be used as aggregate for concrete or asphalt, sand for golf course preparation, and other purposes. The operation is being done at a target rate of 0.4M m^3 per year. To lower the water level during the dry season to the level low enough to create a condition where in natural river flows are realized in the upper area and middle area reservoir beds, and to let the flow of the water supplied during this period transport the sedimentation on the upper and middle area portions of the dam reservoir beds to the downstream area portion but limited to not exceeding the effective volume of the downstream area portion [4].

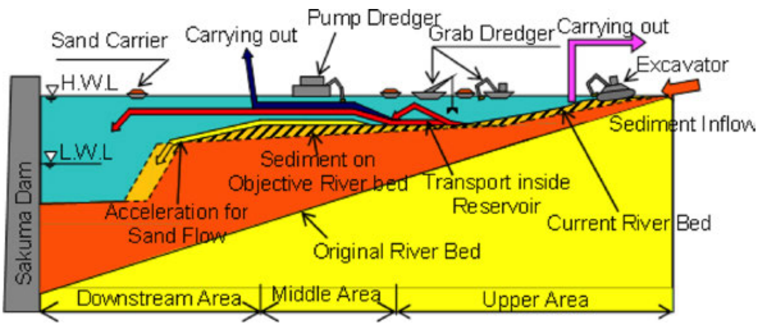


Fig. 2
Countermeasures to the Sedimentation of the Sakuma Dam
Contre-mesures à la sédimentation de l'Barrage Sakuma

Fig. 3
Photo of dredgers in Sakuma reservoir
Photo de dragues dans réservoir Sakuma

3.2. Futatsuno dam

The Futatsuno dam reservoir is constructed in 1962 at middle reach of the Kumano River, which flows southward to the Pacific Ocean. The specifications of Futatsuno dam is shown in Table 2.

Table 2
Specifications of Futatsuno dam

<table>
<tr><td>Catchment Area</td><td>801km^2</td><td rowspan="3">Dam</td><td>Type</td><td>Arch</td></tr>
<tr><td>Design flood</td><td>9,600m^3/s</td><td>Height</td><td>76m</td></tr>
<tr><td rowspan="3">Power plant</td><td rowspan="2">Name:
Totsukawa No. 2</td><td>Crest length</td><td>210.6m</td></tr>
<tr><td rowspan="2">Reservoir</td><td>Initial capacity</td><td>43Mm^3</td></tr>
<tr><td>Max. output:
58MW</td><td>Sediment volume (2016)</td><td>17Mm^3</td></tr>
</table>

As countermeasures to lower the riverbed in its back sand area, it has been carried out excavating and dredging (approximately 0.08Mm^3/y). Most of excavated sediment has been conveyed to the disposal areas. One of the disposal areas was ensured by business of local government (Totsukawa Village). Firstly, we laid a cut-off channel at a meandering channel, and the meandering channel was disused. Totsukawa Village and EPDC have reclaimed the meandering part by using sedimentation. The capacity is 1.7 million cube meters, Totsukawa Village have 1.0 million cube meters, EPDC have 0.7 million cube meters. The site is used as a public land for "village revitalization" (Fig. 4). In addition to that, flushing and sluicing has been carried out. The way of operations for flushing and sluicing is divided into 3 stages. The first stage is drawing of reservoir water level. The second stage is keeping free flow state in several hours and sediment flushing and sluicing. The third stage is restoration of reservoir water level. In second stage, the sand is largely discharged downstream from the dam. (Fig. 5)

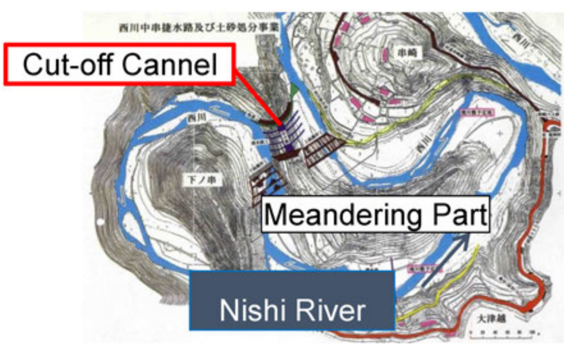


Fig. 4
Plan of a public land for "village revitalization"
Plan d'une terre publique pour "revitalisation" village

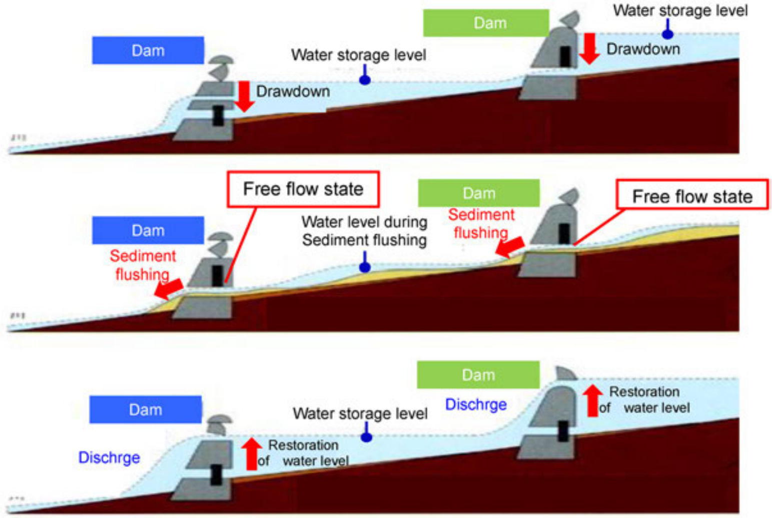


Fig. 5
Flushing and sluicing methodologies
Méthodes de rinçage et de lavage au sluice

3.3. Taki dam

The Taki dam reservoir is constructed in 1961 at middle reach of the Agano River, which flows northward to the Nihonkai. The specifications of Taki dam is shown in Table 3.

Table 3
Specifications of Taki dam

Catchment Area	1,979km^2	Dam	Type	Gravity
Design flood	5,100m^3/s		Height	46m
Power plant	Name: Taki		Crest length	264m
		Reservoir	Initial capacity	27Mm^3
	Max. output: 92MW		Sediment volume (2016)	9Mm^3

As countermeasures to lower the riverbed in its back sand area, it has been carried out dredging (Fig. 6) (approximately 0.1Mm^3/y). Excavated sediment has been conveyed to the disposal areas. And then, flushing and sluicing as test has been carried out from 2015. After analyzing result of monitoring sedimentation management, sedimentation countermeasures will be strengthened.

Fig. 6
Photo of dredgers in Taki dam reservoir
Photo de dragues dans le réservoir du barrage de Taki

3.4. Setoishi dam

The Setoishi dam reservoir is constructed in 1958 at middle reach of the Kuma River, which flows westward. The Kuma River has a trunk length of 115km and drains a catchment area of 1,880km^2. The Kuma River basin is characterized by the fragile geology, where heavy rainfalls produced and flood flows transport extremely large quantities of sediment. The specifications of Setoishi dam is shown in Table 4.

Table 4
Specifications of Setoishi dam

<table>
<tr><td>Catchment Area</td><td>1,629km^2</td><td rowspan="3">Dam</td><td>Type</td><td>Gravity</td></tr>
<tr><td>Design flood</td><td>6,000m^3/s</td><td>Height</td><td>26.5m</td></tr>
<tr><td rowspan="3">Power plant</td><td rowspan="2">Name:
Setoishi</td><td>Crest length</td><td>139.4m</td></tr>
<tr><td rowspan="2">Reservoir</td><td>Initial capacity</td><td>10Mm^3</td></tr>
<tr><td>Max. output:
20MW</td><td>Sediment volume (2016)</td><td>1Mm^3</td></tr>
</table>

As countermeasures to lower the riverbed in its back sand area, it has been carried out dredging (approximately 50,000m^3/year) at no flood season, in condition to minimum water level as free fall condition with fully opened gates. Further, sediment sluicing at flood season will be planned. As test, sediment sluicing has started in 2016 (Fig. 7). The result of sluicing test has been monitored from upstream to downstream of dam about physically and ecological condition, after this it will be estimated with the interested party.

Fig. 7
Photo of sediment sluicing in Setoishi Dam
Photo de sluice sédiments dans Setoishi Dam

3.5. Yambara dam

The Yambara dam reservoir is constructed in 1963 at middle reach of the Kuzuryuu River, which flows westward to the Nihonkai. The Kuzuryuu River has a trunk length of 116km and drains a catchment area of 2,930km^2. The specifications of Yambara dam is shown in Table 5.

Table 5
Specifications of Yambara dam

Catchment Area	143km^2	Dam	Type	Gravity
Design flood	1,060m^3/s		Height	23m
Power plant	Name: Yugami		Crest length	114.6m
		Reservoir	Initial capacity	0.9Mm^3
	Max. output: 54MW		Sediment volume (2016)	0.6Mm^3

The aim of sediment management at Yambara dam is to improvement of the downstream river environment which is not flowed enough sediment volume. So that, for sediment managements sediment sluicing, sediment replenishment and hydro – suction sediment removal system as test were chosen. Sediment sluicing is done by opening the scour gate at flood season. Sediment replenishment is done by temporary storage at high – water channel in downriver after excavating sedimentation in reservoir. Hydro – suction sediment removal system which can intake and discharge sediment using only the water level differences without the mechanical force is developed at our research institute in recent years and tasted in fields at Yambara dam in 2017 (Fig. 8-9).

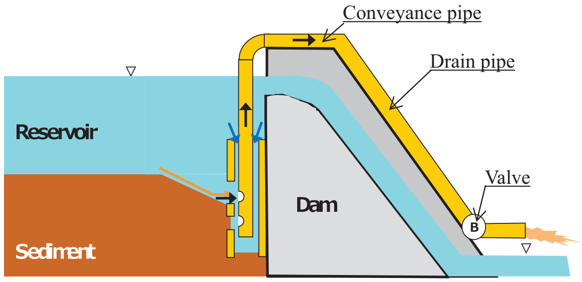
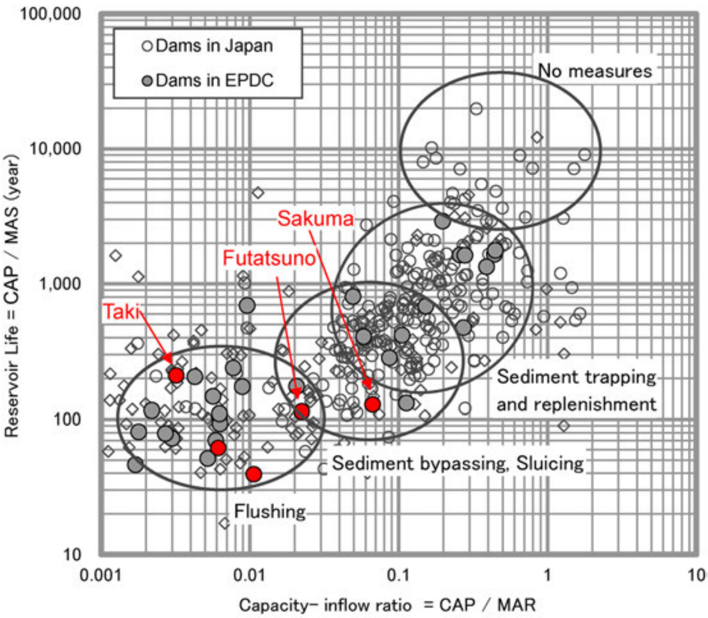


Fig. 8
Layout of Hydro – suction sediment removal system in Yambara Dam
Présentation de l'Hydro - élimination des sédiments dans le système d'aspiration Barrage Yambara

Fig. 9
Photo of Hydro – suction sediment removal system in Yambara Dam
Photo de l'Hydro - élimination des sédiments dans le système d'aspiration Barrage Yambara

4. CASE STUDIES

The sediment management options given in the examples above are influenced particularly a function of both the reservoir life and the capacity inflow ratio. It has been analyzed Japanese dams based on 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) as shown in Fig. 10.



CAP: Original total storage capasity Volume
MAS: Mean annual sediment inflow
MAR: Mean annual runoff
CAP: Capacité totale de stockage d'origine Volume
MAS: Apports sédimentaires annuelle moyenne
MAR: Ruissellement annuel moyen

Fig. 10
Representatibe sediment management options in Japan [5]
Representatibe les options de gestion des sédiments au Japon

At large annual storage dam Sakuma dam the dead storage is filled in sediment storage slowly. If current sedimentation countermeasure will be extend, Sakuma dam reservoir is fully filled with sediment hundreds of years later. According to Fig. 10, Sakuma dam is suited to sediment bypassing or sluicing. But according to past study, these methods are difficult economically. So that to avoid the future condition, Full-fledged sedimentation control measures needed in the near future. In the comparatively smaller Futatuno dam and Taki dam sediments will be planned that bypassing at water intakes from an indirect catchment with diversion in times of floods carrying the majority of fines into reservoir. At small dam, Setoishi dam and Yambara dam are operated like a water intake of a run- of- river hydropower plant with annual flushing. After this, more economic countermeasure with new technical as hydro suction is going to be adopted while doing PDCA.

5. CONCLUSION

Reservoir sedimentation produces directly aggradations of upstream riverbed and obstacle for intake and outlet functions and indirectly leads to operational problems and sediment routing problem with environmental issue of dams downstream sooner or later. Most reservoirs are affected by sedimentation processes. Despite general knowledge of sedimentation processes, these phenomena were largely underestimated or not adequately taken into account in the past design, layout, construction and maintenance of dams and reservoirs. Although hydropower is rightly regarded as a sustainable energy resource and is highly valuable in view of achieving climate protection goals, the sustainable use of storage plants would be questionable without applying adequate reservoir sedimentation management techniques. In spite of no quick remedy to countermeasure reservoir sedimentation dramatically, some methods exist that select suitable options for each reservoir considering with reservoir size, life and basin. Not only the technical feasibility, but also the economic advantages and ecological acceptability should be considered. Five cases from Japanese hydropower reservoir are representative or typical for sediment countermeasure. For sustaining reservoir and hydropower, reservoir sedimentation management will be active and adaptive more and more.

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