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STUDY ON THE APPLICABILITY OF THE ASSET MANAGEMENT FOR RESERVOIR SEDIMENT MANAGEMENT *

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1. INTRODUCTION

In Japan, the asset management is now being introduced in the road engineering and many other areas of public infrastructure, in preparation for a predicted rapid increase in the cost of maintaining all public infrastructures. However, in the dam engineering, mechanical equipments with short service lives such as gates and valves has only been studied, but the applicability and effectiveness of the asset management in this field have not been clarified.

In order to sustain function of dams for more than a century and to avoid the burden of their maintenance cost being concentrated on the next generation, we must clarify challenges to apply asset management to dams, which are made up of a variety of elements such as dam body, spillways, mechanical and electric

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* *Étude sur la pertinence des techniques de gestion du patrimoine à la gestion des dépôts de sédiments dans les retenues.*

equipments with different service lifetimes and functions to lower their life cycle costs (LCC) and to smooth their annual maintenance costs.

Present annual average maintenance cost of dams is a little more than 300 million yen for the dams which were surveyed in Japan, and its largest category is “operation and control equipments” at 20% of the total maintenance cost. In recent years, reservoir sedimentation problems have often occurred and a variety of countermeasures should have been taken with much cost mainly in Chubu and other regions where large sediment loads flow into reservoirs. Sedimentation is also progressing at reservoirs where the sediment production is not particularly high among many dams constructed in 1950-1960, it is estimated that sedimentation will reach the planned level between 40 and 50 years from the present day [1]. In the near future, strategic dam asset management including preventive countermeasures for reservoir sedimentation will be an important challenge.

The Japan Water Agency maintains a group of water resource development dams consisting of five dams including Takayama Dam which was completed in 1969 on the upstream of Kizu river (Fig. 1). This research is focusing on these dams to study how to prolong their service lifetimes through sedimentation countermeasures and to clarify precautions to apply the asset management procedure to dam reservoirs by taking sedimentation countermeasures.

2. ORGANIZATION OF THE STATE OF SEDIMENT DEPOSITION IN KIZU RIVER UPSTREAM DAM GROUP

Table 1 shows the state of sedimentation in the Kizu River upstream dam group (FY2006). It shows that sedimentation of 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 Takayama Dam, Shorenji Dam, and Muroo Dam which were constructed more than 30 years ago have already reached 40 to 50% of the planned sedimentation. Regarding the annual fluctuation of sediment load at the Takayama Dam, annual average sedimentation is approximately 100,000m^3 and the maximum one in a single year is up to 620,000m^3. The maximum annual sedimentation at the other dams is about 5% to 12% of planned sedimentation capacity, and the past maximum sedimentation in a single year was equivalent to that occurring in a 5 to 12 year period (Table 2) [2].

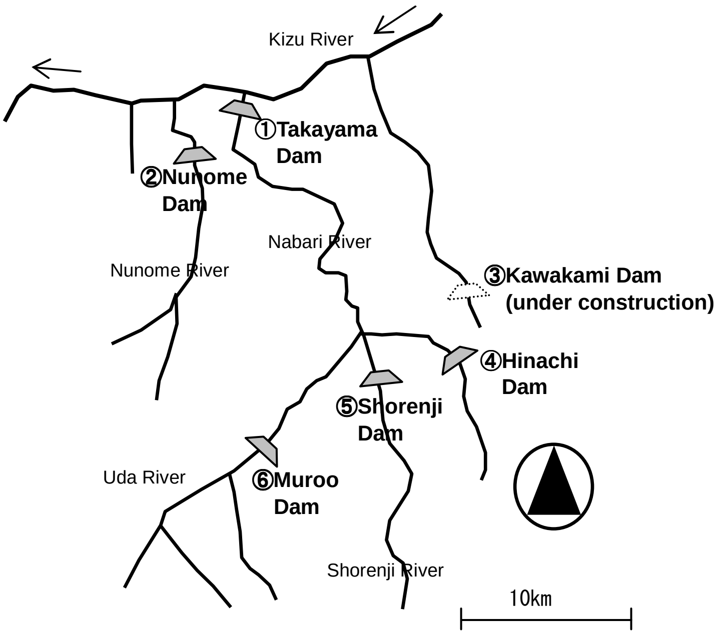

Fig. 1
Kizu River Upstream Dam Group on the Yodo River System
Ensemble de barrages situés en amont de la rivière Kizu sur le système fluvial de la rivière Yodo

(1) Barrage de Takayama
(2) Barrage de Nunome
(3) Barrage de Kawakami
(en cours de construction)
(4) Barrage de Hinachi
(5) Barrage de Shorenji
(6) Barrage de Muroo

Table 1
Sedimentation Rate of the Kizu River Upstream Dam Group (2006)
Vitesse de sédimentation de l'ensemble de barrages situés en amont de la rivière Kizu (2008)

	Years elapsed	Planned sedimentation capacity in 100 years (10^3m^3)	Actual sedimentation in 2006(10^3m^3)	Sedimentation rate
Takayama Dam	37	7,600	3,648	48.1%
Shorenji Dam	36	3,400	1,484	43.6%
Muroo Dam	32	2,600	1,120	43.1%
Nunome Dam	16	1,900	243(344)	12.8% (18.1%)
Hinachi Dam	9	2,400	410	17.1%

※ Sedimentation rate in the above table is a value based on the planned sedimentation
※ The values in brackets for the Nunome Dam represent sediment already dredged from its auxiliary dam

Table 2
Actual Maximum Annual Sedimentation in the Upstream
Kizu River Dam Group
Quantité annuelle maxi. de la sédimentation de l'ensemble de barrages situés en amont de la rivière Kizu

	Planned Sedimentation capacity in 100 years(10^6 m^3)	Actual maximum annual sedimentation		
		Sedimentation (10^3 m^3)	Percentage of planned sedimentation capacity	Occurrence probability assessment
Takayama Dam	7.6	621	8.2%	1/52 years
Shorenji Dam	3.4	336	9.9%	1/35 years
Muroo Dam	2.6	314	12.1%	1/45 years
Nunome Dam	1.9	230	12.1%	1/51 years
Hinachi Dam	2.4	140	5.8%	1/12 years

3. ASSET MANAGEMENT OF DAMS THROUGH SEDIMENTATION COUNTERMEASURES

3.1. STATE OF ASSET MANAGEMENT OF DAMS THROUGH SEDIMENTATION MEASURES [3]

Efforts have been made to introduce the asset management in many fields including paving, bridges, ports and harbors, water supply and sewage systems, and so on, in the face of the soaring cost of maintaining the expanding stock of public infrastructures and resulting financial dilemmas. The purposes of the asset management is to reduce life cycle costs and smooth the burden of paying these costs in order to improve efficiency, and at the same time to clarify and to fulfill the responsibility to explain the relationship between covering maintenance cost and the level of services.

Efforts have been made to apply the asset management to machinery and equipment with short service lifetimes used at dams, to diagnose the deterioration of hydropower dams [4] and to survey the state of dam maintenance costs [5]. But an overall image of the asset management including dam bodies has not been clarified. This is presumably a result of the fact that a dam body has such a long service lifetime which is difficult to specify, and that the need to discuss the optimum repair plan is generally low at a relatively new dam.

State Water which is an enterprise owned by the State of New South Wales in Australia has prepared the Total Asset Management Plan, and evaluates dam risk and presents examples of the grounds for the price of water [6]. It also touches on the difficulty of applying the optimum renewal decision method to major facilities with lifetimes that exceed 200 years and for which there is no standard deterioration curve. The U.S. Bureau of Reclamation uses facility reliability indices based on restrictions on reservoirs and their operation, and on response to safety advisories to perform the asset management of important dams.

3.2. APPLICATION OF THE ASSET MANAGEMENT TO DAMS

Infrastructure assets (infrastructure assets for daily human life) are generally predicted to be used semi-permanently and characterized by long service lifetimes. In case of dams, dam body that is the major asset is also assumed to have an extremely long service lifetime, but it is important to evaluate its reliability since deterioration of the body could have serious consequences.

A breakdown of normal maintenance costs based on research by Kondo et al. [5], shows that a little more than 20% are “operating and control equipments” costs, between 10% and 15% are “discharge and intake equipments”, “repairs and other maintenance and management equipments”, and “reservoir countermeasures” costs respectively. Cost reductions are expected to be achieved through the asset management mainly in the cost analysis of maintaining machinery and equipment, and electrical equipment etc. which have relatively short service lives.

Sedimentation is handled by setting 100 year capacity as the planned sedimentation capacity. But it is possible to prolong service lifetimes by taking appropriate sedimentation countermeasures which play an important role in the study of the life cycle costs of dams.

Since, as explained above, the duration of service life and the priority of management activity vary between facilities, it is necessary to apply asset management according to these differences (Table 3).

The level of services provided to manage assets usually varies according to needs. In particular, when its object is an extremely long period, it is difficult to determine needs. At the decision making level, it is classified as shown in Table 4.

Table 3
Categorization of Facilities and Management Priorities by Renewal Period
Catégorisation des installations et des priorités de gestion
par la fréquence de renouvellement

Renewal period	Facility etc.	Management Priorities	Remarks
Short (a few years to a few decades)	- Machinery & equipment - Electrical equipment - Buildings	- Reducing total cost of inspections, improvement, repair, and renewal	- Improving the service level - Responding to technological progress
Long (a few decades to a few centuries)	- Reservoir (sedimentation)	- Prolonging service lifetime - Lowering life cycle costs	- If appropriate measures are taken, renewal period is prolonged.
Super long (unclear)	- Dam body	- Inspections - Reducing maintenance costs - Risk assessments	- If appropriate management is performed, renewal is unnecessary for a very long time, and the present value of renewal costs cannot be assessed.
Contingent	- Reservoir slopes - Landslides - Earthquake response etc.	- Inspections - Emergency response	- Response when constructing to a stipulated level.

Table 4
Categorization Based on Decision-making Level
Catégorisation en fonction du niveau de prise de décision

	Decision-making level	Implementing organization level
Body	- Policy-making departments of governmental and public bodies.	- Implementation departments of governmental and public bodies (Japan Water Agency)
Service level	- Judgments accompanying change of service level - Decisions to construct, improve functions, or to demolish	- Ensuring a service level stipulated by policies - Construction and maintenance of structures stipulated by the plan
Means to satisfy responsibility for explanation	- River improvement plans, basic water resource development plans, policy evaluations.	- Annual reports, evaluation committee, project evaluation, implementation plan, maintenance plan, explanations for users etc.
Principal evaluation indices	- Effectiveness of policies	- Efficiency of ensuring service level

3.3. ASSET MANAGEMENT OF DAMS BY SEDIMENTATION COUNTERMEASURES

Reservoir sedimentation volume is clarified by periodical measurements. In general, sedimentation countermeasures are taken only in the cases of increasing sedimentation has obstructed the functions of dams. Therefore, large scale sedimentation countermeasures were taken often including disaster restoration following the inflow of sediment or redevelopment to ensure reservoir capacity. Dams where no particular obstruction of reservoir functions has occurred, only sedimentation surveys are performed.

When a large-scale sedimentation countermeasure is taken, obtaining a large area of disposal site is important, and it is necessary to reduce costs by sediment recycling and by taking advantage of the tractive force of the river. Since blocking the continuity of sediment transport by dams impacts river, coastline and the ocean environment, it is necessary to restore sediment downstream from dams. However, the quantity of sediment must be restored downstream to conserve the environment and the environmental benefits of this downstream restoration have not been evaluated.

Therefore, by clarifying that taking sustained sedimentation countermeasures are beneficial from the cost perspective through the asset management, it is possible to reduce life cycle costs and the environmental impacts of dams at the same time.

3.4. COST OF IMPLEMENTING COUNTERMEASURES

Makio Dam received the inflow of vast quantities of sediment as a result of Nagano Prefecture West Earthquake (1984) for a total of 9 years, sedimentation countermeasures were taken to remove approximately 5.48 million m^3 of sediment at a total cost of about 30 billion yen [7].

a) If it is assumed that the project cost per cubic meter is identical to Makio Dam, it would cost from 10 to 40 billion yen per dam for removing sediment equal to the sedimentation capacity of the entire Kizu River dam group (1.9 to 7.6 million m^3/dam).

b) If it is impossible to obtain a disposal site near a dam and it is assumed that, at the most, costs are incurred transporting sediment to the sea, the sediment treatment cost per unit of volume for the transportation distance L (km) is represented by Eq[1] according to Oya et al. [8].

$$C = p \cdot L + q \qquad [1]$$

where C =sediment disposal cost; p = 75 yen/m^3/km and q = 3,000 yen/m^3 based on research by Oya et al. From the upstream dams on the Kizu River to Osaka Bay, L = approx. 100km, so the cost of disposing of sediment equal to the sedimentation capacity of each dam increased from about 20 to 80 billion yen.

It means that, by the simple average for 100 years of each dam, the cost is 100 million yen to 400 million yen/year in case a) and it is from 200 million yen to 800 million yen/year in case b).

Considering that it will accumulate every year as countermeasures are needed for the next fifty years, the amount needed each year can be represented by Eq[2].

$$C_r = \frac{C_t \cdot r}{(1+r)^n - 1} \qquad [2]$$

where C_r = annual required amount;, C_t =countermeasure project cost; interest rate r = 4%; accumulation period n = 50 years. In case a), it is from 70 million to 260 million yen/year, and in case b) it is from 130 million to 920 million yen/year.

According to research by Kondo et al. [5], the average annual maintenance cost of the existing dams is a little more than 300 million yen and "operation and control equipments" costs that account for more than 20% of total costs, is the highest cost category. If it is premised that the dams will function for more than 100 years, the sedimentation countermeasure cost may exceed this cost category. Therefore, it is important to apply asset management not only to the electrical and the machinery equipment categories that are now the major maintenance cost categories, but also to sedimentation countermeasures.

3.5. SEDIMENTATION COUNTERMEASURE IMPLEMENTATION SCENARIOS

If these measures are simplified premised on sustaining function of dams for a long period exceeding a century, three scenarios can be considered (Fig. 2); taking measures to smooth the inflowing sediment load after the service level has been reduced in the absence of countermeasures (Scenario 1), ensuring the initially planned 100 year sedimentation capacity by taking large scale restoration measures after the service level has been reduced in the absence of countermeasures (Scenario 2), and reducing the frequency of large scale restoration measures by taking sedimentation control measures (Scenario 3).

With sustained measures, restoring sediment downstream using the tractive force of the river can mitigate the blockage of sediment transport by the dam, and simplify the task of utilizing the sediment as a resource. On the other hand, in order to implement large-scale restoration, large disposal site and transportation system are necessary and they may cause the environmental adverse impacts whose cost cannot be evaluated. (Table 5)

Table 5
Comparison of Continuous Measures and Large-scale Restoration
Comparaison des mesures continues et
et de la restauration lourde

	Continuous measures	Large-scale restoration
Transportation, Disposal site	Tractive force of the river can be used.	Requires a large disposal site and transport system
Environmental impact	Blockage of sediment transport by restoring sediment downstream.	Environment impact caused by muck yard and transport road
Effective utilization	Simplifies effective utilization of sediment as a resource	Difficult to effectively use the sediment as a resource

If the inflowing sediment load is small or the river flow rate is so high that the hydraulic flushing removes large quantity of sediment load, Scenario 1 is effective by taking smoothing measures that is inflowing sediment load = discharged sediment load. If it is easy to obtain a sediment processing site and to transport sediment, Scenario 2 is effective. If, in addition to the reduction in tractive force caused by the construction of the dam, the region around the dam is urbanized so that it is difficult to dispose of or to transport the sediment, it is necessary to study combining measures and the time to implement them based on Scenario 3: performing sedimentation control measures to postpone large-scale restoration as long as possible and to minimize its frequency.

Scenario 3 becomes Scenario 1 and 2 depending both on an initial investment and its implementing time, and on continuous measures and their starting time. Therefore, there is also a generalized investment Scenario for cases premised on permanent reservoir maintenance.

Normally, to consider life cycle cost, the study includes the cost of decommissioning, but when investment is made looking ahead 200 years into the future, the present price based on the normal discount rate of 4% becomes zero and cannot be evaluated. Therefore, premised on a dam’s functions being maintained for a long period, the life cycle cost can be represented by Eq[3].

$$LCC = \sum C_i + \sum C_m + \sum C_r \qquad [3]$$

where LCC = life cycle cost of sedimentation countermeasure, C_i = initial investment, C_m = sustained countermeasure cost (converted to present prices by Eq[3]), C_r = cost of large-scale measure (converted to present prices by Eq[3]). It means that although sedimentation countermeasures differ from reconstructing a facility as in the case of roads, bridges, etc. (demolishing and reconstructing an old facility), it is possible to represent in a form such that the large scale restoration resembles the renewal of another facility.

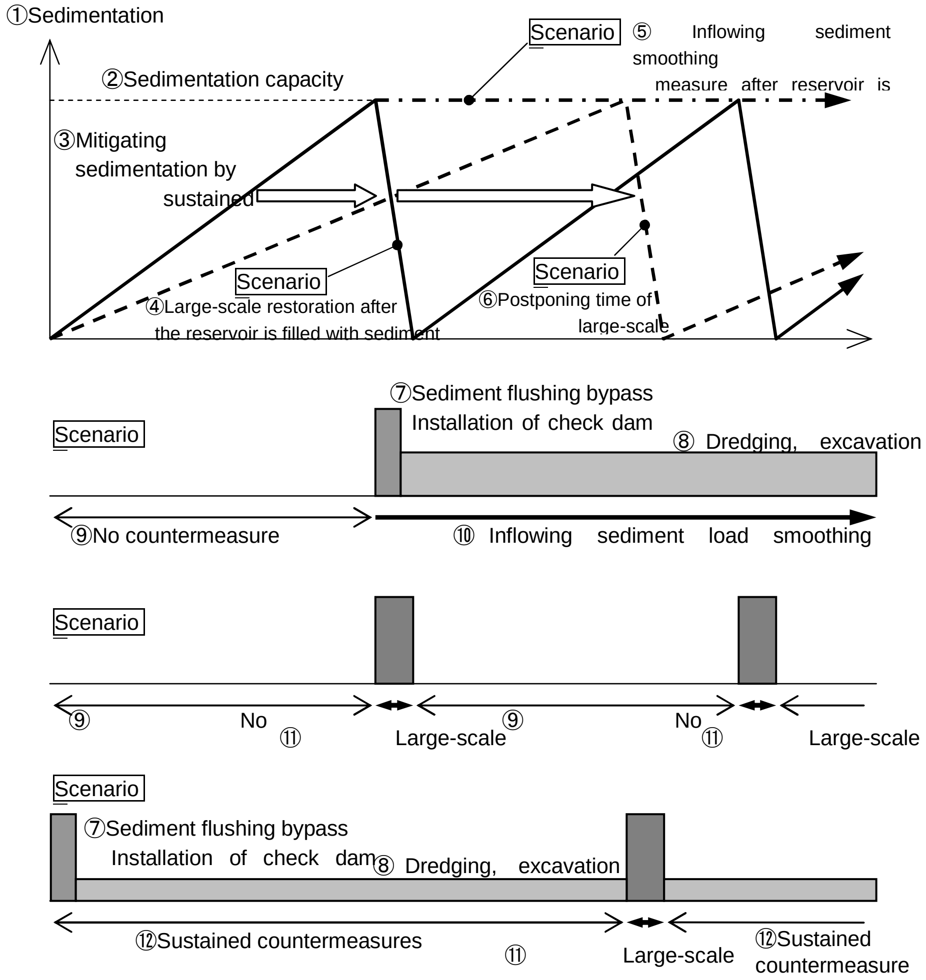

Fig. 2

Schematic of Sedimentation Countermeasure Scenarios and their Costs
Visualisation graphique des contre-mesures concernant la sédimentation et leurs coûts respectifs

(1) Sédimentation,
(2) Capacité de sédimentation,
(3) Réduction de la sédimentation par des mesures durables
(4) Restauration lourde lorsque le réservoir est rempli de sédiments
(5) Mesures visant à réduire les sédiments entrant dans le réservoir lorsque celui-ci est rempli de sédiments
(6) Durée de renvoi d'une restauration lourde
(7) Chasse, by-pass, contre les barrages
(8) Dragage, etc
(9) Aucune contre-mesures
(10) Mesures facilitant la décharge des sédiments entrants
(11) Restauration lourde
(12) Contre-mesures durables

4. APPLICATION OF SEDIMENTATION COUNTERMEASURES TO THE KIZU RIVER UPSTREAM DAM GROUP

4.1. STUDY CONDITIONS

Table 6 shows the sedimentation countermeasures were studied and key points in long-term management.

4.1.1. Clarifying the properties of sedimentation in each dam reservoir

Since sediment can be removed depended on its particular diameter by each sedimentation countermeasure, the particular diameter of the inflowing sediment load is an important factor to study the applicability of various countermeasures. The particle diameter of inflowing sediment load is classified into three categories: washload (d≦0.075mm), sand (0.075<d<2.0mm), and gravel (2.0mm≦d). Table 7 shows the results of the clarification of the properties (quantity and quality) of inflowing sediment load and deposited sediment load in the Kizu River upstream dam group.

4.1.2. Setting the target sedimentation rate

As stated above, the actual maximum annual sedimentation (maximum value of inflowing sediment load occurring unexpectedly) is approximately from 5% to 12% of the planned sedimentation capacity. When a dam is operated independently without backup dams, to ensure stable reservoir functions even in the event of an unexpected inflow of sediment, the capacity of sedimentation should be maintained constantly to ensure leeway from about 5% to 12%. So the target sedimentation rate for case studies of each dam when operated independently was set at 80%. (Assuming that sedimentation load in the reservoir is controlled within 80% of the planned sedimentation capacity).

4.2. CASE STUDY OF TAKAYAMA DAM

A case study was carried out on sedimentation countermeasures at Takayama dam that is located at the furthest downstream of the dam group and is the largest reservoir among them.

4.2.1. Effects and costs of countermeasures

a) Cost of dry excavation with the reservoir emptying

In addition to normal sedimentation countermeasure methods, “dry excavation” is also compared (see Table 6). Dry excavation is performed by stopping its operation for one year at an interval of a specified number of years, completely emptying the reservoir and removing sediment by dry works. Therefore, to perform dry excavation, it is necessary to carry out a comparative study with other methods to determine whether or not it is effective considering the tradeoff such as demerits by the loss of reservoir functions caused by draw down operation and merits of removing sediment by low cost dry excavation.

Table 6
Sedimentation Countermeasures Studied
Étude des contre-mesures portant sur la sédimentation

Countermeasure	Focus and costs incurred
Excavation	Mechanically discharging natural soil from inside the reservoir onto the land - Initial investment: none in particular - Running cost: excavation cost
Dredging	Mechanically discharging sediment from inside the reservoir onto the land. It is more costly than excavation. - Initial investment: none in particular - Running cost : dredging cost
Sediment check dam (+ Excavation)	Installing a sediment check dam at the upstream end of the reservoir and mechanically discharging sediment captured in the check dam from the check dam onto the land. - Initial investment: cost of building a sediment check dam - Running cost: cost of excavating the sediment check dam
Flushing	Temporarily draw down to create an open channel flow inside the reservoir so that tractive force will flush out the sediment. - Initial investment: installing a sediment flushing gate - Running cost: Wear prevention measures of flushing gates and channels, and according to circumstances, compensation for reduced energy generation
Sediment bypass	Bypassing inflowing sediment load downstream through a tunnel so it does not settle in the reservoir. - Initial investment: Installing the sediment bypass - Running cost: Wear prevention measures of tunnel invert
Dry excavation with the reservoir emptying	Once each specified number of years, completely reservoir emptying so that all deposited sediment is moved to the land by dry excavation. - Initial investment: none in particular (when there is no draw down system, it must be installed) - Running cost: excavation, compensation for reduced energy generation, compensation for capacity loss

The cost of dry excavation should include the loss of the capacity itself caused by reservoir emptying in addition to compensation for reduced power generation and excavation unit price. This loss-cost can be calculated as below.

Table 7
Properties of the Inflowing and Deposited Sediment at the
Kizu River Upstream Dam Group
Propriétés des sédiments entrants et déposés dans l'ensemble de barrages situés en amont de la rivière Kizu

	Annual average inflowing sediment load (m^3)	Annual inflowing sediment load by particle diameter (m^3)			Washload capture rate	Average annual sedimentation (m^3)	Annual sedimentation by particle diameter (m^3)		
		Washload ≦0.075mm	Sand 0.075<<2.0mm	Gravel 2.0mm≦			Washload ≦0.075mm	Sand 0.075<<2.0mm	Gravel 2.0mm≦
Takayama Dam	104,550	46,770 44.7 %	53,380 51.1 %	4,400 4.2 %	44.3%	78,500	20,720 26.4 %	53,380 68.0 %	4,400 5.6 %
Shorenji Dam	41,740	29,080 69.7 %	11,390 27.3 %	1,270 3.0 %	57.9%	29,500	16,840 57.1 %	11,390 38.6 %	1,270 4.3 %
Muroo Dam	45,510	31,070 68.3 %	14,250 31.3 %	190 0.4 %	73.9%	37,400	22,960 61.4 %	14,250 38.1 %	190 0.5 %
Nunome Dam	23,550	15,400 65.4 %	7,980 33.9 %	170 0.7 %	82.8%	20,900	12,750 61.0 %	7,980 38.2 %	170 0.8 %
Hinachi Dam	56,810	36,760 64.7 %	19,860 35.0 %	190 0.3 %	71.4%	46,300	26,250 56.7 %	19,860 42.9 %	190 0.4 %

If excavation is done during a non-flood period, only the water use capacity is used. Therefore, the loss-cost for the lost reservoir capacity is calculated by allocating the cost of water supply capacity to the operator of a multi-purpose dam (allocation cost). However, the following study uses the relationship of the cost allocation with the water use capacity at the Hinachi Dam that is the newest of the Kizu River upstream dam group.

- Assuming that the water use function can be provided for 100 years, the cost per unit capacity ($1m^3$) per year is calculated as:
- (cost of water use capacity)/ (water use capacity) / (100 years).
- Based on the above, it is possible to calculate the loss-cost for stopping the operation for one year.

If the cycle of emptying the reservoir is long, sudden sedimentation will likely occur. Considering the fact that there is a 1/10 year to 1/50 year probability of the occurrence of the maximum annual sedimentation that has occurred in the past in the Kizu River dam group, this study assumes that the reservoir will be emptied every 10 years. Table 8 shows the cost-loss of dry excavation with the reservoir emptying as calculated based on conditions at the Hinachi Dam. Table 9 also shows costs necessary to perform water level draw down excavation at the Takayama Dam based on the above.

Table 8
Loss of Capacity by the Draw Down
(Calculated based on the Hinachi Dam)
Perte de la capacité en raion des dépôts
(calculée sur la base des données concernant le barrage de Hinachi)

Water supply capacity	Allocation of cost of water for public water supply systems	Annual required cost for 100 years of water supply services	Capacity unit price
15.3 million m^3	¥34,843,490,000	¥348,435,000	23 yen/m^3/year

Table 9
Cost Required to the draw down at Takayama Dam
(once/10 years)
Coût de la vidange du barrage de Takayama
(une fois tous les 10 ans)

Compensation for reduction of power generation	Cost-loss of capacity loss
43.7 million yen/year (unit price: 8.76 million yen/hr)	31.740 million yen (Actual loss 317.4 million yen/time)

b) Effects and cost of the sedimentation countermeasures

The effects of implementing each sedimentation countermeasure hypothesized by this study are organized considering the application to the study of maintenance plans over long periods of time, and hypothesizing the “annual sediment removal rate (percentage of inflowing sediment load which can be removed by taking the countermeasure)”. The effects and costs of each sedimentation countermeasure are presented on Table 10.

Table 10
Effects and Cost of Implementing the Sedimentation Countermeasure Menu
Coût et effets de la mise en oeuvre de l'ensemble des contre-mesures concernant la sédimentation

	Cost		Inflowing load removal rate(%)*			Annual sediment removed (m^3/year)		
	Investment to build the facility (initial cost)	Running cost	Wash-load	Sand	Gravel	Washload (*including natural removal) Inflowing sediment 46,770	Sand Inflowing sediment 53,380	Gravel Inflowing sediment 4,400
Excavation	—	4,000 yen/m^3	10%	50%	100%	28,123	26,690	4,400
Dredging	—	35,000 yen/m^3	100%	100%	100%	46,770	53,380	4,400
Sediment check dam (+ excavation)	5.4 billion yen/dam (sediment check dam)	4,000 yen/m^3	10%	70%	100%	28,123	37,366	4,400
Flushing	10,1 billion yen/channel (sediment flushing gate installation)	22 million yen/year	100%	100%	50%	46,770	53,380	2,200
Sediment bypass	13.163 million/channel (constructing sediment bypass)	121 million yen/year	50%	60%	100%	36,410	32,028	4,400
Dry excavation with the reservoir emptying	—	2,500 yen//m^3 (excavation cost) 75 million yen/year (compensation for reduction of power generation, water supply loss)	100%	100%	100%	46,770	53,380	4,400

*Inflowing load removal rate (%): Assumed by the sedimentation measures case in Japan [2]

4.2.2. Study of combined countermeasures

The previous section of this report presented the sediment removal rate of each type of countermeasure. Aside from dredging and dry excavation, sedimentation will continue until eventually the sedimentation capacity is exhausted since these measures cannot achieve removal rates of 100%. Considering the need to continuously ensure reservoir functions, it has been hypothesized that even after these countermeasures have been taken, dredging or dry excavation are also performed at the point where the target sedimentation rate has been reached. Table 11 shows the effectiveness and the cost of implementing combinations of countermeasures. This results show that countermeasures except flushing are effective when combined with dry excavation. In case of sediment flushing, it is more effective to combine with dredging since there is little residual sediment after flushing and dry excavation is relatively costly (because of the small quantity handled).

Table 11
Results of Studies of Combination Countermeasures
Résultats des mesures combinées

	Quantity removed (m^3/year)	Quantity which cannot be completely removed (m^3/year)	[Proposed combination] Annual cost (1,000 yen)	
			Dredging	Dry excavation
Sediment check dam (＋excavation)	69,889	34,661	1,213,135	214,084
Excavation	59,213	45,337	1,586,795	256,788
Sediment bypass	72,838	31,712	1,109,920	202,288
Flushing	102,350	2,200	77,000	84,240

4.2.3. Evaluating the proposed sedimentation countermeasures at the Takayama Dam

The super long-term sediment control plan for the Takayama Dam was studied by evaluating the combinations suggested above. The results are shown in Fig. 3, Fig. 4, and Table 12. Since investment in the future exceeding 200 years is difficult to evaluate as it reaches almost zero in current prices, the evaluated cost is the total cost converted to current prices 300 years in the future. Based on this concept, the proposed countermeasure based on [excavation + dry excavation] is the most economical solution. Sediment bypass and flushing countermeasures provide low sedimentation rate, but their initial investment means that they are uneconomical in terms of their total cost.

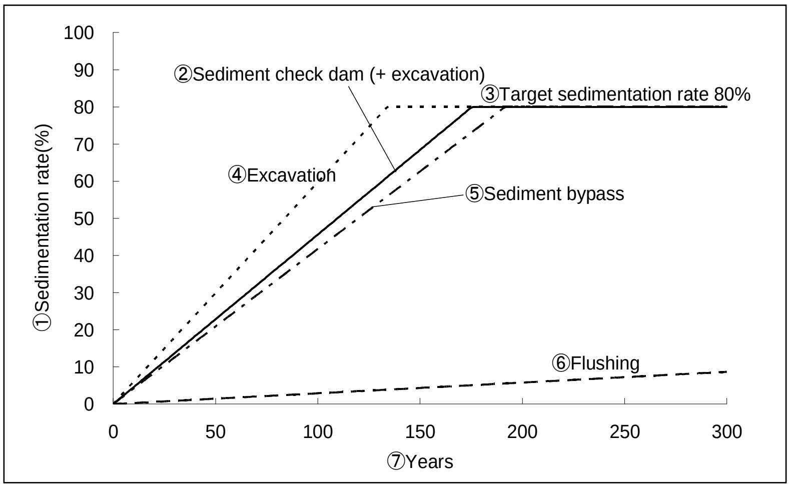

Fig. 3
Takayama Dam: Change Over Time of Sedimentation Rate by Each Sedimentation Countermeasure
Barrage de Takayama ; Évolution dans le temps de la vitesse de sédimentation en fonction de chaque contre-mesure spécifique

(1) Taux de sédimentation (%)
(2) Barrage de contrôle de la sédimentation (+ excavation)
(3) Taux de sédimentation visé : 80%
(4) Excavation
(5) By-pass sédiments
(6) Chasse
(7) Années

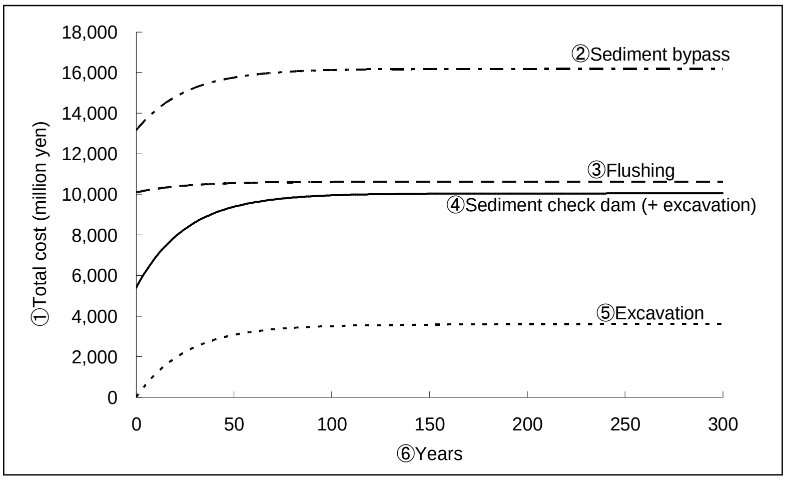

Fig. 4
Takayama Dam: Change Over Years of Total Cost by Each Sedimentation Countermeasure
Barrage de Takayama ; Évolution dans le temps du coût total en fonction de chaque contre-mesure spécifique prise contre la sédimentation

(1) Coût total (en millions de yens)
(2) Dérivation concernant les sédiments
(3) Chasse
(4) Contre-barrage (+excavation)
(5) Excavation
(6) Années

4.3. STUDY OF APPLICABILITY OF SEDIMENTATION COUNTERMEASURES

4.3.1. Study method

The results of the study on Takayama Dam were used to study the applicability of the same proposed sedimentation countermeasures to other four dams (Hinachi, Shorenji, Muroo and Nunome Dams). Table 13 was based on the Takayama Dam. It organizes the basic methods of calculating the cost of sedimentation countermeasures at each dam.

Table 12
Total Cost of Each Countermeasure After 300 Years
Coût total de chaque contre-mesure après 300 ans

Countermeasure	Combined with	Total cost after 300 years (million yen)
Sediment check dam (+ excavation)	+ Dry excavation	10,050
Excavation	+ Dry excavation	3,609
Sediment bypass	+ Dry excavation	16,191
Flushing	+ dredging	10,625

Table 13
Basic Methods of Calculating Sedimentation Countermeasure Cost at Each Dam
Principes des méthodes de calcul du coût des contre-mesures pour chaque barrage concerné

Sediment check dam (+ excavation)	- The land acquisition cost (impact on back water of sediment check dam) is calculated using specific dam body area of the sediment check dam based on the specifications of the Takayama Dam.
Sediment bypass	- Tunnel cost computed by same unit price as Takayama Dam - The body volume of the diversion dam is calculated based on the specific sedimentation capacity of each dam based on the specifications of the Takayama Dam - The cost of the intake gate is the same as at the Takayama Dam. - Land acquisition cost is the same as that at the Takayama Dam - Tunnel diameter is the same as in the specifications of the Takayama Dam
Flushing	- The sediment spillway used for flushing is a 1,000m tunnel assuming it is bored in natural rock at all dams. - Costs of training dam, intake gate, etc. are same as those at the Takayama Dam. - Tunnel diameter and compensation for reduced power generation are identical to those at the Takayama Dam (Nunome and Muroo Dams do not generate power, so compensation for reduced power generation are not counted for these dams.)

4.3.2. Evaluating the proposed sedimentation countermeasures at each dam

Super long-term sediment control plans for four dams in addition to Takayama Dam (Hinachi, Shorenji, Muroo and Nunome Dams) were studied. The results are shown in Table 14. The table shows that at all dams, as in the case of Takayama Dam, the countermeasure of “excavation + dry excavation” is economically beneficial. This clearly shows that the applicability of proposed countermeasures such as sediment bypass or flushing which are implemented by making a facility investment at the initial stage and are intended to reduce the inflowing sediment is relatively low since the overall inflowing sediment load is small in the Kizu River dam group.

Table 14
Kizu River Upstream Dam Group: Total Cost After 300 Years of Each Countermeasure (unit: million yen)
Ensemble de barrages situés en amont de la rivière Kizu : Coût total après 300 ans de mise en oeuvre des contre-mesures (Unité : en millions de yens)

Countermeasure	Combined with	Takayama Dam	Shorenji Dam	Muroo Dam	Nunome Dam	Hinachi Dam
Sediment check dam (+excavation)	Dry excavation	10,050	4,526	3,729	2,453	3,506
Excavation	Dry excavation	3,609	987	1,043	570	1,384
Sediment bypass	Dry excavation	16,191	24,111	29,769	20,226	18,765
Flushing	Dredging	10,625	10,625	10,575	10,575	10,625

If the inflowing sediment load at each dam is assumed to be 4 times of the present volume (see Table 2) are shown in Table 15 (For example, trial calculation of the average annual sedimentation is 314,000m^3 (78,500m^3 × 4 times) at Takayama Dam). According to this concept, the applicability of flushing and sediment bypass will be improved overall. This result confirms the fact many cases of flushing and sediment bypass measures have been taken on the Tenryu River System [9] [10], and these long-lasting sediment countermeasure facilities are presumably effective over the long term.

Table 15
Kizu River Dam Group: Total Cost of Each Countermeasure After 300 Years [Assuming the inflowing sediment load is 4 times of the present volume]
Ensemble de barrages situés en amont de la rivière Kizu : Coût total de chaque contre-mesure (En supposant que la charge des sédiments entrants est 4 fois supérieure au niveau actuel)

Countermeasure	Combined with	Takayama Dam	Shorenji Dam	Muroo Dam	Nunome Dam	Hinachi Dam
Sediment check dam (+excavation)	Dry excavation	26,781	8,545	8,795	4,741	10,620
Excavation	Dry excavation	19,583	4,533	5,672	2,446	8,038
Sediment bypass	Dry excavation	18,405	24,180	30,036	20,237	19,354
Flushing	Dredging	10,625	10,625	10,575	10,575	10,625

4.4. Precautions when Studying Asset Management of the Kizu River Upstream Dam Group

Based on the results of the above study, there are some precautions to implement the asset management at the Kizu River upstream dam group in the future.

4.4.1. Restoring excavated sediment to the downstream river

From the points view of sustainable countermeasures of reservoir sedimentation and the continuity of sediment movement in the sediment routing system, sediment which has been excavated and removed from each reservoir should be placed downstream and allowed to return to the downstream river course. The quantity of sediment disposed of this way is restricted by conditions A to C shown in Fig.5.

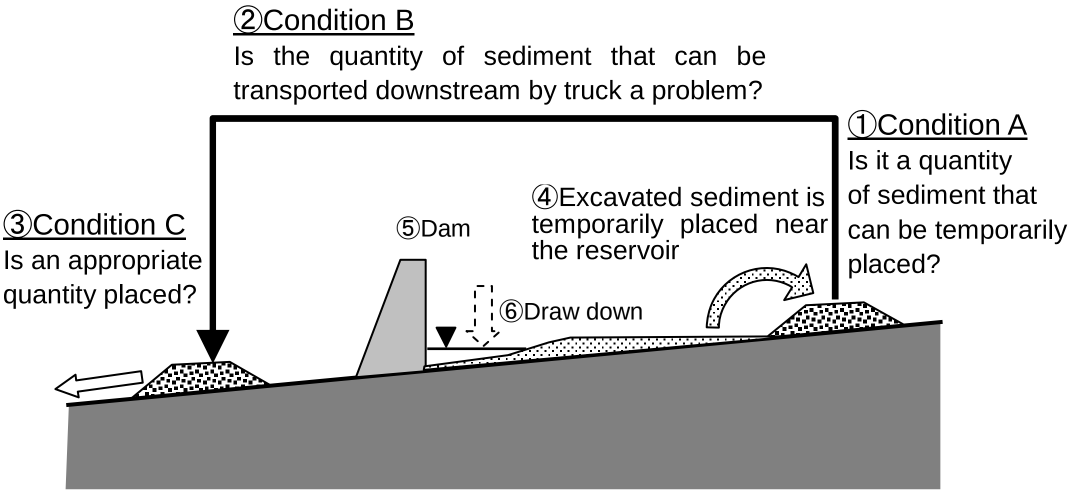

Fig. 5
Method of Disposing Sediment to Restore it to the Downstream River
Méthode de traitement des sédiments à rendre à la rivière en aval

(1) Condition A: Est-ce qu'il s'agit d'une quantité de sédiments qui peut être déposée temporairement ?
(2) Condition B: Est-ce que la quantité transportable en aval par camion pose un problème ?
(3) Condition C: Est-ce qu'une quantité appropriée est déplacée ?
(4) La quantité de sédiments excavés est elle placée à proximité du réservoir ?
(5) Barrage
(6) Drawdown

4.4.2. Study of optimization of sediment removal methods

The study should focus on the following points in order to achieve more efficient sediment removal.

a) As the result of this study, it has been shown that the dry excavation with the reservoir emptying is economically feasible even if it needs compensation both for reduced power production and water use loss rather than other countermeasures requiring initial facility investment such as sediment bypass, flushing sediment etc.
b) The above results suggest the possibility of "the optimization of sediment removal methods as a dam group" that is removing sediment with low costs by linking a dam group.

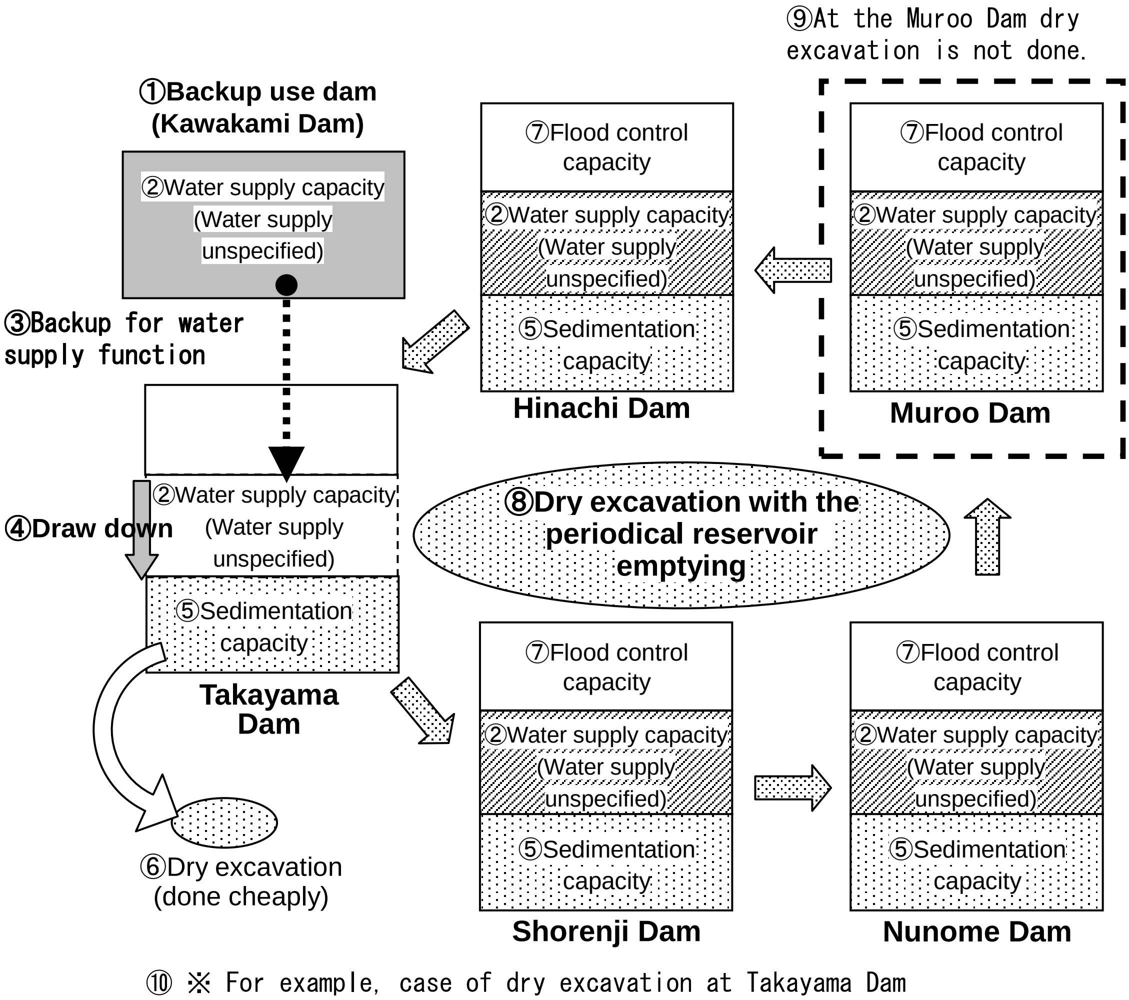

Fig. 6
Schematic Diagram of Integrated Operation of Dams by an N+1th Dam
Diagramme schématique de l'exploitatoin intégrée des barrages par la méthode N+1ème barrage

(1) Barrage de réserve (Barrage de Kawakami)
(2) Capacité de l'approvisionnement en eau (volume de l'approvisionnement en eau non spécifié)
(3) Réserve destinée à l'approvisionnement en eau
(4) Dépôt
(5) Capacité de sédimentation
(6) Excavation à sec (effectuée à coût élevé)
(7) Capacité de contrôle des crues
(8) Excavation à sec accompagnée d'un vidange périodique du réservoir
(9) Les excavations à sec ne sont pas effectuées pour le barrage de Muroo
(10) Par exemple ; le cas d'une excavation à sec concernant le barrage de Takayama
(11) Excavation à sec méthode économique
(12) Volume de stockage des crues

Based on the these results, considering the fact that it is difficult to pay compensation for water use loss which dry excavation actually causes, and that dry excavation is performed with low costs in the future, long-term maintenance based on the integrated operation including backing up water supply capacity and ensuring potential water resources, etc. must be studied in order to "optimize sediment countermeasures as a dam group." Fig. 6 shows a schematic diagram of coordinated dam group operation by N+1 dams. The minimum number of dams considered to be essential is N dam and +1 is installed for maintenance.

- Dry excavation with the reservoir emptying which is inexpensive because it is land excavation is performed at all dams in rotation, and a dam is positioned as a "refresh dam" while the draw down.
- The N+1th dam provides supplementary backup for the decline in reservoir functions while the draw down.

CONCLUSION

In this study, inflowing sediment properties and a variety of sedimentation countermeasures on dams including Takayama dam located on upstream of Kizu River were discussed with [long-term reservoir maintenance] as the key. Based on the results, precautions to perform the asset management of dam reservoirs by sedimentation countermeasures were discussed.

As the result of this study, it has been shown that the dry excavation with the reservoir emptying is economically feasible even if it needs compensation both for reduced power production and water use loss rather than other countermeasures requiring initial facility investment such as sediment bypass, flushing sediment etc.

The above results suggest the possibility of "the optimization of sediment removal methods as a dam group" that is removing sediment with low costs by linking a dam group. Based on the above results, considering the fact that it is difficult to pay compensation for water use loss which dry excavation actually causes, and that dry excavation is performed with low costs in the future, long-term maintenance based on the integrated operation including backing up water supply capacity and ensuring potential water resources, etc. must be studied in order to "optimize sediment countermeasures as a dam group."

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SUMMARY

In Japan, at many dams constructed during the period of high speed growth following World War II, it is estimated that sedimentation will reach the planned level between 40 and 50 years from the present day, so that in the future, strategic dam asset management including preventive maintenance type sedimentation countermeasures will be an important challenge.

Five dams including The Takayama Dam which was completed in 1969 are now being maintained as a group of water resource development dams located on the upstream Kizu river. In this study, we studied the characteristics of inflow sediment of the Kizu River upstream dam group and feasibility of various sedimentation management measures. Especially, in this research, in addition to normal sedimentation countermeasure methods (Excavation, Dredging, Sediment check dam (+ Excavation), Flushing, Sediment bypass), a comparative study of “Dry excavation” is also performed. Dry excavation is performed by shutting down the dam for one year at an interval of a specified number of years, completely emptying the reservoir and removing sediment by dry excavation.

As a result of the case study of long-term maintenance of the Kizu River upstream dams, it has been shown that more economical results at all the dams are obtained by carrying out the dry excavation with the reservoir emptying (predicting compensation for reduced power production and compensation for water use loss) than by countermeasure methods requiring initial facility investment (for example, sediment bypass, flushing sediment etc.). The above results suggest the possibility of “optimization of sediment removal methods as a dam group (cheaply removing sediment by linking a dam group)”.

Based on the above results, considering the fact that it is difficult to pay compensation for water use loss which dry excavation actually causes, and that dry excavation is performed very cheaply, in the future, long-term maintenance based on integrated operation (backing up water supply capacity, ensuring potential water resources, etc.) must be studied in order to “optimize sediment countermeasures as a dam group.

RÉSUMÉ

On estime que dans le cas de nombreux barrages construits au Japon durant la période de croissance économique accélérée qui a suivi la Seconde guerre mondiale la sédimentation atteindra le niveau prévu dans 40 à 50 ans à compter d’aujourd’hui. Ainsi, dans le futur, la gestion stratégique du patrimoine des barrages, y compris les contre-mesures contre la sédimentation du type maintenance préventive constituera un important défi à relever.

Cinq barrages, incluant le Barrage de Takayama dont la construction a été achevé en 1969, sont actuellement entretenus comme un groupe de barrages destinés au développement des ressources en eau situées en amont sur la rivière Kizu. Dans cette étude, nous avons étudié les caractéristiques des sédiments entrant dans les réservoirs du groupe de barrages situés en amont sur la rivière Kizu ainsi que la faisabilité de diverses mesures de gestion de la sédimentation. Notamment, dans cette recherche, en plus des méthodes ordinaires de contre-mesures contre la sédimentation (extraction, dragage, barrage de contrôle des sédiments (+ extraction), opérations de chasse, dérivation pour les sédiments), nous avons également mené une étude comparative sur « l’extraction à sec ». L’extraction à sec est réalisée en suspendant l’opération du barrage pendant un an à des intervalles spécifiées de plusieurs années, en vidant totalement le réservoir et en retirant les sédiments au moyen de l’extraction à sec.

Les résultats de l’étude de cas portant sur la maintenance à long terme des barrages situés en amont sur la rivière Kizu ont démontré que des résultats plus économiques ont été obtenus pour tous les barrages en procédant à l’extraction à sec avec le réservoir vide (prévoyant la compensation pour la production

réduite d'électricité et compensation pour la perte d'utilisation de l'eau) que par les méthodes de contre-mesures nécessitant un investissement initial dans les installations (par exemple, dérivation pour les sédiments, pertuis de chasse des sédiments, etc.). Les résultats susmentionnés suggèrent la possibilité d'une « optimalisation des méthodes d'élimination des sédiments pour un groupe de barrages (élimination peu chère des sédiments en reliant plusieurs barrages) ».

En se basant sur les résultats susmentionnés et considérant le fait qu'il est difficile de verser une compensation pour la perte d'utilisation de l'eau que provoque effectivement l'extraction à sec et que l'extraction à sec peut être effectuée à des coûts très réduits, la maintenance à long terme basée sur l'opération intégrée (capacité d'alimentation d'eau en réserve, garantie de ressources potentielles en eau, etc.) doit être étudiée afin « d'optimiser les contre-mesures concernant les sédiments dans le cas d'un groupe de barrages ».