RESERVOIR SEDIMENTATION MANAGEMENT IN HYDROPOWER STATION CONSIDERING PROPERTIES OF SEDIMENTATION AND FACILITY CONDITION

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Abstract: Reservoir sedimentation is one of the most important problems which influence on sustainability of hydropower operation. There are two major kinds of hydropower stations, which are storage and regulating reservoir power stations. These two power stations are very different not only in reservoir capacity and reservoir operation rules, but also surrounding infrastructures and sedimentation condition in reservoirs. This paper analyses the current status of sedimentation problems in storage and regulating reservoirs. The results showed some useful properties, one is the difference of sedimentation impact on surrounding infrastructures, and the other is the relationship of reservoir operation and sedimentation condition. Considering these properties, effective and economical reservoir sedimentation management measures were proposed, which were mainly conducted by draw-down operation.

Key words: hydropower station, reservoir sedimentation, regulating reservoir, draw down operation

1 Introduction

Sustainability of hydropower stations are endangered by reservoir sedimentation. Practically many reservoirs of hydropower stations are under sedimentation control or under planning. In 2005, Japan Electric Power Civil Engineering Association researched 354 reservoirs of hydropower stations, which have over 15m height dam or over 1 million m^3 water capacity, in order to analyze the impacts of increasing sedimentation [1]. Based on this analysis, 95 reservoirs were influenced by increasing sedimentation, and the major influence was flood water level rise at upstream river s.

There are 2 major kinds of reservoirs of hydropower stations, one is storage reservoir, and the other is regulating reservoir. They are very different not only in reservoir operation rules but also surrounding infrastructures and sedimentation condition. However, few studies have analyzed these differences. Therefore, this paper focused on the properties of reservoir sedimentation in order to plan effective and strategic sedimentation management measures.

In this paper, we analyze reservoir sedimentation of hydropower stations considering the kinds of reservoirs. Based on these analysis, we propose new classification of reservoirs and discuss appropriate sedimentation control measures for each types by showing these advantages with numerical and economical analysis.

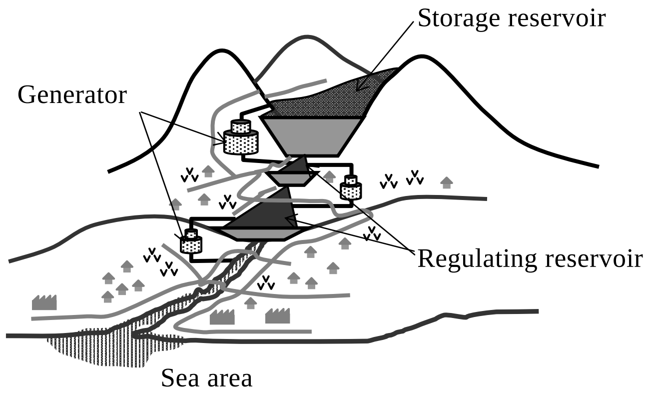


Figure 1. Location and position of hydropower stations

2 Reservoir sedimentation in hydropower station

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]. This chapter investigates functions of storage and regulating reservoirs, and analyzes sedimentation properties considering operation systems.

2.1 Storage and Regulating reservoirs

A cascade hydropower stations are usually placed in one river as shown in Figure 1 where the large generator with the large storage reservoir for power peak are on the upper stream and smaller generators with the smaller reservoirs for level power need are on the downstream of the river. Storage reservoir is working as a catchment of seasonal rainfall such as typhoons in rainy season and snow melting floods. Regulating reservoir is made for adjustment between water supply and power demands in the short term such as per a day or a week.

Storage and regulating reservoirs are very different in two points of views. Figure 2 shows the relation of storage and regulating reservoir capacities that are located in the same river. By comparing two kinds of reservoirs from total capacity point of view, the storage reservoirs are

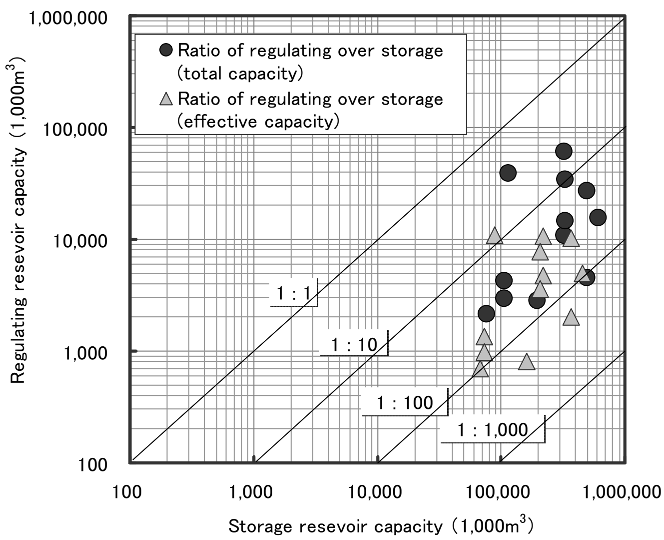


Figure 2. Comparison of storage and regulating reservoir capacities located along the same river

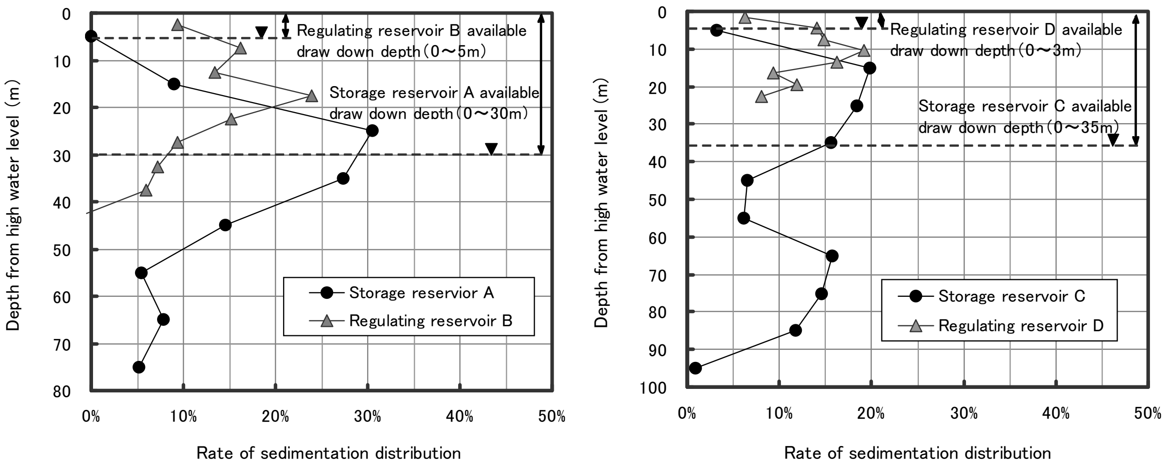


Figure 3. Rate of sedimentation distribution

about 3 to 100 times larger than the regulating ones. Regarding to the effective capacity that can be used for power generation, the storage reservoirs are about 10 to 200 times larger than the regulating ones. These differences in two points of views are caused by the difference of effective reservoir water depth. Averaged effective water depth in storage reservoirs is more than 25 meters, and that in regulating reservoir is less than 5 meters.

2.2 Characteristics of reservoir sedimentation and dam facility conditions

In order to select an appropriate sediment management strategy according to conditions of reservoirs, characteristics of sedimentation (position, sediment inflow rate) and dam facility conditions were measured by J-Power Electric Company. In total, 14 storage and 21 regulating reservoirs are operated and monitored by J-Power. The average ages after dam completion are 47 years old in storage reservoirs and 43 years old in regulating ones.

Figure 3 shows rate of vertical sedimentation profiles in reservoirs. Storage reservoir A and regulating reservoir B are located in the same river. Reservoir C and D are in the same relationship.

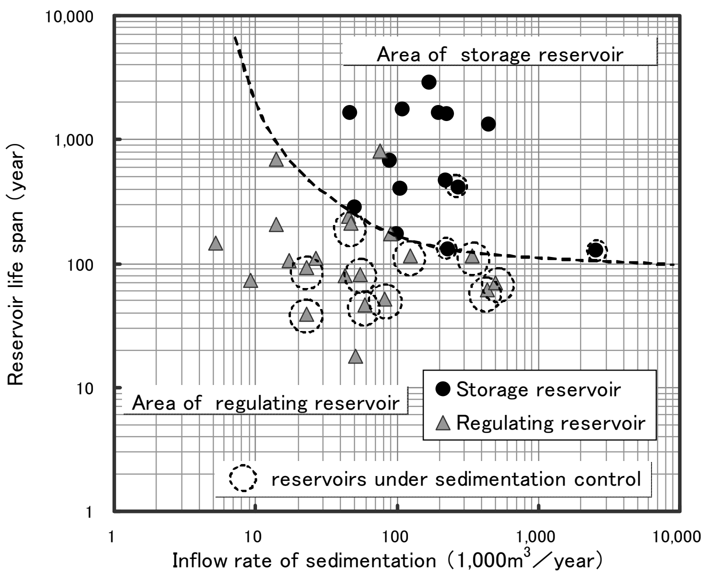


Figure 4. Relation of inflow rate of sediment and reservoir life span

Table 1. Impacts of reservoir sedimentation on infrastructures (average)

Items	Storage reservoir (14 dams)	Regulating reservoir (21 dams)
Total capacity(average)	195,500,000m^3	11,900,000m^3
Effective capacity(average)	149,800,000m^3	3,700,000m^3
Rate of sedimentation to total capacity	11.0%	22.3%
Rate of sedimentation to effective capacity	6.5%	4.31%
Rate of reservoir that has inundation area	57.1％	71.4%
Area of inundation	4,100m^2 / a reservoir	22,700 m^2 / a reservoir
Road length of inundation	0m / a reservoir	403m / a reservoir
Bridge affected by flood water level	0.1 bridge / a reservoir	1.5 bridge / a reservoir

Note) These data are averaged figures of dams which J-Power owns.

It was found that there is high rate of sedimentation at high water level in regulating reservoirs, which causes high flood water level. Available effective water depth and vertical sedimentation profiles are correlated, which indicates that control of reservoir water level can be effective for sedimentation control.

Figure 4 shows relation of inflow rate of sediment and reservoir life span. Life span can be defined as the ratio of the reservoir total capacity over annual inflow sediment volume. Plot areas of storage reservoirs and regulating reservoirs are separated. Highlighted reservoirs by dotted circle are ones under sedimentation control. Many regulating reservoirs are highlighted because of high sedimentation near high water level. Moreover, it was noticed that the necessity of sedimentation control did not depend on sediment inflow rate, but on the reduction of reservoir life spans.

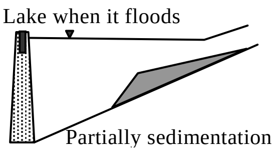
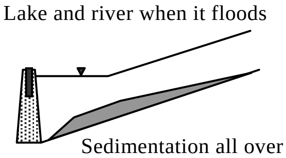
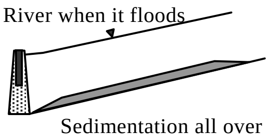
Table 1 shows impacts of sedimentation in regulating and storage reservoirs on surrounding infrastructures (bridge and road). Flood water level is the maximum flood water level under design flood discharge. It can be noticed that regulating reservoir has a severe sedimentation problem more than storage reservoir. Because the regulating reservoir has about 5 times inundation area, 15 times number of affected bridges compared with storage reservoir. Moreover, no affected road was found in storage reservoirs. There are two reasons that make these differences; the first reason is location of reservoirs, and the second one is sedimentation condition determined by reservoir operation. Compared to storage reservoir sites, regulating reservoirs are located relatively downstream river near large cities that have more infrastructures like roads, bridges, farms, factories and houses around reservoirs. Regulating reservoir usually has very small available effective water depth so the coming sediment will be deposited in almost higher water level.

It can be concluded that it is more important to implement sedimentation control in regulating reservoirs than in storage reservoirs. .

3 Effective sediment management measures for regulating reservoirs

Since we already know that sedimentation management for regulating reservoirs is very important, effective management measures considering properties of sedimentation and reservoir operation should be planned. Regulating reservoirs can be classified into three types by shape of flood water level and condition of sedimentation. Table 2 summarizes characteristics of these types, which are river, lake and intermediate types.

Table 2. Effective measures of sedimentation management for three regulating reservoir types

Type	Shape of flood water level Condition of sedimentation	Height of dam*	Design flood volume*	Ratio of spillway gate height to dam height (%)*	Number of dams	Effective sedimentation management measures
Lake		58m	2,700m³/s	13%	5 (26%)	Draw down operation during flood and guide sedimentation to lower dead space. Excavate some sedimentation for total management.
Intermediate		42m	4,000m³/s	29%	9 (48%)	Draw down operation during flood and guide sedimentation to lower dead space or pass through the gate. Excavate some sedimentation for total management.
River		27m	8,000m³/s	54%	5 (26%)	Draw down operation during flood, and pass sedimentation through the gate.

*These data are averaged figures of dams which J-Power owns.

Also table 2 shows effective sedimentation management measures for each type of reservoirs. According to the condition of each type, shear velocity, deposition and erosion location during flood event, appropriate sediment measures can be proposed as shown in Table 2.

Lake type reservoir is relatively large reservoir which looks like lake even in the design flood and has sedimentation partially in the upstream of reservoir. Lake type reservoir has large dam whose average height is 58m, and has small design flood volume whose average is 2,700m^3/sec, and average ratio of spillway gate height to dam height is 13%.

River type reservoir is relatively small one that looks like river and has sedimentation all over the reservoir area. River type reservoir has relatively small dam whose height is 27m, and design flood discharge is large about 8,000m^3/sec. And the ratio of spillway gate height to dam height is 54%.

Intermediate type reservoir, looks like between lake and river types even in the design flood and has sedimentation all over the reservoir. Intermediate type reservoir has dam whose height is 42m, and design flood discharge and the ratio of spillway gate height to dam height are around 4,000m^3/sec and 29% respectively.

Sediment management measures by draw down operation for each type of reservoir are proposed. Effectiveness of draw down operation depends on the type of reservoirs. In the river type reservoir, bed load material is easily passed through the spillway gate, while hardly possible in the lake type. In lake and intermediate types of reservoir, there will be remained sedimentation located at upstream reservoir area even after draw down operation, and combination with excavation will be needed for total sediment management.

3.1 River type reservoir

3.1.1 Summary of verification on river type reservoir

To check the physical feasibility of the measure proposed, we conducted numerical analysis for one reservoir. The selected reservoir has 9,930,000m^3 storage capacity, 1,692 km^2 catchment area, and has been under operation since 1958. It has some problems by sedimentation which is one of the most important ones is rising flood water level in the middle reservoir area. Recently, we have been excavating sedimentation which is inconvenient for reservoir management.

Table 3 shows the results of numerical analysis for river type. No action for sediment management for CASE-A1 is needed in next 28 years. While, Draw down operation during flood is selected for CASE -A2. Finally, annual excavation strategy of 30,000 m^3 is selected for CASE -A3.

We used the 1D numerical model and fit the model to actual phenomenon by using surveyed data in 28 years. In the model, the amount of bed material load and suspended load is calculated by Ashida-Michiue formula [2].

3.1.2 Result of verification on river type reservoir

Figure 5 shows the location of sediment deposition in the reservoir for three cases. In CASE-A1, sedimentation was increasing equally all over the reservoir. This made flood water level higher, and infrastructures around the reservoir was more affected. In CASE-A2 and A3, sedimentation was increasing near the dam, and decreasing in the middle of reservoir. This made flood water level low in middle area, then it is effective to conduct these 2 cases for total sediment management. These 2 cases are very different from sedimentation control point of view but have very similar effectiveness.

Figure 6 shows annual change of total sedimentation in the reservoirs within 28 years. In CASE-A1, total sedimentation was generally increased during 28 years, but in CASE-A2 and A3, total sedimentation remained constant without change. That means it is sustainable to implement these 2 strategies for sedimentation control.

Table 3. Cases of numerical analysis for river type reservoir

Case	Scenarios for sediment management
CASE-A1	・No sedimentation control in next 28 years.
CASE-A2	・Sedimentation control in next 28 years. ・The control means draw down operation during flood
CASE-A3	・Sedimentation control in next 28 years. ・The control means excavation of sediment in reservoir which is amount of 30,000m^3 a year.

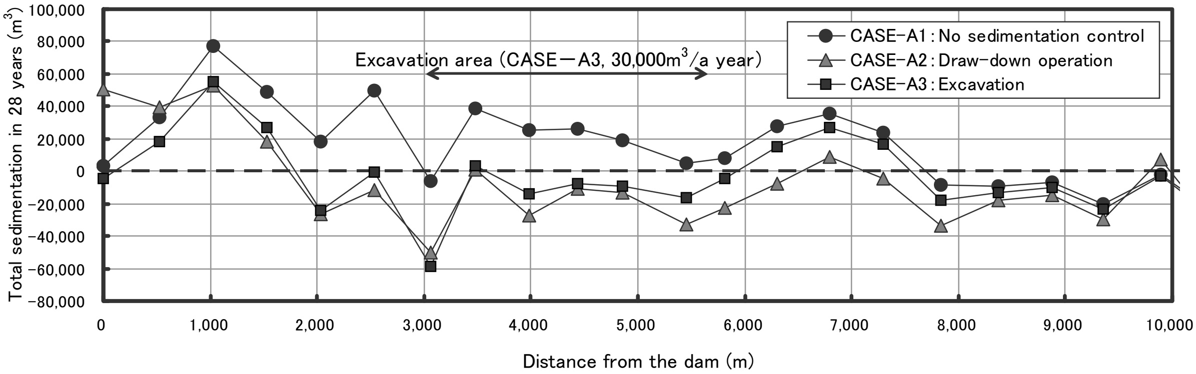


Figure 5. Sedimentation position in the results of calculation (river type)

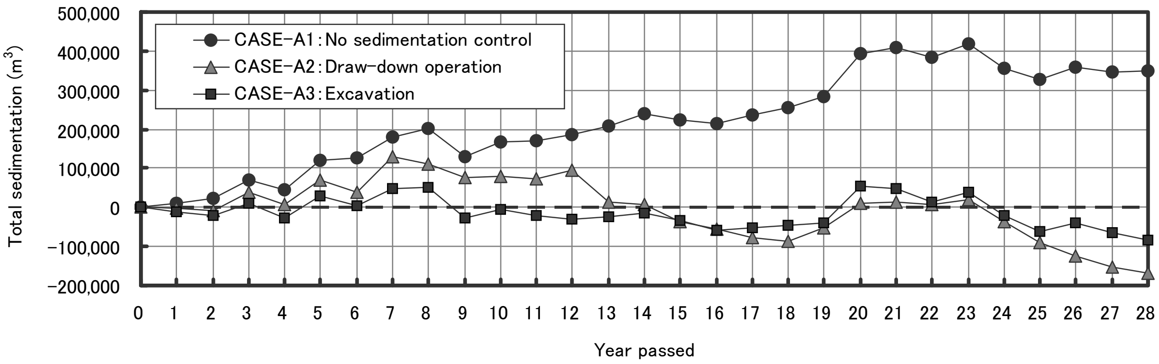


Figure 6. Calculated annual sedimentation volumes for river type

Table 4. Cost comparison of sedimentation measures for river type in 30 years (million¥)

Case	Item	Cost/30 years
CASE-A2 Draw down operation	Generation loss by the operation	300
	Maintenance of facility	210
	Generation loss by the maintenance	126
	Examination and Analysis needed	430
	Total	1,066
CASE-A3 Sediment excavation 30,000m³/yr	Excavation and disposal	3,300
	Generation loss by the excavation	540
	Fixture of disposal area	510
	Examination and Analysis needed	80
	Total	4,430

Table 4 shows the cost comparison of two effective strategies for sedimentation management measures. It is more economical to apply draw down operation (CASE-A2) compared to excavation strategy (CASE-A3).

3.2 Intermediate type reservoir

3.2.1 Summary of verification on intermediate type reservoir

To check the physical feasibility of the sediment measure, we conducted numerical analysis for one reservoir, which has 4,420,000m^3 capacity and 217 km^2 catchment area, and has been under operation since 1960. Reservoir sedimentation caused several problems as flood water level rise near the bridge over the reservoir, which needs clearance between flood water level and the bridge. Recently, sediment management strategies have been considered in these reservoirs.

Table 5 shows cases of the numerical analysis and scenarios for sediment management for intermediate type. CASE-B1 is simulated where no sediment measure was implemented in the next 22 years, CASE-B2 implemented draw down operation during flood events, CASE-B3 used excavation strategy about 30,000m^3 sediment volume every year. CASE-B4 is simulated as combined method of draw down and excavation strategies, and the annual excavated sediment volume is 15,000m^3.

We used the 1D numerical model and fit the model to actual phenomenon by using surveyed data in 22 years. In the model, the amount of bed material load and suspended load is calculated by Ashida-Michiue formula [2].

Table 5. Cases of numerical analysis for intermediate type reservoir

Case	Scenarios for sediment management
CASE-B1	・No sedimentation control in next 22 years.
CASE-B2	・Sedimentation control in next 22 years. ・The control means draw down operation in flood
CASE-B3	・Sedimentation control in next 22 years. ・The control means sediment excavation in reservoir which amount is 30,000m^3 a year.
CASE-B4	・Sedimentation control in next 22 years. ・The control includes sediment excavation and draw down operation, amount of excavation is 15,000m^3 a year.

3.2.2 Result of verification on intermediate type reservoir

Figure 7 shows the status of sedimentation in the reservoir for four cases. In every CASE sedimentation was located near the dam, because there was a vacant zone of sedimentation. In CASE-B1, sedimentation was increasing in the middle area and near the dam. This made flood water level higher in the middle of the reservoir, and the clearance between water level and the bridge was decreasing. In CASE-B2, sedimentation was increasing in the middle area and near the dam as in CASE-B1. That can explain the same result as in CASE-B1. Therefore, the sediment management strategy for CASE-B2 is not worth as sedimentation control. In CASE-B3, sedimentation was not increasing much all over the reservoir, and this did not make flood water level higher in middle area. That scenario is worth as sedimentation control. In CASE-B4, sedimentation was increasing near the dam, but decreasing in the middle reservoir area. This did not make flood water level higher in middle area. This case is worth as sedimentation control.

It is effective to use two scenarios of CSAE-B3 and B4 in order to implement total sediment management control. These cases are very different from each other in the ways of sedimentation control, but very similar in the effectiveness of the results.

Figure 8 shows annual change of total sedimentation volume in the reservoirs in 22 years. In CASE-B1 and B2, total sedimentation was generally increasing in 22 years, but in CASE-B3 and B4, total sedimentation were not increasing frequently, but almost remain constant. This remaining means that it is sustainable to conduct these two ways of sedimentation control.

Table 6 shows the cost comparison of three sedimentation management measures. It is not enough only to make draw down operation, CASE-B2. CASE-B4 is the measure combined draw down operation and excavation. It is still economical to consider CASE-B4 more than only excavation, CASE-B3.

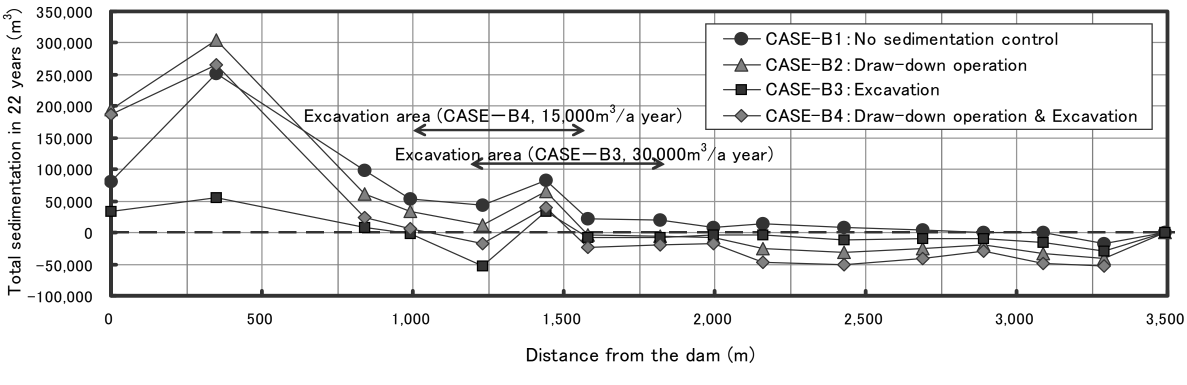


Figure 7. Sedimentation position in the results of calculation (intermediate type)

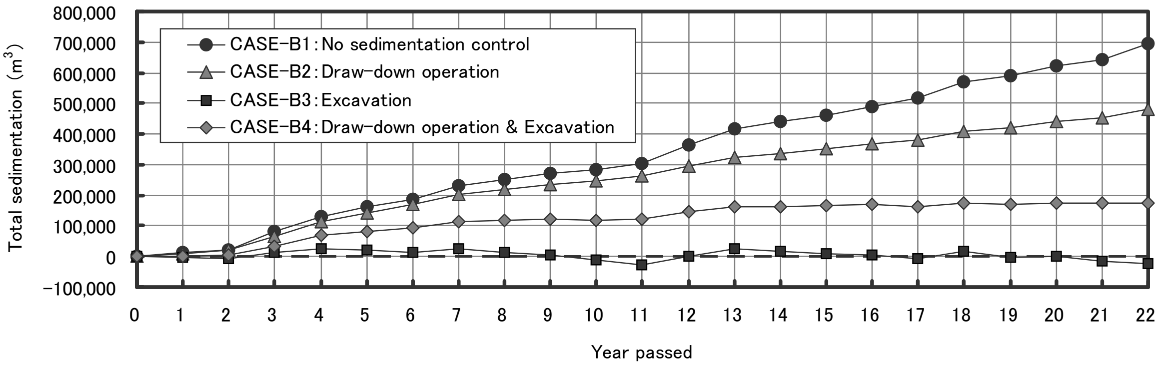


Figure 8. Calculated annual sedimentation volumes for intermediate type

Table 6. Cost comparison of sedimentation measures for intermediate type in 30 years (million¥)

Case	Item	Cost/30 years
CASE-B2 Only implement one strategy of Draw-down operation	Generation loss by the operation	300
	Maintenance of facility	210
	Generation loss by the maintenance	105
	Examination and Analysis needed	430
	Total	1,045
CASE-B3 Only implement one strategy of Excavation 30,000m^3/yr	Excavation under water	4,500
	Fixture of harbor	140
	Fixture of disposal area	510
	Examination and Analysis needed	80
	Total	5,230
CASE-B4 Combination of two strategies Draw down operation Excavation 15,000m^3/yr	Generation loss by the operation	300
	Maintenance of facility	210
	Generation loss by the maintenance	105
	Excavation under water	2,700
	Fixture of harbor	140
	Fixture of disposal area	390
	Examination and Analysis needed	510
	Total	4,355

3.3 Result of the verifications

We verified the effectiveness of draw down operation for sedimentation control in regulating reservoirs. Regulating reservoir is usually under operation of smaller available effective water depth, and it causes much deposition in the same area of reservoir. On the other hand, it is very effective to make regulating reservoir under unusual operation, which is to make the dam water level to below usual available effective water depth. Draw down operation reduces the head of power generation, but still more economical solution than excavation.

4 River environment and effective utilization

It is not enough only to take care of infrastructure around reservoir and life span of reservoir, but also we have to think about downstream river environment below the dam, and effective utilization of sediment.

Dam interrupts continuous sedimentation transport along river. No matter how long the reservoir as hydropower station facility lasts, it will not worth as the river environment get worse [3] [4].

Keeping downstream river environment healthy is the important issue from the sustainability of hydropower operation point of view.

In Japan, we do not have much sand to construct the infrastructures, and we have destroyed mountains to get sand. Sand in rivers is usually under strict regulation to protect rivers, especially for construction, and the regulation has covered the reservoir sedimentation [5]. Thus there is a miss-match between much sand in reservoirs and need for construction. We have to explain to river management office and river basin stakeholder that there is a way to take out sand from reservoir without damaging the river.

5 Conclusion

The paper presents the reservoir sedimentation in hydropower stations, considering operation rules of storage of regulating reservoirs. Based on useful sedimentation characteristics and dam facility condition, we can propose suitable measures against reservoir sedimentation by classifying the regulating reservoir to three types. The following points can be concluded:

1) Since sedimentation in regulating reservoir is dominant to surrounding infrastructures more than the storage one, it is more important to manage sedimentation in regulating reservoir than storage one.
2) It is effective to classify regulating reservoir into three types; lake, river, and intermediate type, and we can propose the measures for each type. The measures for river type and intermediate type which are mainly conducted by draw down operation which is physically effective and economically feasible comparing to other alternative measures.
3) It is important to consider the downstream river environment below dams and to consider effective utilization of sediment for sustainable hydropower operation.

References

[1] Japan Electric Power Civil Engineering Association, Research and enlightment on reservoir sedimentation in hydropower station, 2006.(in Japanese)

[2] Kazuo Ashida, Michiue Masanori, Study on Hydraulic Resistance and Bed-Road Transport Rate Alluvial Stream, Jurnal of Japan Society of Civil Engneers, vol.206 pp56-69, 1972. (in Japanese)

[3] S.A. Kantoush, Tetsuya Sumi, Akira Kubota, Geomorphic response of rivers below dams by sediment replenishment technique, River Flow 2010-Dittrich, Koll, Aberle & Geisenhainer (eds), 2010.

[4] Tetsuya Sumi, S.A. Kantoush, Integrated Management of Reservoir Sediment Routing by Flushing, Replenishing, and Bypassing Sediments in Japanese River Basin, 8th International Symposium of Ecohydraulics, 2010.

[5] Masaru Banda, Tetsuya Sumi, Recycling Business Making of Reservoir Sedimentation from Viewpoint of Sediment Resource Management, 15th Proceedings of River Engineering JSCE, 2009. (in Japanese)