NEW METHOD OF EXPANDING RESERVOIR CAPACITY AND DISCHARGE FUNCTIONS

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ABSTRACT

Dam reservoirs in Japan have small catchment basins, so the interval between rainfall and runoff is short, making it difficult to control flooding by operating the gates of dams. Therefore, since 1976, almost all dams with small catchment basins built to control flooding have been gateless dams. However, there are more than 170 dams with flood control gates that were constructed before 1976, and in the 30 years that have since elapsed, maintenance and management costs for the gates have risen sharply, so some dams originally built with control gates are being reconstructed as gateless dams. To achieve this, the dam's flood control capacity must be increased by (1) raising the dam height, (2) revising the apportionment of reservoir capacity, (3) revising the flood control plans, or (4) excavating the reservoirs. In considering these options, past cases of improvements made to convert to gateless dams were examined. The results revealed that (1) raising the height of a dam with small reservoir capacity can yield improvements by raising the crest only by a few meters, (2) the apportionment of the reservoir capacity and (3) the flood control plan can be revised by clarifying the management of the dam since its completion and the state of the downstream river during flooding, and (4) excavating the reservoir is more expensive than the other methods since the work must be done while the dam is in operation. This paper outlines the methods for reconstructing control-gate dams as gateless dams, and introduces examples.

INTRODUCTION

The total land area of Japan is only 378,000 km^2 and 73% of its surface area is occupied by mountains. Thus, the rivers are steep and the distance from source to ocean is short. In addition, part of Japan is in the temperate Asian monsoon climate zone, resulting in an average national annual rainfall of 1,500 mm and as much as 2,700 mm in regions of heavy rainfall. As a result, an intense rainfall can abruptly increase the flow rate in rivers, causing flood disasters. Since the modernization of Japan, the government has invested heavily in flood control countermeasures such as improving rivers, building retarding basins, and constructing dams.

In principle, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) executes river flood control countermeasures, and manages the dams constructed to

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control flooding. A total of 526 dams now operate under the MLIT including 116 dams managed directly by the Ministry and another 410 managed by prefectural governments.

The dams managed by the MLIT generally have a large flood control capacity, where the flood control effects extend to the downstream part of the river on which the dam is constructed. The dams managed by prefectural governments work effectively as flood control countermeasures on medium to small rivers and on tributaries of large rivers.

Among the dams in Japan, the average catchment area of reservoirs intended to control flooding is 140 km^2, their average effective reservoir capacity is 17,600,000 m^3, and their average flood control capacity is 6,000,000 m^3, smaller than that of dams in other countries.

GATELESS DAMS

Many of the dams managed by the MLIT and operated by prefectural governments were constructed during and after the 1960s. These include dams built for the sole purpose of flood control as well as multi-purpose dams that in addition to providing flood control, also supply water to public supply systems, for industrial use, for irrigation, and for generating electric power. During the 1960s, almost all dams managed by prefectural governments used flood control gates. However, when these dams had reservoirs with small catchment areas and were used to control flooding by operating their gates, the following problems occurred.

(1) Runoff occurred soon after rainfall and given the limits to predicting the inflow rate caused by localized concentrated torrential rainfall, it was difficult to appropriately operate the gates.
(2) Gate operation requires a certain number of skilled personnel, so the management cost rose.
(3) Maintenance of the gates, such as repainting, is expensive.

To resolve such problems, dams without control gates on the spillways, referred to as gateless dams, are now planned. Because the hydraulic design of a spillway is directly linked to the design of the dam body in the case of a gateless dam, the operation of the reservoir is completely fixed. Adopting a gateless dam for flood control that is as effective as a dam with control gates requires a larger flood control capacity, which increases the scale of the dam. But, without control gates, failure to control a flood because of human error occurs far less often than at dams with gates, and so it is possible to reduce the number of personnel required, thereby lowering the management cost.

The MLIT has stipulated the design conditions for required load and water level, etc. for the design of dams based on the Cabinet Order Concerning Structural Standards for River Management Facilities enacted in July 1976, but the River Management and Sabo Works Technology Standards were revised in the same year, clarifying specific design methods based on the provisions of the Cabinet Order. Provisions for the structure of spillways of dams in the revised River Management and Sabo Works Technology Standards included the following commentary.

"Spillways of dams whose catchment area is approximately 20 km^2 or smaller and of dams where the rainfall equivalent to the flood control capacity is approximately 50 mm or less, should not have gates, and at least emergency spillways should have a structure without gates."

The design flood of a dam means the flood flow rate adopted for measures to maintain the safety of a dam body even when the flood flows past the dam location, and dams in Japan are designed with emergency spillways to allow the design flood to safely flow downstream.

Under such circumstances, dams constructed since the 1980s, specifically those with large catchment areas directly managed by the MLIT, have been constructed with control gates, but those dams with small catchment areas managed by prefectural governments have almost all been constructed as gateless dams. Among the 116 dams managed by the MLIT, 23 dams have no flood control gates, and among the 410 dams managed by prefectural governments, 235 dams have no flood control gates. There are 175 dams with control flood gates.

RECONSTRUCTION AS A GATELESS DAM

Dams with flood control gates built before the 1980s are managed in the face of the above problems, but some of these dams have been in operation for more than 30 years. As these gates approach the end of their service life, they must be replaced, which will clearly be very expensive. In addition, the national and prefectural governments, which for many years have faced public demand for efficient administration, have continued to reduce staff and there are no longer enough personnel to manage public works facilities. Furthermore, the construction of more public works increases the management cost, but it is generally more difficult to obtain the budget needed to manage these facilities than funds to invest in new ones, resulting in a severe shortage of management funds. For these reasons, a number of prefecture-managed dams with flood control gates have been reconstructed as gateless dams.

To reconstruct a control-gate dam as a gateless dam that continues to provide the same level of flood control, it is generally necessary to increase its flood control capacity. Such reconstruction in Japan in the past has used the following methods:

(1) Raising the dam height
(2) Revising the apportionment of reservoir capacity
(3) Excavating the reservoir
(4) Revising the flood control plan

Regarding (1) raising the dam height, in concrete gravity dams, concrete is typically placed from the toe of the downstream side of the dam body to the crest, raising the height of the dam while maintaining the basic triangular shape. But at dams managed by prefectural governments, because their flood control capacity was originally small and only a small increase of capacity is needed to convert them to gateless dams, the top of the dam body need only be raised by 1–2 meters, while continuing to satisfy the design conditions of a concrete gravity dam. Regarding (2) revising the apportionment of reservoir capacity, the approaches considered include revising the service water capacity, which was ensured by the initial plan, to transfer a portion to flood control capacity, and revising the planned sedimentation capacity based on past performance and building a sediment check dam at the upstream end of the reservoir to transfer sedimentation capacity inside the reservoir to flood control capacity. Regarding (3) excavating the reservoir, excavating natural ground around the reservoir or part of the riverbed at the upstream end of the reservoir is usually very expensive. Concerning (4) revising the flood control plan, considering the progress in the construction of levees along the downstream river courses since the dams were completed, increasing the maximum discharge from the dam to efficiently use the flood control capacity is also considered.

Reconstructing a control-gate dam as a gateless dam involves the following steps:

(1) Raising the dam body or excavating the reservoir
(2) Reconstructing the crest spillway or orifice (outlet) by removing the gates, etc.
(3) Building additional emergency flood spillways and installing slope toe retaining walls

Step (1) expands the flood control capacity, and in some cases, based on studies of various methods such as revising the apportionment of the reservoir capacity or revising the flood control plan as explained above, the most feasible method has been raising the dam height or excavating the reservoir. Step (2) involves removing the flood control gates on the crest spillway or the orifice for flood control to change them to a gateless overflow spillway or orifice that performs the intended flood control. In Step (3), dams generally ensure the required discharge capacity by combining the orifice for flood control and overflow spillways to discharge the dam's design flood; removing the control gates from the orifice for flood control usually lowers the discharge capacity, so it is necessary to increase the emergency overflow spillway's discharge capacity so that the dam design flood complies with the present standards.

EXAMPLES OF RECONSTRUCTION TO GATELESS DAMS

Three examples of the reconstruction of a dam with control gates to convert it to a gateless dam, which have recently been completed in Japan, are introduced.

Sugo Dam

The Sugo Dam is a concrete gravity dam completed in 1979 to control floods and provide supplementary water supply to ensure the flow rate of rivers during droughts in Hyogo Prefecture in central Japan (see Fig. 1.) The outlet equipment of the Sugo Dam was an orifice for flood control without a gate (H1.3 m × W1.3 m) and an emergency overflow spillway with a roller gate. The catchment area of the Sugo Dam is small, only 8.73 km^2, and for the following reasons, the gate was removed to reconstruct the dam as a completely gateless dam.

(1) In cases where the time between rainfall and runoff was short and the runoff exceeded the design flood, it was difficult to appropriately operate the gate.
(2) It had become difficult to provide staff to manage dam operations during a flood.
(3) The time for replacing the gate was approaching, but the cost was going to be high.

The reconstruction work at the Sugo Dam started in 2005 and was completed in 2009 at a cost of 1.5 billion yen. Figure 2 shows the dam after reconstruction.

Figure 1. Panoramic View of the Sugo Dam (Before Reconstruction)

Figure 2. Downstream View of the Sugo Dam (After Reconstruction)

When the Sugo Dam was reconstructed, the dam design flood was revised from the initially planned 250 m^3/s to 260 m^3/s, which complies with the Cabinet Order Concerning Structural Standards for River Management Facilities. Table 1 shows the specifications before and after the reconstruction.

Table 1. Specifications of the Sugo Dam (Before and After Reconstruction).

Item		Before reconstruction	After reconstruction	Remarks
Dam specifications	Dam crest elevation	223.0 m	223.7 m	Remove two crest gates, and add two free overflow crests. Remove a conduit gate, and add orifice outlet. Raise a dam height by 0.7m.
	Dam height	55.0 m	55.7 m	
	Dam crest length	157.0 m	Same as on left	
Capacity specifications	Total reservoir capacity	1,950,000 m^3	Same as on left	
	Effective reservoir capacity	1,700,000 m^3	Same as on left	

The reconstruction involved removing the gate of the emergency spillway and constructing new overflow spillways without gates. A study was done to determine the scale of the emergency overflow spillway that needed to be installed to discharge the design flood. To maintain the basic triangular shape of the dam body, the limit to which the dam body could be stably increased was 0.77 m, and if the height of the dam was increased by less than 1 m, it would not be necessary to relocate the road around the reservoir. At the toe of the right side of the dam body, there was a service water use discharge facility, so it was best to install the emergency overflow spillway on the left side, for which the maximum length was 75 m, so the dam body was raised 0.7 m, and four emergency spillways (overflow length of 40 m) were installed on the left side of the dam body. Excavating the reservoir was considered, but the amount excavated would be 553,000 m^3, and carrying out this work while the reservoir was operating would have been an expensive, unrealistic proposal.

To install the emergency overflow spillway on the left side, the dam body was excavated to build the overflow and a dam toe retaining wall was installed. The piers at the overflow were installed about 2 m downstream from the dam axis, shortening the overflow crest (see Figure 3).

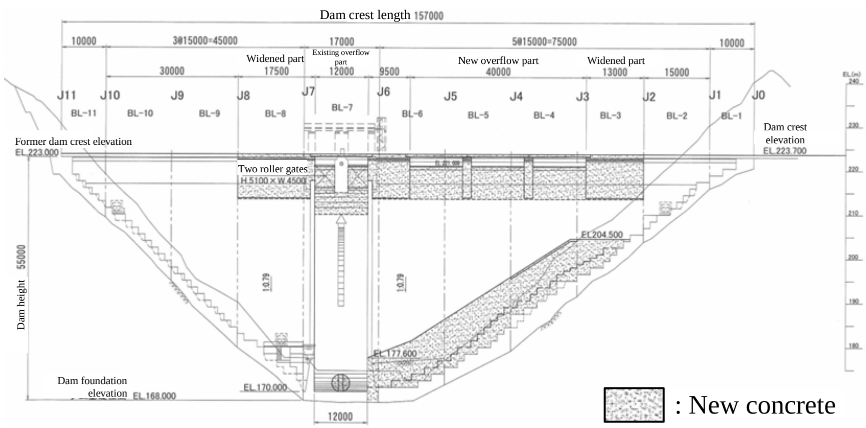


Figure 3. The Sugo Dam(After Reconstruction).

Tobe Dam

The Tobe Dam is a concrete gravity dam completed in 1976 to control flooding and to provide supplementary water to maintain the river flow rate during droughts in Aomori Prefecture in northern Japan (see Fig. 4). Flood control depended on one hollow-jet valve (diameter 1.7 m) installed at the center of the dam body and two Tainter gates installed on the crest (H5.17 m × W5.50 m). The catchment area of the dam is small, only 8.3 km^2, and for the following reasons, the gates were removed to convert the dam to a gateless dam.

(1) In cases where the time between rainfall and runoff was short and the runoff exceeded the design flood, it was difficult to appropriately operate the gate.

(2) Flood control had to be done using the one hollow-jet valve and 2 Tainter gates, which were difficult to operate.

(3) Many skilled operators were required for the gate and valves, and these facilities are very expensive to replace.

Table 2. Tobe Dam Specifications (Before and After Reconstruction).

Item		Before reconstruction	After reconstruction	Remarks
Dam Specifications	Dam height	43.0 m	Same as on left	Remove two crest gates, and cut down two free overflow crests. Remove a conduit gate, and add orifice outlet.
	Dam crest length	158.0 m	Same as on left	
	Dam body volume	84,310 m^3	Same as on left	
Capacity specifications	Total reservoir capacity	1.42 million m^3	Same as on left	
	Effective reservoir capacity	1.12 million m^3	Same as on left	

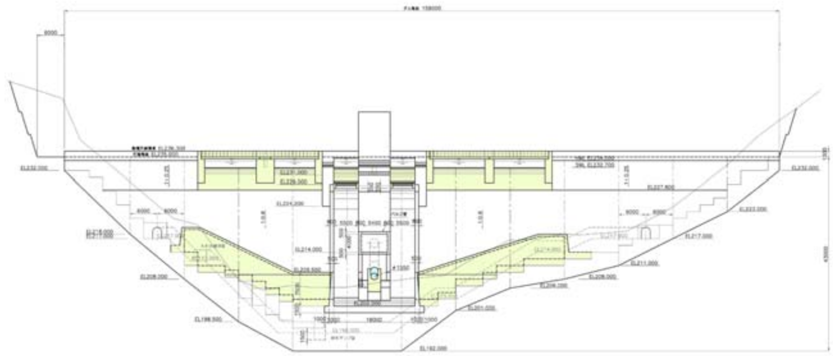
Figure 4. Downstream View of the Tobe Dam (Before Reconstruction).

Figure 5. Downstream View of the Tobe Dam (After Reconstruction).

The reconstruction work on the Tobe Dam started in 2007 and was competed in 2010 at a cost of 970 million yen. Figure 5 shows the dam after the work was completed.

It was necessary to expand the flood control capacity in order to convert to a gateless dam, but the capacity for maintaining the river flow rate during a drought based on past experience was barely used, and the results of a survey of the river flow rate and the habitat environment of fish, etc. downstream from the dam showed that supplementary water from the Tobe Dam was not needed to maintain the river flow rate, even during a drought. Thus, the capacity for maintaining the flow rate of the river was transferred to flood control capacity, ensuring the capacity required for flood control without raising the height of the dam.

To reconstruct the Tobe Dam, the hollow-jet valve was removed and a discharge pipe (diameter of 1.5 m) was installed as an orifice. The Tainter gates were removed and replaced with flat orifices of 0.55 m in height and 4.5 m in width, which satisfy the flood control plan. The overflow depth on the emergency overflow spillway was 1.3 m so the dam body did not need to be raised, and four overflow spillways ranging in width from 9.7 to 9.9 m were installed on the left and right of the dam body. To install the emergency spillways, the dam body was excavated to form the overflow part and a dam toe retaining wall was installed (see Figure 6).



Legend

New concrete

New steel pipe

Figure 6. The Tobe Dam(After Reconstruction).

Bibai Dam

The Bibai Dam was completed in 1982 to control floods, supply water to urban water supply systems, and provide supplementary water to maintain the flow of the river during droughts in Hokkaido in northern Japan (see Figure 7). The Bibai Dam controlled flooding with one orifice radial gate installed at the center of the dam body (H3.0 m × W2.0 m) and two crest radial gates (H7.1 m × W4.5 m). The catchment area of the Bibai Dam is small, only 24.63km^2, and for the following reasons, it was reconstructed by removing its gates to convert it to a gateless dam.

(1) It was necessary to operate three gates, which was a complex procedure.

(2) The catchment area is small, so there was a danger that the runoff from rainfall would occur so quickly that the gates could not be operated in time.

(3) It took many control personnel to operate the gates and valves, and it is very expensive to replace these facilities.

The work executed on the Bibai Dam started in 2000 and was completed in 2004 at a cost of 1.21 billion yen. This reconstruction reduced the number of management personnel needed at the Bibai Dam from 6 to 3, and it lowered the annual maintenance cost by more than 20%. Figure 8 shows the dam after completion of the work.

Table 3. Bibai Dam Specifications (Before and After Reconstruction).

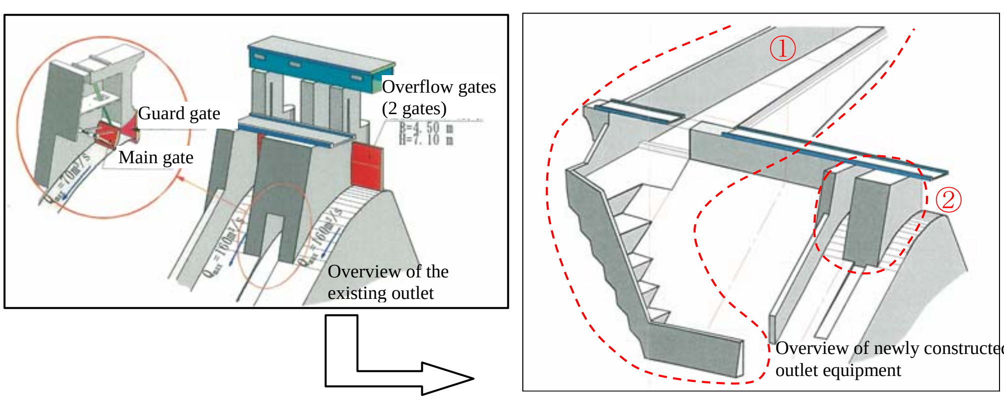
Item		Before reconstruction	After reconstruction	Remark
Dam specifications	Dam height	35.5 m	Same as on left	Remove two crest gates, and add an free overflow crest of 49m length and a spillway. Remove a conduit gate, and add orifice outlet.
	Dam crest length	228 m	Same as on left,	
	Dam body volume	84,000 m^3	Same as on left	
Capacity specifications	Total reservoir capacity	1,500,000 m^3	Same as on left	
	Effective reservoir capacity	1,090,000 m^3	Same as on left	

Figure 7. Panoramic View of the Bibai Dam (Before Reconstruction).

Figure 8. Panoramic View of the Bibai Dam (After Reconstruction).

It was necessary to expand the Bibai Dam's flood control capacity in order to convert it to a gateless dam, but at this dam, the foundation is fragile, with low-strength layers of coal. The plan was therefore to lower the dam height by installing a sediment check dam upstream from the reservoir, as it would have been difficult to raise the dam, even to convert it to a gateless dam. Therefore, the orifice spillway was closed because it would be difficult to reconstruct, the two existing crest gates were removed and an overflow crest spillway for flood control was installed. The water level was calculated for the downstream river in a case where the discharge rate was increased by the new overflow spillway, and it was confirmed that the inundated area would not increase, even when the existing maximum discharge flow rate of 95 m^3/s was increased to 154 m^3/s.

For the emergency spillway, a study was made on the facility required to discharge the design flood of 390 m^3/s at the same design flood level as in the original plan. Installing an emergency overflow spillway on the dam body would have made the cost of reconstructing the dam body high. Therefore, it was decided to install a side-overflow type emergency overflow spillway on the upstream side on the left of the dam body to reduce the reconstruction cost (see Figure 9).



①New emergency spillway and dam toe retaining wall
②Removal of crest gate(after removal, crest spillway)
Removal and closure of orifice gate

Figure 9. Overview of the Bibai Dam Outlet Equipment (Before and After Reconstruction).

CONCLUSIONS

Since 1976, dams built to control floods in small catchment areas in Japan are gateless dams in order to simplify their management. However, dams that were completed before 1976 include about 170 with control gates. To simplify dam management and lower the management cost, more dams with control gates will need to be reconstructed as gateless dams. Methods for converting control-gate dams to gateless dams include (1) raising the dam height, (2) revising the apportionment of reservoir capacity, (3) revising the flood control plans, and (4) excavating the reservoirs. However, past cases of improvements to convert dams to gateless dams showed that (1) for a dam with a small reservoir capacity, it is sufficient to raise the crest by a few meters, (2) the apportionment of reservoir capacity and (3) the flood control plan can be revised by clarifying the management of the dam since its completion and the state of the downstream river during flooding, and (4) excavating the reservoir is more expensive than other methods because the work is done while the dam is operating.

In the future, technologies for converting gate dams to gateless dams should be systematized to encourage the reconstruction of dams as gateless dams in order to simplify dam management and lower management costs.

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