HYDRAULIC DESIGN IN UPGRADING DAMS UNDER OPERATION

Toshiyuki Sakurai[1], Takayuki Ishigami[2]
[1]*Japan Dam Engineering Center, Tokyo, 110-0008 Japan*
[2]*Hydraulic Engineering Research Group, Public Works Research Institute, Tsukuba, 305-8516 Japan*
Email: sakurai@jdec.or.jp

ABSTRACT: In Japan, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) presented a "MLIT's Vision to Upgrade Dams under Operation" in June 2017. The vision introduces countermeasures to advance the upgrading of existing dams by applying both structural and non-structural measures to ensure that they are used more effectively than in the past.
There are cases raising the dam body and increasing the discharge capacity of the discharge facilities etc. in the past. At some existing dams, improvement projects are currently under construction.
There are challenges in hydraulic design of improvement and additional construction of discharge facilities in dam upgrading different from the construction of a new dam. Methods to cope with these challenges have been examined by hydraulic model experiments and so on. In this report, the outline of three major technologies to increase the discharge capacity in dam upgrading, cutting dam body, drilling dam body and tunnel spillway, are introduced. And taking Nagayasuguchi dam remodeling project as a representative example, the contents of the hydraulic design of the existing dam redevelopment project are explained.

Keywords: Dam upgrading, Increase of discharge facility, Cutting dam body, Drilling dam body, Tunnel spillway, Hydraulic design

1. INTRODUCTION

In Japan, dams completed so far played a major role in both flood control and water use. On the other hand, it is becoming more important to effectively utilize existing infrastructure stocks while reducing the total cost, under the constraints of a falling productive-age population and a severe financial situation. Based on this recognition, MLIT presented a "MLIT's Vision to Upgrade Dams under Operation" in June 2017 [1]. The vision introduces countermeasures to advance the upgrading of existing dams by applying both structural and non-structural measures to ensure that they are used more effectively than in the past (Table 1).
Regarding "(4) Improving Facilities for a more Advanced Functionality" listed as one of the measures, there are cases raising the dam body and increasing the discharge capacity of the discharge facilities etc. in the past. At some existing dams, improvement works are currently under construction.
There are challenges in hydraulic design of improvement and additional construction of discharge facilities in dam upgrading different from the construction of a new dam. Methods to cope with these challenges have been examined by hydraulic model experiments. In this report, the outline of major technologies to increase the discharge capacity in dam upgrading is

introduced and the contents of the hydraulic design of the existing dam redevelopment project are explained, taking Nagayasuguchi dam remodeling project as a representative example.

Table 1: Measures to develop and accelerate dam upgrading

(1) Life Extension of Dam
(2) Promoting Efficiency and Advancement of Maintenance
(3) Flexible and Reliable Operation to Optimally Utilize the Capacity of the Facility
(4) Improving Facilities for a more Advanced Functionality
(5) Responding to Climate Change
(6) Addition of Hydropower
(7) Conservation and Revitalization of River Environment
(8) Regional Promotion utilizing the Dams
(9) Promoting Dam Upgrading Technologies Overseas
(10) Development and Implementation of Technologies to Promote Dam Upgrading

2. TECHNOLOGIES TO INCREASE THE DISCHARGE CAPACITY

In the facility improvement of the existing dams, efforts to increase discharge facilities and to raise dams are being carried out for various reasons, such as changing the flood control plan, changing the water usage plan, and improving functions and so on. The outlines of three technologies, which are typical when increasing comparatively large capacity of discharge capacity, improvement of the crest discharge facilities, improvement of the discharge facilities in a dam body and constructing new tunnel spillways are described as bellow.

2.1 Improvement and expansion of the crest discharge facilities (cutting dam body)

This technology is to improve or expand the overflow type discharge facilities installed at the crest of the dam and the orifice type discharge facilities with a design water head of 25 m or less. The technique of cutting from the top of the dam body is often used. Since the remodeled part is near the top of the dam, there are few problems concerning dealing with large water pressure. In addition, if it is not necessary to install a temporary coffering facility by lowering the reservoir level, construction work becomes relatively easy.

In the dams constructed early period, both the flood control spillway and the emergency spillway may be adopting a discharge facility with a gate. In such dams, when the catchment area is small and the flow rate increases rapidly during flood, the discharge facility is remodeled gateless type facility in order to improve the certainty of the flood control function.

Remodeling to gateless will also reduce the burden of operation and maintenance. In order to remodel the emergency spillway to gateless type, the method to expand the overflow width is usually adopted. The challenges of this method are whether it can be placed at the top of the dam body, or whether it can safely flow down to the downstream river channel by dissipating the discharged water flow energy. In order to solve these challenges, a new emergency spillway is installed on the lake bank in the reservoir, or a training wall is installed on the downstream of the dam along with the expansion of the overflow width at the dam crest.

As a case with a purpose other than increase the discharge capacity, at the Yamasubaru dam and Saigo dam in Miyazaki Prefecture (managed by Kyushu Electric Power Co.), to improve the function of passing through sediment, cutting down the existing dam body and remodeling the discharge facilities are in progress.

Regarding the method of cutting the dam body, Nagayasuguchi dam in Tokushima Prefecture (managed by MLIT), which is undergoing remodeling work, is the largest case in terms of cutting depth in history in Japan. It is planned to cut the dam body at the maximum depth of about 37 m and to install two additional discharge facilities. As for Nagayasuguchi dam, it is described the content of hydraulic design in chapter 3.

2.2 Improvement and expansion of discharge facilities in a dam body (drilling dam body)

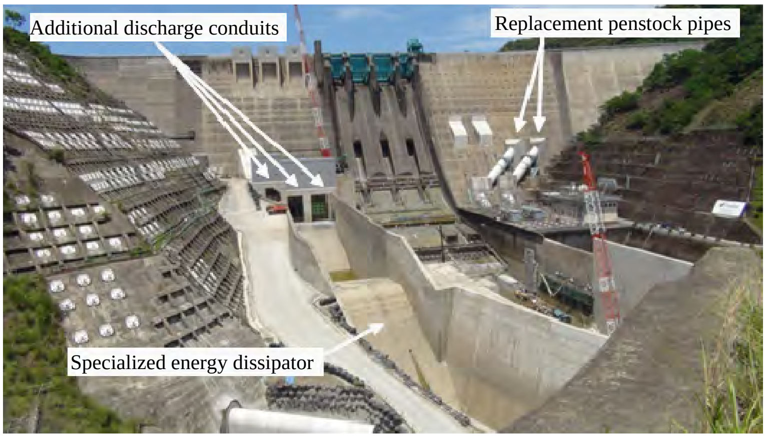
This technique is to drill a hole in an existing dam body and to install an additional discharge facility. Usually it is applied to a gravity type concrete dam. In Japan, it is sometimes difficult to lower the reservoir level due to restrictions on the reservoir operation for the purpose of water use, and construction under large water depth conditions is required, so the technology of a temporary coffering upstream side of the dam is important.

A discharge facility with an acting water head exceeding 25 m is defined as a high pressure discharge facility and the flow velocity becomes high speed during discharge, so it is necessary to prevent cavitation damage due to a local negative pressure generation. For that purpose, it is required to reduce the flow velocity inside the pipe, but since the size and numbers of holes that can be drilled in the dam body are restricted by the dam structure, from the economical point of view, increasing the flow velocity to increase the discharge capacity is advantageous. Furthermore, it is difficult for the additional discharge facility to arrange the inlet and outlet of the discharge pipe straight on the relationship with the arrangement of the existing discharge facilities. In this case, a complicated curved shape is adopted, but a local pressure drop tends to occur in the curved part of the large diameter discharge pipe. In order to cope with these problems, the examination of the water pressure acting at the inside wall of the bending part by a hydraulic model experiment was carried out [2]. Currently, it is possible to do rational design.

As an example of drilling of the dam body, the remodeling of Tsuruda Dam in Kagoshima prefecture (managed by MLIT) is the largest scale previously recorded in Japan. Three additional discharge conduit pipes (diameter: 4.8 m, drilled cross section: height 6.0 m and width 6.0 m) and two replacement penstock pipes for power generation (diameter: 5.2 m, drilled cross section: height 6.4 m and width 6.4 m) will be installed (Figure 1). In the temporal coffering work at the construction of the remodeling of Tsuruda Dam, in addition to the conventional construction method of assembling the steel coffering gates after installing the foundation pedestal concrete in the water upstream of the dam, a new technology of a floating type coffering facility requiring no pedestal was developed. As a result, large depth diving work was reduced, cost reduction and safety assurance were achieved.

If the discharge rate of discharge facility in a dam body is small, it can be discharged to the existing energy dissipator, but in the case of large scale facilities such as Tsuruda Dam, a specialized energy dissipator is newly constructed.

As for Tsuruta Dam, as well as Nagayasuguchi dam, the hydraulic design was examined while confirming the flow condition by the hydraulic model experiments (Figure 1).



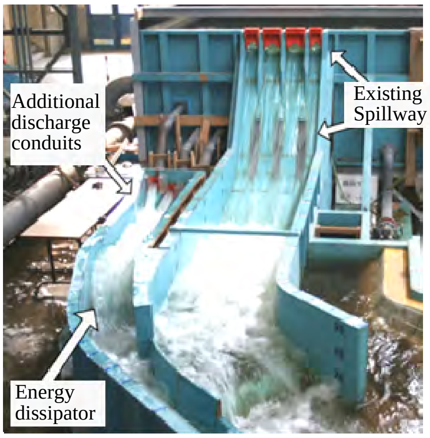


Figure 1: Construction situation of Tsuruda dam (June 2017) (left) and hydraulic model (right)

2.3 New construction of tunnel spillway

When it is difficult to cut or drill the existing dam body due to restrictions on dam type and dam structure in order to add large capacity discharge facilities, it is selected to construct a new tunnel spillway in the mountains around the dam. As a representative example, there are two dams of Kanogawa dam in Ehime prefecture and Amagase dam in Kyoto prefecture. Both dams are managed by MLIT and are currently under remodeling construction.

The tunnel spillway of Kanogawa dam is 11.5 m in tunnel diameter, 457 m in length, about 1,000 m^3/s in discharge capacity. The tunnel spillway of Amagase dam is 10.3 m in tunnel diameter, 617 m in length, about 600 m^3/s in discharge capacity.

Because they are long pipe channels acting relatively large hydraulic pressure, they were designed as pipe flow facilities where the cross section of the tunnel channels were large and the flow velocities were suppressed to around 10 m/s. Due to the pipe flow, air suction at the inflow portion may cause vibrations of the gate at the outlet and disturbance of the flow condition. In order to reduce air suction, it is necessary to deepen the position of the inflow part, but since they are large-scale facilities and such arrangements are difficult, inlet part shapes were examined by the hydraulic model experiment to suppress the generation of the suction vortex.

In construction of the inlet part in the reservoir of Amagase dam, a shaft-type underwater working machine which can perform excavation work and so on underwater by remote control from the land developed by a private company was adopted.

Both dams' facilities have large discharge capacities and need energy dissipators, but due to constraints on the arrangement within the downstream river channel, Kanogawa dam has a compact designed stilling basin with steps and baffle piers (Figure 2), the energy dissipator of Amagase dam will be installed as underground type in the mountains.

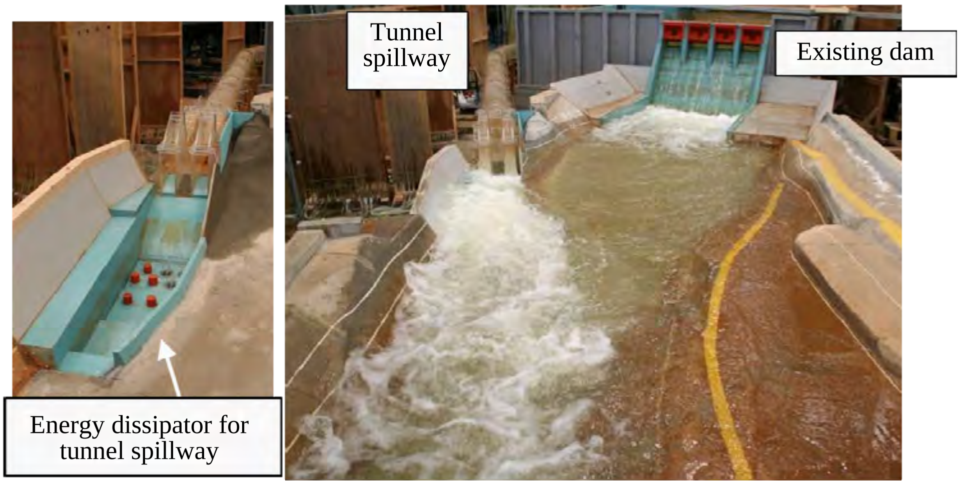


Figure 2: Hydraulic model experimet situation of Kanogawa dam tunnel spillway

3. HYDRAULIC DESIGN IN NAGAYASUGUCHI DAM REMODELING PROJECT

3.1 Outline of Nagayasuguchi dam remodeling project

Nagayasuguchi dam is a multipurpose dam built in 1956 in Tokushima prefecture for flood control, power generation and irrigation water supply. The dam type is a gravity type concrete dam, with the dam height 85.5 m, total water storage capacity 54,278,000 m^3, effective water storage capacity 43,497,000 m^3, catchment area 538.9 km^2. Nagayasuguchi dam remodeling project is to modify the dam for the purpose of increasing the flood control capacity, maintaining of normal function of the river water flow and improving the water quality of the discharged water [3]. Regarding the increase of the flood control capacity, based on the flood control plan of the Nakagawa River System, in order to secure the flood control capacity required, a part of the dam body on the right bank will be cut out and the two additional new spillways will be installed (Figure 3).

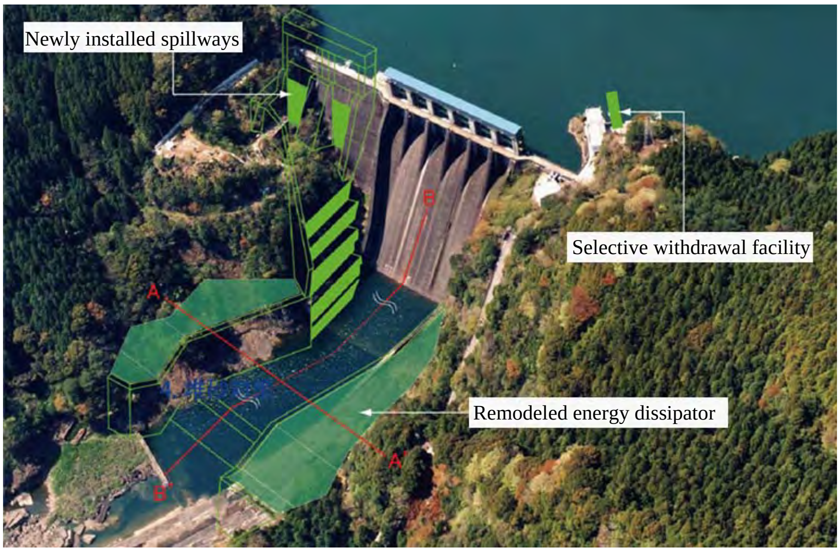


Figure 3: Outline of Nagayasuguchi dam remodeling project

3.2 Hydraulic design by hydraulic model experiments

The hydraulic design by hydraulic model experiments of the newly installed spillways of Nagayasuguchi dam remodeling project was carried out at the Public Works Research Institute from 2008 to 2012. It was confirmed that required functions and safety as described below were secured under conditions such as predetermined water level and discharge rate; whether the required discharge capacity is secured, whether the water pressure acting on facilities such as the training channel part and the energy dissipator is within an allowable range, and whether a stable flow situation is formed. In the case that they were not secured, the design of the facilities was revised.

Specifically, the examinations on the overflow crest part, the training channel part, the energy dissipator (the existing facilities and newly installed facilities released flood discharges merge with each other) and the downstream river channel were implemented (Figure 4).

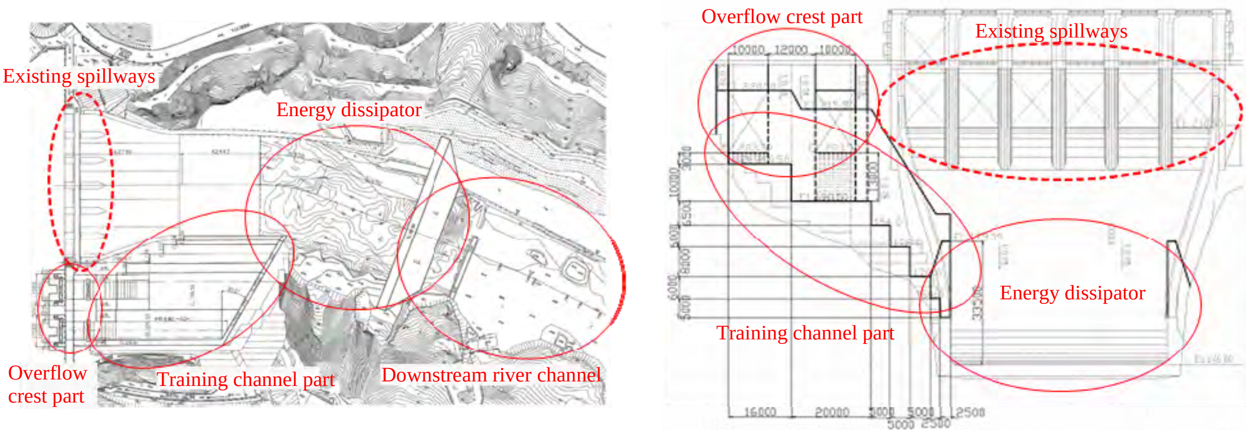


Figure 4: Plan view (left) and downstream view (right) of the original design shape

First, a hydraulic model of the original design shape by desktop design work was created, water was flowed under conditions of predetermined water level, discharge rate, etc., and flow conditions were checked. The overflow crest part was important to determine the flood control function of the dam, it was necessary to confirm whether a predetermined discharge rate was able to discharge at a predetermined water level and derive a relational equation between the water level and discharge rate. Usually, it is studied with a large scale partial model (Figure 5), which extracts only the overflow crest part, apart from the whole model (Figure 5) including the other parts of discharge facilities.

Figure 6 shows the situation of the hydraulic model experiment with the original design shape of Nagayasuguchi dam.

The following problems were recognized from the experimental results of the original design. In the overflow crest part, the discharge rate at the predetermined water level was insufficient. At the training channel part, the water flow from the overflow crest hit the training wall with momentum and dropped to the energy dissipator (stilling basin) without energy dissipation. In the original design shape of the energy dissipator installing only sub-dam, the water stream on the left bank largely creeped up in the area where the discharged water from the existing spillway merged into the discharged water from the newly installed spillways.

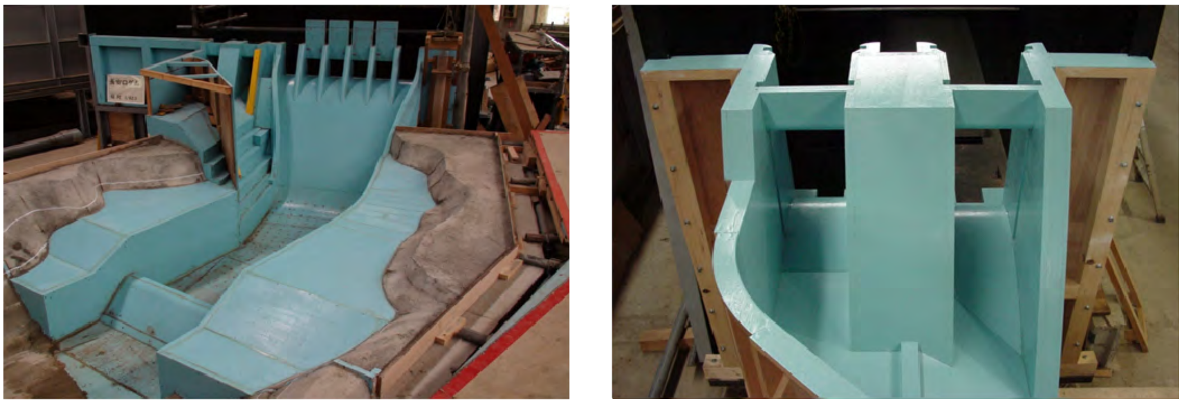


Figure 5: The whole model (scale:1/62.5) (left) and the patial model of crest part (scale:1/40) (right)

Figure 6: Flow stiation of hydraulic model experiment (training channel part: original desgin)

In order to improve these problems in the original design shape, as for the overflow crest part, by lowering the overflow crest top height on the river side discharge facility and changing the shapes of the overflow crests from the trapezoidal overflow spillway to the standard shape of overflow spillway, the required discharge rate was secured.

Regarding the training channel part, various shapes such as changing the position and angle of the training wall, installing the slope and so on had been examined trial and error. The final shape that separates and diffuses the discharged water from both spillways of the mountain side and the river side was developed. As a result, the water level of the training channel part could be kept low and the height of the training wall could be reduced.

As for the energy dissipator, a safe design shape for the dam and the downstream river channel was obtained by improving the planar shape and installation of the side channel walls. The final design shape is shown in Figure 7, and the situation of the hydraulic model experiment with the final shape is shown in Figure 8.

In addition, as shown in Figure 9, examinations on the flow situation in the case where discharge from existing spillways occurred during the construction of the new energy dissipator were also conducted by hydraulic model experiments.

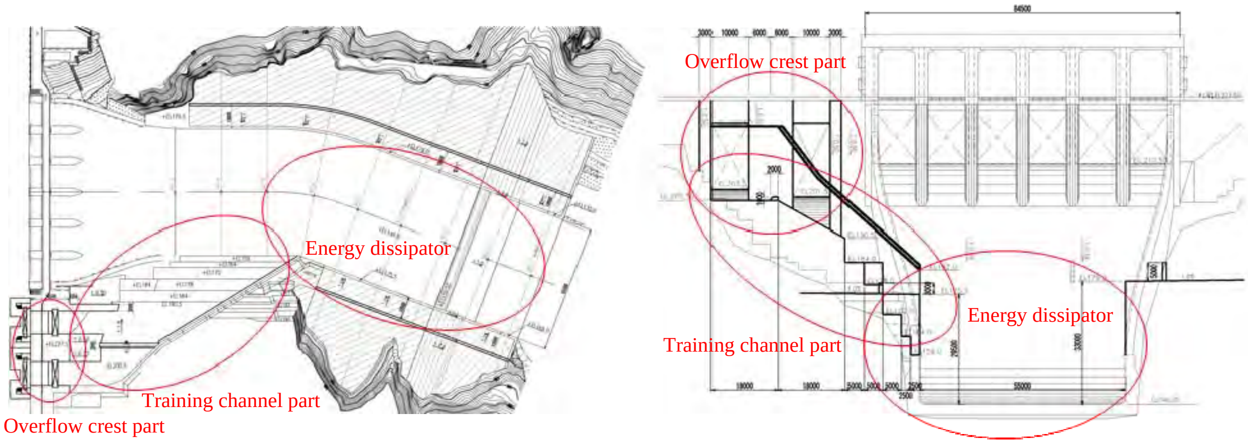


Figure 7: Plan view (left) and downstream view (right) of the final design shape

Figure 8: Flow stiation of hydraulic model experiment (training channel part: final desgin)

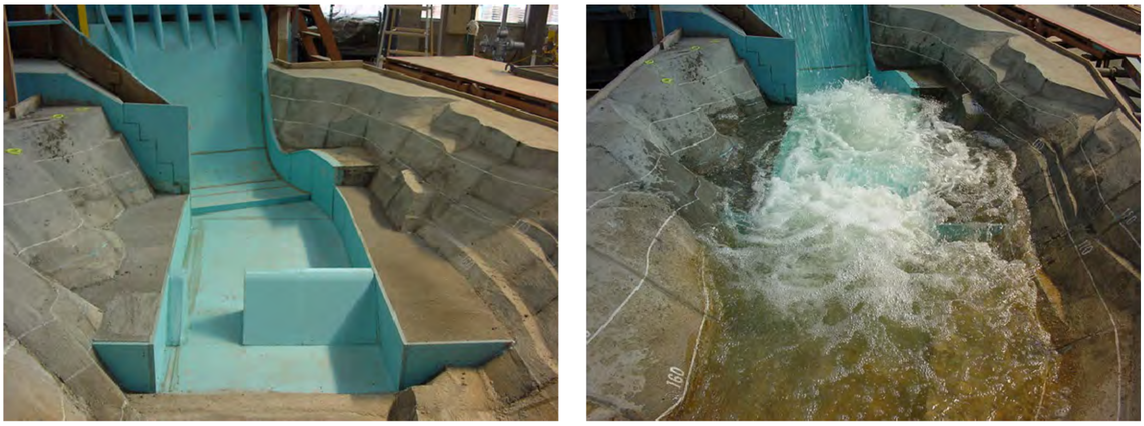


Figure 9: Flow stiation of hydraulic model experiment of the construction stage

4. CONCLUSION

In the hydraulic design for upgrading dams, it is important to secure the required discharge function and to ensure the safety of the dam body and the downstream river channel with respect to the flow condition downstream of the dam which changes greatly due to an increase of discharge capacity.
In addition, since it is necessary to carry out the remodeling construction work while operating the existing dam, the examinations how to secure the function of the existing dam under construction and how to minimize the influence of discharge from the existing dam on construction work are important.
Regarding the technologies to increase the discharge capacity in Japan, in the past few years, the largest historical projects of three representative methods of cutting dam body, drilling dam body and tunnel spillway have been started and are currently under construction respectively. Many technical experiences and knowledge have been accumulated in various fields through the implementation of these designs and constructions, and it is expected to be utilized them for future upgrading dams under operation.

REFERENCES

[1] Water and Disaster Management Bureau, MLIT. (2017). MLIT's Vision to Upgrade Dams under Operation. (in Japanese)

[2] Kashiwai, J. and Miyawaki, C. (1999). Pressure characteristics of curved portion of circular conduit pipe. *Dam Engineering*, Vol. 9, No. 4, 245-252. (in Japanese)

[3] Nakagawa River Office, MLIT. Website “Nagayasuguchi dam remodeling project”. http://www.skr.mlit.go.jp/nakagawa/dam/outline/index.html (in Japanese)

第10回 EADC 発表論文

ダム再生における水理設計

櫻井寿之*1
石神孝之*2

1. はじめに

日本では，これまでに整備されてきたダムが，治水・利水の両面から大きな役割を果たしてきている。一方で厳しい財政状況や生産年齢人口の減少などの状況の中，トータルコストを縮減しつつ，既存ストックを有効活用することが重要になってきている。このような認識のもと，既設ダムを有効活用するダム再生をより一層推進する方策を示した「ダム再生ビジョン」[1) が国土交通省によってとりまとめられ，平成29年6月に公表された（表―1参照)。

方策の一つとして挙げられている「(4) 高機能化のための施設改良」については，ダムの施設改良として，既設ダムのかさ上げや放流設備の増強等が実施された事例があり，現在実施中のダムもある。

ダム再生における放流設備の改良や増設における水理設計では，新規のダム建設とは異なる課題がある場合があり，水理模型実験等によって課題への対応が検討されてきている。本報告では，これらのダム再生における主要な放流設備増強技術の概要を紹介するとともに，代表事例として長安口ダム改造事業を取り上げて，再開発事業の水理設計の内容を報告する。

表―1 ダム再生を発展・加速させるための方策

(1) ダムの長寿命化
(2) 維持管理における効率化・高度化
(3) 施設能力の最大発揮のための柔軟で信頼性のある運用
(4) 高機能化のための施設改良
(5) 気候変動への適応
(6) 水力発電の積極的導入
(7) 河川環境の保全と再生
(8) ダムを活用した地域振興
(9) ダム再生技術の海外展開
(10) ダム再生を推進するための技術の開発・導入

2. 放流設備増強技術

既存ダムの施設改良において，治水計画の変更，利水計画の変更，機能改善等の様々な理由から放流設備増強やダムのかさ上げ等が実施されてきている。以降では，比較的大容量の放流能力を有する放流設備を増強する場合に代表的な，堤頂放流設備の改良・増設，堤体放流設備の改良・増設，トンネル洪水吐きの新設の３つの技術の概要を紹介する。

2.1 堤頂放流設備の改良・増設（堤体切削）

堤頂に設置される越流形式の放流設備や作用水頭が25m 以下のオリフィス形式の放流設備等を改良・増設するものであり，堤体を上部から開削して施工する手法がよく用いられる。改造部分が堤頂付近の施工となるため大きな水圧への対応に関する課題は少ない。さらに，貯水位を低下させることなどで仮締切等の対応が不要となる場合には，比較的施工が容易となる場合もある。

比較的初期に建設されたダムでは，常用洪水吐きと非常用洪水吐きのどちらもゲート調節型式の放流設備が採用されていることがあり，そのようなダムで，集水面積が小さく洪水時の流量増加が早い場合には，洪水調節機能の確実性を向上させるために，放流設備をゲートレス化する場合がある。ゲートレス化は維持管理の負担を軽減することにもつながる。非常用洪水吐きをゲートレス化するためには，越流幅を拡大することが多く，堤頂部に配置することができるか，放流される水脈を減勢して安全に下流河道に流下できるかといった点が課題になる。これらを解決するために，貯水池内の湖岸に新たな非常用洪水吐きを設置したり，堤頂部の越流幅の拡大と合わせてダム下流面に堤趾導流壁を設置したりする工夫がされている。

放流能力増強以外の目的を持った事例として，宮崎県の山須原ダム，西郷ダム（九州電力）では，土砂を通過させる機能を高めるため，既設の堤頂部放流設備について堤体を切り下げて大きなゲート放流設備とする改造が行われている。

*1 一般財団法人ダム技術センター 首席研究員
*2 国立研究開発法人土木研究所 水工研究グループ 水理チーム 上席研究員

堤体を開削する手法については，現在改造工事を施工中の徳島県の長安口ダム（国土交通省）がその開削深さにおいて既往最大規模の事例である。最大で深さ約37mの開削が行われており，２つの大規模ローラーゲートを有する放流設備が増設される予定である。長安口ダムについては３章にて水理設計の内容を報告する。

2.2 堤体放流設備の改良・増設（堤体削孔）

堤体放流設備の改良・増設は，既設のダム堤体に穴をあけ，放流設備を増設する手法で，基本的には重力式コンクリートダムに適用される。日本では，利水目的の貯水池運用上の制約から貯水位を大きく低下させることが難しい場合があり，大水深条件での施工が求められるため，ダム堤体上流側の仮締切の技術が重要となる。

作用水頭が25mを超える放流設備は高圧放流設備と定義され，放流時に流れが高速となるため，局所的な負圧の発生等によるキャビテーション損傷を防止する必要がある。そのためには管内流速を小さくする必要があるが，堤体にあけることができる穴の大きさや数はダムの構造により制約があるため，経済性からは流速を大きくして放流能力を増加させることが有利である。さらに，増設放流設備では，既設の放流設備の配置との関係から放流管の呑口と出口を直線上に配置することが困難なことがある。その場合，複雑に湾曲する形状が採用されるが，大口径放流管の湾曲部では局所的な圧力低下が生じやすくなる。こうした課題に対して，水理模型実験による湾曲部の壁面作用圧力に関する検討[2]によって，現在では合理的な設計が可能となっている。

堤体削孔の事例としては，鹿児島県川内川の鶴田ダム（国土交通省）にて，増設放流管３条（直径4.8m，削孔断面：高さ6.0m×幅6.0m），付替発電管２条（直径5.2m，削孔断面：高さ6.4m×幅6.4m）を増設したものが既往最大規模である（図―１参照）。鶴田ダム増設放流設備の施工における仮締切では，ダム上流の水中に台座コンクリートを設置後，鋼製の仮締切扉体を組み上げる従来の工法の他に，台座が不要な浮体式仮締切の新技術が開発され，大深度潜水作業を軽減し，コスト縮減や安全性向上が実現された。

堤体放流設備は流量が小さければ，既設の減勢工に放流する形式とすることができるが，鶴田ダムのように大規模な場合には専用の減勢工が新設される。

鶴田ダムについても長安口ダム同様に水理模型実験で流況を確認しながら設計形状が検討された（図―１参照）。

2.3 トンネル洪水吐きの新設

大容量の放流設備を増設する際にダム型式やダムの構造上の制約から既設ダム堤体を切削または削孔することが困難な場合には，ダム堤体周囲の地山内にトンネル洪水吐きが新設される。事例としては，現在施工中の愛媛県肱川の鹿野川ダム（国土交通省）と京都府淀川の天ヶ瀬ダム（国土交通省）の２つがある。

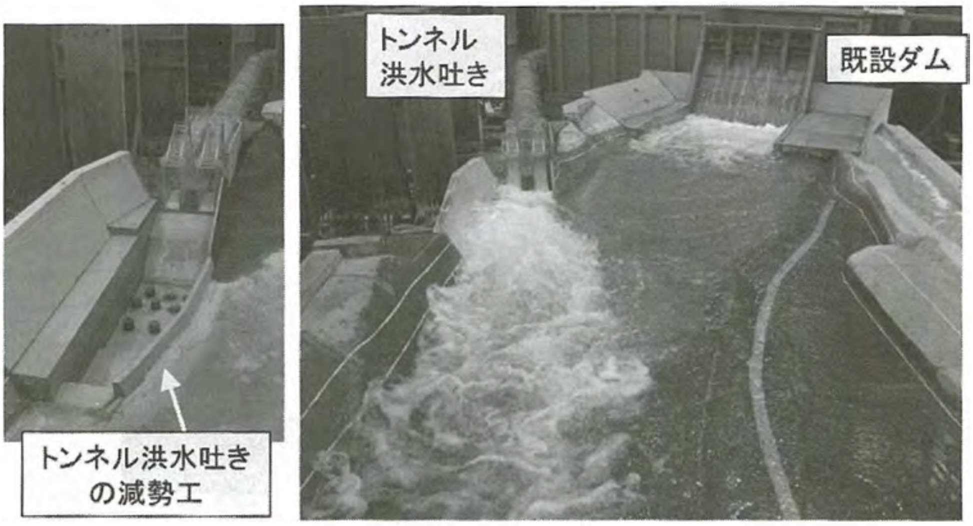
鹿野川ダムのトンネル洪水吐きは，トンネル直径11.5m，延長457m，放流量約1,000㎥/s，天ヶ瀬ダムは，トンネル直径10.3m，延長617m，放流量約600㎥/sである。

比較的大きな水圧の作用する延長の長い設備となるため，トンネル水路の断面が大きく，流速を10m/s程度に抑えた管路流の施設として設計されている。管路流のため，流入部で空気を吸い込むと出口でのゲートの振動や流況の乱れを招く懸念がある。空気混入を減らすには流入部の位置を水面から深くする必要があるが，大規模な施設であり，そのような配置が難しいため，水理模型実験によって吸い込み渦の発生を抑える流入部形状が検討された。

天ヶ瀬ダムの貯水池内流入部施設の施工においては，民間企業が開発した陸上から遠隔操作で水中の掘削等の作業が行えるシャフト式水中作業機が採用された。

両ダムとも放流量が大きく，減勢工が必要になるが，河道内の配置の制約があり，鹿野川ダムでは段差やバッフルピアを配置することでコンパクトな減勢池形状とし（図―２参照），天ヶ瀬ダムでは地山内に減勢工を設置する工夫がされている。

図―1　鶴田ダムの改造状況（2017年6月）（左）と水理模型（右）



図—2　鹿野川ダムトンネル洪水吐きの水理模型実験状況

3.　長安口ダム改造事業における水理設計

3.1　長安口ダム改造事業の概要

長安口ダムは，那賀川水系那賀川に，洪水調節，発電，かんがい用水の補給を目的として，1956年（昭和31年）に建設された多目的ダムである。ダム形式は，重力式コンクリートダムであり，堤高85.5m，総貯水容量54,278,000m³，有効貯水容量43,497,000m³，流域面積538.9km²である。長安口ダム改造事業は，長安口ダムの洪水調節能力の増強，那賀川における流水の正常な機能の維持及び放流水の水質改善を目的としてダム改造を行うものである[3]。洪水調節能力の増強については，那賀川水系の治水計画に基づき，長安口ダムに要求される洪水調節能力を確保するため，堤体の右岸の一部を切り欠いて２門の新設洪水吐きの増設を行うものである（図—３参照）。

3.2　水理模型実験による水理設計

長安口ダム改造事業に関して，土木研究所にて2008年度から2012年度に，水理模型実験により新設洪水吐き等の水理設計が実施された。所定の水位・流量等の条件において，求められる放流能力が確保されているか，導流部や減勢工等の施設に作用する水圧が許容される範囲内か，安定した流れが形成されているかなど，必要とされる機能や安全性が確保されていることを確認し，確保されていない場合は施設の形状等が修正された。

具体的には，図—４に示す新設洪水吐きの越流部，導流部，既設及び新設洪水吐きからの放流水が合流する減勢工及び下流河道を対象に検討された。

最初に机上設計による原案形状の縮小模型が製作され，所定の水位・流量等の条件で通水され，流況等が確認された。手順としては，上流から越流部，導流部，減勢工，下流河道の順に機能が確認される。ここで，越流部はダムの洪水調節機能を決定する重要なもので，所定の水位で所定の流量が流れるかを確認し，水位と放流量の関係式を導く必要があり，多くの場合は，他の減勢工等の部分と合わせた全体模型（図—５参照）とは別に，越流部のみを抽出した大きな縮尺の抽出模型（図—５参照）で検討される。

長安口ダムで実施した原案形状での水理模型実験の状況を図—６に示す。

原案形状の越流部では所定の水位での放流量が不足していた。導流部については越流部からの水流が勢いを持ったまま導流壁に当たり，さらに減勢することなく減勢工（減勢池）に落下していた。副ダムのみを設置した減勢工の原案形状では，既設洪水吐き及び新設洪水吐きからの水流が合流する領域で左岸側の水脈が大きく這い上がる状況となった。

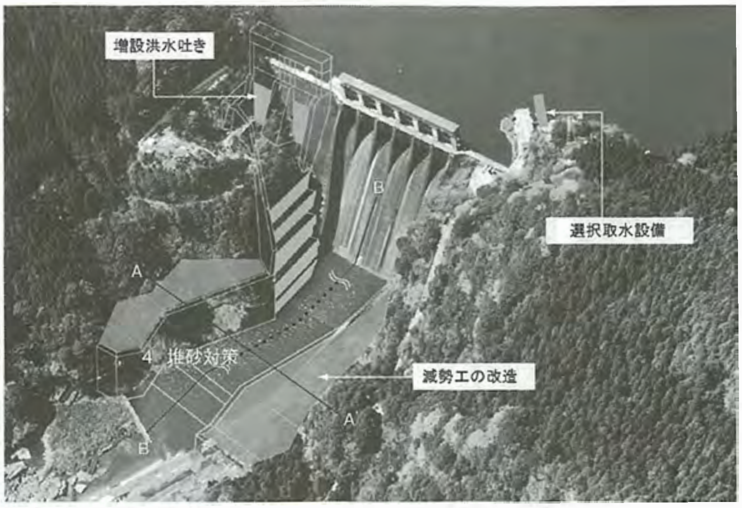
これらの原案形状での課題に対して，越流部については，川側の越流頂標高を低くし，越流頂の形状を台形越流頂から標準越流頂に変更することで，必要な放流量が確保された。

導流部については，導流壁の位置・角度の変更，スロープの設置など様々な形状が試行錯誤的に検討され，山側と川側の両者の洪水吐きからの水脈を分離・拡散する形状が考案された。その結果，導流部の水位を低く抑えることができ，導流壁の高さを低くすることが可能になった。

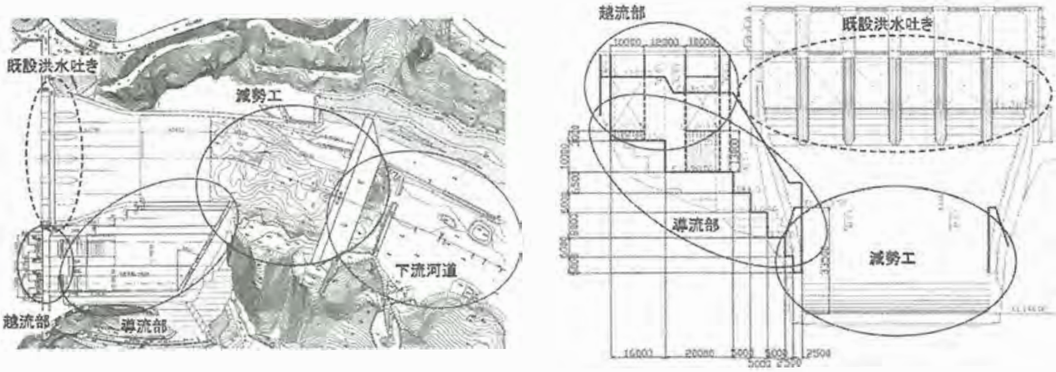
減勢工については，平面形状の修正や側壁天端の水路壁の設置により，一部減勢工側壁を越水する場合があるが，側壁高を低く抑えることができ，下流河道に対しては十分な安全性を確保することができた。

図—７に修正した最終的な形状及び図—８にその形状での水理模型実験の状況を示す。

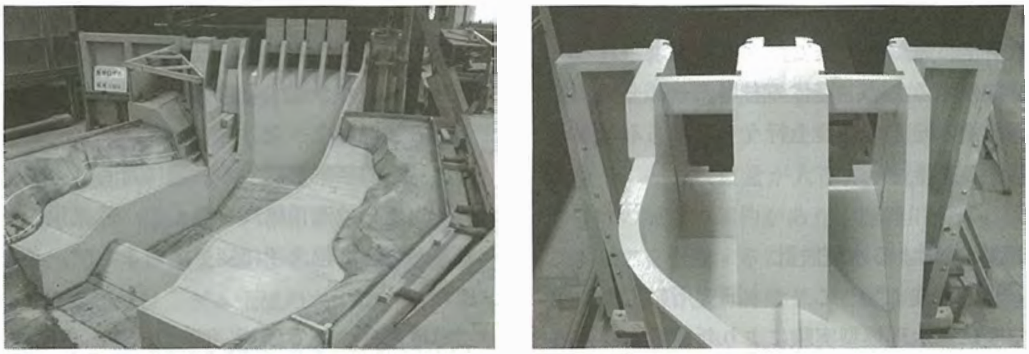
また，図—９に示すように，減勢工の施工途中に既設洪水吐きからの放流が生じた場合の流況についての水理模型実験も実施されている。



図—3　長安口ダム改造事業の概要

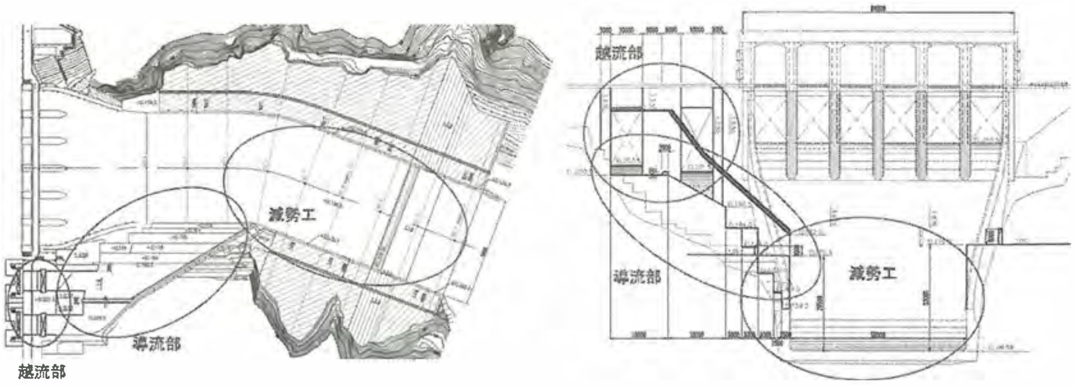


図—4　原案形状の平面図（左）と下流面図（右）

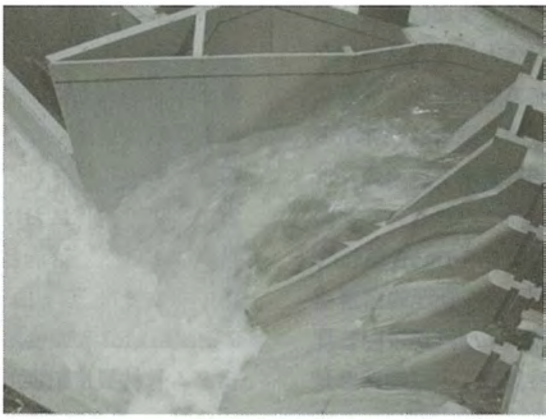


図—5　全体模型（縮尺 1/62.5)（左）と越流部抽出模型（縮尺 1/40)（右）

図—6　水理模型実験での流況（導流部：原案形状）



図—7　最終形状の平面図（左）と下流面図（右）



図—8　水理模型実験での流況（導流部：最終形状）

図—9　施工途中の水理模型実験での流況

4.　おわりに

ダム再生における水理設計上の留意点は，必要な放流機能の確保と放流機能の増強によって大きく変化するダム下流の流況について，ダム堤体と下流河道の安全性を確保することである。

また，既設のダムを運用しながら施工する必要があり，施工中の既設ダムの機能をいかに確保するか，また既設ダムからの放流が工事に及ぼす影響をいかに小さくするかの検討が重要になる。

日本のダムの放流設備増強に関しては，この数年の間に，堤体切削，堤体削孔，トンネル洪水吐きの代表的な３つの手法について，それぞれ既往最大規模の工事が開始され，施工が進められている。これらの設計や施工を実施する中で多くの技術的な知見が各分野で蓄積されてきており，今後のダム再生への活用が期待される。

参 考 文 献

1) 国土交通省 水管理・国土保全局：ダム再生ビジョン，2017年
2) 柏井条介，宮脇千晴：円形放流管湾曲部の圧力特性，ダム工学，Vol.9，No.4，pp.245-252，1999年
3) 国土交通省那賀川河川事務所ホームページ（長安口ダム改造事業）