Rehabilitation of Hydropower Plants by Dam Tunneling

M. Kashiwayanagi
Senior manager, Electric Power Development Co. Ltd., Japan

Y. Mizuhashi
Manager, Electric Power Development Co. Ltd., Japan

1. Introduction

Development of high dams in Japan started as construction of gravity dams in 1890s with the spread of Portland cement. Now about 2600 dams of which height is more than 15m are under operation. These dams have supported the economic basis of Japan by utilization of stored water and have contributed to protecting human life and social property by flood control. From the above viewpoints, it seems that the Japanese public accepts benefit of dams.

Meanwhile, few promising dam sites are left since almost all dam sites, which are economically feasible and environmentally friendly, have been developed already in not so large national land of Japan. Therefore, it got to be more difficult to promote a development plan of a dam than before even though the plan is approved as the optimum development method after many-faced evaluation.

In comparison with totally new development plans, rehabilitation plans that make use of existing dams have advantages such as those cited below, and therefore it is expected that the demand for their positive implementation will increase in Japan:

1) mitigating the impact on the environment,
2) meeting immediate developmental requirements due to a shorter execution period,
3) realizing a more economical exploitation, and
4) making the best use of unused energy.

In addition to re-development plan by improvement of a dam and a supplement of facilities, a wide area re-development plan which produces a new function by coordinating plural dams and reservoirs has been put into practice in recent years.

From the design aspects of dams, Dr. Mononobe devised seismic coefficient method in 1925, which started a dam design system and the Japan Commission on Large Dams practically completed it by establishing the Design Standard of Dams in 1957. Accordingly, some of the existing dams which were constructed before the said standards were established have less resistance to earthquake and insufficient spillway capacity compared with recent ones. Safety of these dams shall be improved since most of them have worked efficiently to date and are expected to maintain the function in the years ahead. Therefore, some of those dams are under reinforcement works in proportion to the degree of importance considering characteristics of each dam site.

These major re-development plans are summarized as shown in Table-1. In some cases, however, innovative engineering methods need to be introduced to maximize these effects, and this is the urgent issue to be addressed.

Among all redevelopment plans, some examples of hydropower plants that have been rehabilitated by dam tunneling are introduced in this report.

Because only a few cases are known in Japan in which the concrete of an existing gravity dam has been excavated or modified after completion as of the beginning of 1990's, the safety and construction methodology of a dam during and after execution has become a hot subject. Meanwhile, as the character of Japan's consumption of electricity is to peak at certain time periods, there was an urgent demand to provide peak power. To address this problem, the plan for the extension to the Okutadami hydropower station were carried out to produce peak power using the existing dam facilities, as stated below. And the plan for the Akiha No. 3 hydropower station was carried out to make good use of reservoir water spilt through a spillway. Figure-1 and Table-2 show the locations and outlines of both generation plans. The design and application of dam tunneling will also be discussed in the next section.

2. Outline of dam tunneling method

There are two important points to keep in mind in designing a dam tunneling methodology for an existing concrete dam; 1) the stability of the dam and, 2) the stress around a tunnel.

As for dam stability, it needs to be confirmed whether the monolith to be tunneled satisfies the design requirements (e.g. dam stress, safety factor for sliding and foundation stress) to withstand various loads such as the hydrostatic pressure of the reservoir and seismic loads.

Besides, the stress around a tunnel is influenced by the configuration of excavation and its local load. Although this phenomenon can be modeled simply as stress concentration in an infinite perforated panel, its detailed evaluation of the stress is possible with a highly accurate FEM analysis. On the basis of these

Table-1 Rehabilitation projects of dams in Japan – Recent applications

Projects	Type	Description	Features
Sannokai dam	A	Supplemental water supply for the agricultural use by increasing the dam height	Dam type: Rock fill Previous dam height: 37m Completed in 1952 Modified dam height: 61.5m Completed in 2001
Mitaka dam	A	Supplemental water supply for the agricultural use by increasing the dam height	Dam type: Concrete gravity dam Previous dam height: 32.6m Completed in 1944 Modified dam height: 44m Completed in 2002
Taishakugawa dam	A	Supplemental hydropower by developing the unutilized energy with the enhancement of the capacity of flood discharge and seismic stability	Dam type: Concrete gravity dam Previous capacity: 4.4MW, 720m^3/sec(Flood) Modified capacity: 13.4MW, 1610m^3/sec
Okinawa integrated water supply project	A	Comprehensive operation of existing dams for the stable water supply in the main island in Okinawa	Five (5) dams and connection waterway systems are involved in this Project.
Comprehensive operation project in Awaji island	A,B	Enhancement of water supply and flood mitigation by cooperation of dams	Five (5) dams and connection waterway systems are involved in this Project.
Nagasaki flood mitigation project	B	Enhancement for the flood discharge by the cooperation of existing dams for water supply	Three (3) exiting dams and two (2) new dams are involved in the Project. Completed in 2005
Yamagichi reservoir	C	Enhancement of seismic stability by embankment on the existing dam body	Dam type: Earthfill dam Previous dam height and volume: 35m, 1.4MCM Completed in 1934 Modified dam volume: 2.37 MCM Completed in 2002
Ohmatazawa dam	C	Enhancement of seismic stability	Dam type: Concrete gravity dams Previous dam height: 18.7m Downstream slope: 1 to 0.6 Completed in 1917 Modified dam slope: 1 to 0.94 Completed in 2002
Yamakura dam	C	Enhancement of seismic stability to reduce the possibility of liquefaction during earthquakes by arranging the Soil Mixing Wall in the dam	Dam type: Earthfill dams Previous dam height: 22.5m Completed in 1964 Modified dam slope: 1 to 0.94 Completed in 2002

Type description
A: Enhancement of original function of dams
B: Utilization to new purpose
C: Enhancement of safety of dams

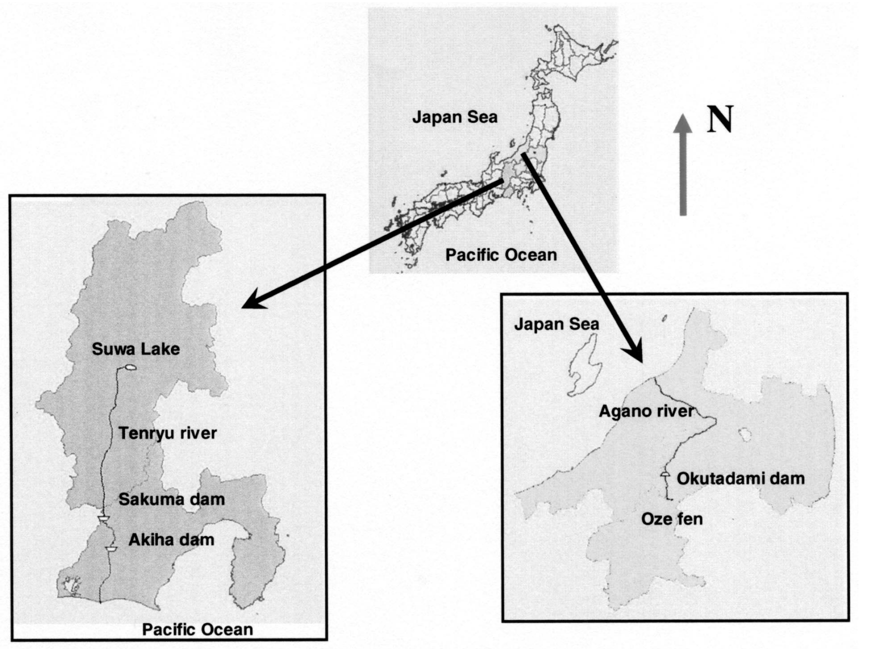


Figure-1 Location map

Table-2 Features of the rehabilitation projects

Name of Power plant	Akiha hydropower plant No.3	Okutadami extension hydropower plant
Year of completion	1991	2003
River	Tenryu	Tadami
Drainage area	4490 km^2	595 km^2
Reservoir	Akiha reservoir (Existing)	Okutadami reservoir (Existing)
	Effective capacity: 7.75 MCM	Effective capacity: 458 MCM
Maximum discharge	116 m^3/sec	138 m^3/sec
Maximum head	47.1 m	164.2 m
Maximum capacity	46.9 MW	200 MW
Annual output	Increase : 348 x 10^{6}kwh Decrease : 252 x 10^{6}kwh	For Peak electricity
Dam	Akiha dam (Existing)	Okutadami dam (Existing)
	Height : 89 m	Height : 157 m
	Crest length : 273.4 m	Crest length : 480 m
Dam tunneling		
Section	Circle with a flat invert	Square with fillets
Length	21 m	32 m
Diameter	6.5 m	6.2 m
Volume	720 m^3 (including the shaft for the intake gate)	1200 m^3
Construction machine		
Drilling (Hydraulic Drifter)	60 mm bit in diameter	102 mm bit in diameter
Tunneling (Breaker)	2300 kg class	2000 kg class
Construction rate	Approx. 1m/day	Approx. 0.6m/harf day

methods, it has to be confirmed that the stress around a tunnel does not exceed the tensile strength of the existing dam concrete but maintains an appropriate safety factor.

The following two points should be taken into account in executing a dam tunneling method:

1) prevention of cracking in concrete beyond the excavated area,
2) reduction of vibration and impact on the dam body kept to a minimum during execution.

A useful reference for achieving these results is the non-blasting tunneling method, which has been developed for the construction of tunnels under the ground with thin overburden in urban area. This method includes two types of techniques; the single-step approach based on machinery excavation, and the two-phase approach in which the outer edge of the excavated section is first drilled and then the internal section crushed. The latter approach is further divided into three subsets according to the machines used to drill the circumference. Table-3 shows these methods one by one.

In the selection of the construction methodology, the higher consideration should be provided in the hardness of the aggregate of the dam concrete, which could affect much on the efficiency of the construction, but less in the strength of the dam concrete itself.

The records of the dam tunneling in Japan are summed up in Table-4, showing in which the smaller scale of tunneling for the installation of discharge conduits has been predominant. In this report, the case histories of larger scales of tunneling for the extension of the hydropower plants are introduced hereinafter.

3. Akiha No. 3 hydropower station

3-1. Outline of the plan

The existing Akiha reservoir (35 MCM in total volume) on the Akiha dam (PG, completed in 1958, dam height: 89 m, and dam volume: 515,000 m^3), which is located in the middle reaches of the Tenryu River in central Japan, is used for power generation by the Akiha No. 1 hydropower station (completed in 1958, output: 45.3 MW, maximum discharge: 110 m^3/sec) and the Akiha No. 2 hydropower station (completed in 1958, output: 34.9 MW, maximum discharge: 110 m3/sec). Due to the affluent flow of the Tenryu River, this area is usually stricken by the discharge through the spillways nearly 100 days a year even though much water usage is carried out through power generation. Thus, there has been a demand for greater efficiency in the use of the reservoir. The Akiha No. 3 hydropower station plan has been coordinated to produce the maximum energy by reviewing the operation efficiency of the existing No. 1 and No. 2 hydropower stations and by taking advantage of unused energy. Figure-2 shows the discharge allocation of the reservoir at original state and after completion.

The Akiha No. 3 hydropower station utilizes the intake facility of the existing No. 1 hydropower station situated on the right bank of the Akiha dam[1)-4)]. From an intake that was built by excavation and modifying the dam body, water is consumed at a maximum volume of 116 m^3/sec and is conducted to the No. 3 hydropower station that has been newly constructed immediately below the right bank of the dam by way of a 70 m-long penstock. Power is generated by means of an effective head of 47.1 m, with a maximum output of 46.9 MW and an annual power generation of 96x10^6 kWh. The water is then discharged to the existing Funagira reservoir from the tailrace tunnel, nearly 3.6 km in length and 6.5 m in inner diameter.

Some sections of the intake and the penstock have been installed by tunneling into the existing concrete of the dam. The tunnel consists of a tubular hole 6.5 m in diameter (area of cut: 34 m^2) and 21 m in length that facilitates the installation of the penstock, and a rectan-

Table-3 Summary of methodologies of dam tunneling

Construction methodology	Outline	Description
Single-step approach	Machinery excavation	TBM, Boring machine, excavation machine are applicable
Two-phase approach	Drilling and breaking	Making consecutive slots by single drilling or multi-slot drilling at the peripheral of the tunnel, followed by machinery breaking
	Cutting and breaking	Cutting by water jet or wire saw followed by the machinery breaking
	High density drilling with small diameter, Drilling with large diameter	High density drilling at the internal of tunnel followed by the peripheral drilling with large diameter boring machine

Table-4 Summary of dam tunneling for the rehabilitation of dams
(Other cases more than 10 are found as of 2005 in Japan.)

Name of dams	Owner	Type of dams	Height	Dam tunneling		Purpose	Construction	
				Diameter	Length		Completion	Method
			m	m	m			
Fujiigawa	Ibaragi Pref.	PG	37.5	8.6 (Enlarge)	20.0	A	1977	Drilling(Φ34mm), Machinery excavation
Yoroibata	MLIT*1)	PG	58.5	4.4	29.0	A	1989	Machinery excavation
Akiha	J-Power	PG	89.0	6.5	21.0	B	1991	Slot Drilling Method (ϕ 60mm, Milti-bits of 5), Machinery excavation
Kakkomi	J-Power	PG	34.0	1.8	4.5	A	1992	High pressure water jet, Static blasting
Naiba	Kagawa Pref.	PG	50.0	2.5	30.0	A	1993	Machinery excavation
Kuki	J-Power	PG	28.0	1.0	3.0	A	1995	Wire saw
Futagawa	Wakayama Pref.	PG	67.4	1.5	23.3	A	1998	Machinery excavation
Nanairo	J-Power	VA	61.0	1.7	5.7	A	2000	Wire saw
Haginari	Akita Pref.	PG	61.0	2.3	25.0	A	2000	Machinery excavation
Ikari	MLIT*1)	PG	112.0	5.0	101.7 (49.1,48.6)	A	2003	Machinery excavation
Okutadami	J-Power	PG	157.0	6.2	35.0	B	2003	Slot Drilling Method (ϕ 102mm), Machinery excavation
Mitaka	Hiroshima Pref.	PG	32.7	2.4	13.0	A, B	2004	Machinery excavation

*1) Ministry of Land, Instrastructure and Transport
Purpose of the dam tunneling A: Discharge for downstream area B: Discharge for Power generation

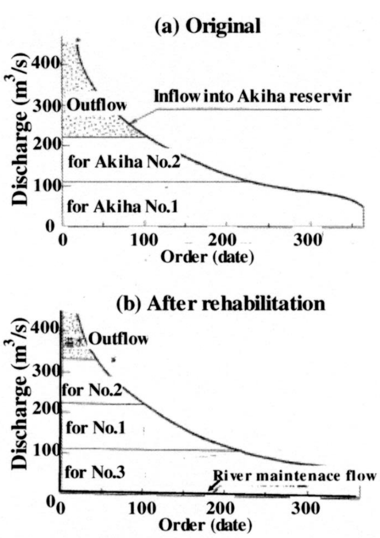


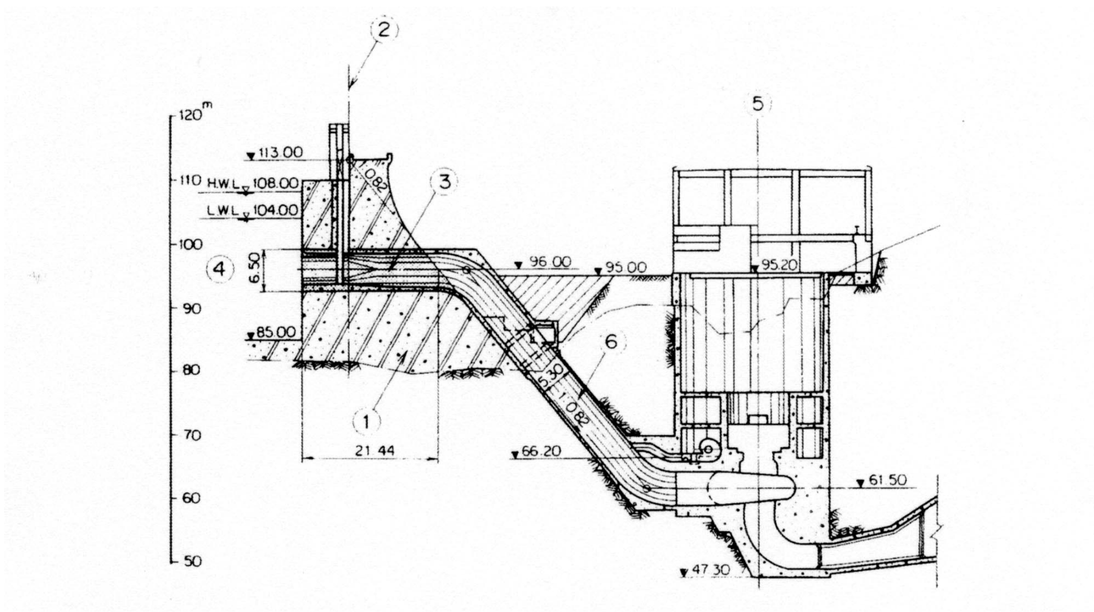
Figure-2 Discharge allocation for each hydropower plant

gular shaft 2.5 m x 7 m in cross-section and 11 m in depth for the intake gate. The total volume of excavation is about 720 m^3. Figure-3 depicts the structure.

3-2. Designing requirements

Regarding dam stability, such elements as dam stress, safety factor for sliding and foundation stress were examined under various conditions with water level and seismic intensity as parameters. As a result, it was confirmed that the safety requirements had been satisfactorily fulfilled.

To evaluate the stress around the tunnel, a profile of the dam that crosses the tunnel axis at right angles was regarded as a two-dimensional perforated plate, where the plate was assumed to be subject to dam stress induced by water pressure, seismic inertia force, dynamic water pressure and self weight of the dam. As a result, the maximum tensile stress of the upper area around the tunnel was calculated as 0.81 MPa under normal conditions without seismic effect. This value was sufficiently smaller than the tensile



① Existing Dam, ② Dam axis, ③ Dam tunneling, ④ Intake, ⑤ Powerhouse, ⑥ Penstock

Figure-3 Profile of the Akiha No.3 power plant

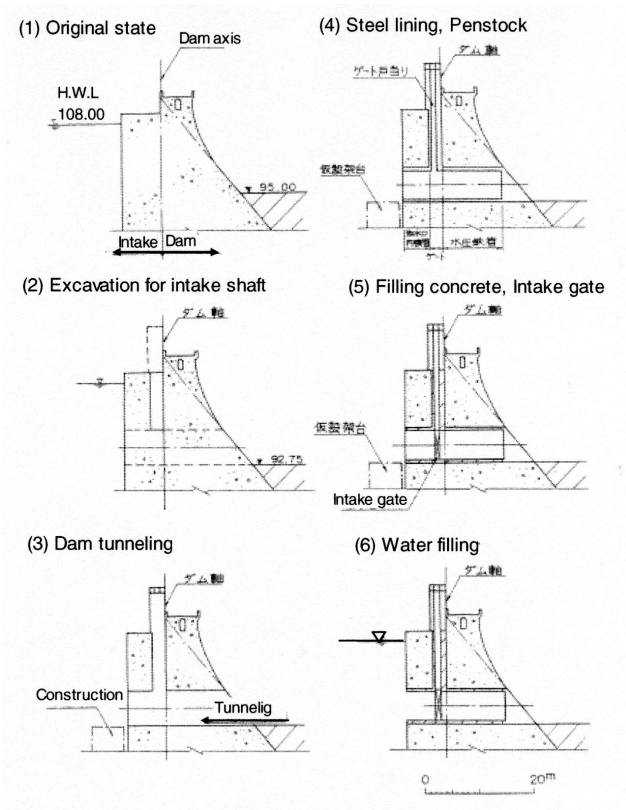


Figure-4 Tunneling methodology of the dam

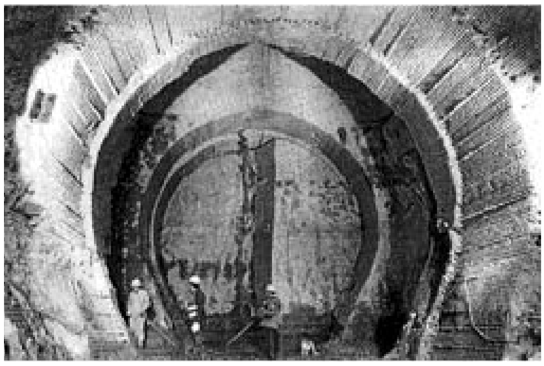
strength of 2.2 MP, which is estimated by the 21.6 MPa of the uniaxial compressive strength of the core (190 mm in bore diameter) extracted from the dam body and, suggesting a safe degree of stress after tunneling.

3-3. Construction method

Because there had been few precedents for this particular tunneling method, the slot drilling technique (SD Technique) was adopted by referring to the non-blasting tunneling method for underground tunnels. The process of the SD Technique is shown below and also in Figure-4. The total length to be drilled in the dam was approximately 2,260 m.

1) Consecutive holes are drilled in the outer periphery and a few strips in the inner section of the drilled area.
2) Crushing is performed by means of a hydraulic breaker (2.3 t class).
3) Crushed slag is removed.

a) Drilling machine



b) After tunneling

Photos-1 Dam tunneling of Akiha dam

During the crushing operation, vibration control was conducted to prevent damage to the dam concrete around the tunnel. As a control value against vibration-induced stress $\sigma = \rho V v$(where, σ: vibration-induced stress, ρ: concrete unit weight, V: the elastic wave velocity of concrete and v: vibration velocity), the stress allowable on the concrete was fixed at 0.22 MPa and the vibration velocity was set below 2.0 kine (cm/sec) by taking a safety factor of 10 into account.

The works of drilling into the dam concrete and of installing the intake gate and the penstock within the dam body had to be conducted below the low water level of the reservoir. Therefore, while these works were being carried out and the water was being discharged, the No. 1 hydropower station was suspended and its forebay closed with stop logs. The shutdown period of the No. 1 hydropower station was set at a minimum duration of 90 days. In the meantime, a series of working processes had to be completed: tunneling into the dam body, installing the intake gate and penstock and laying the filling concrete. These steps required careful preparation on the part of the administrator and precise construction management. Photos-1 was taken during the construction.

3-4. Comparison between observed values and analytical values of stress

As a part of the construction management, the changes in stress induced by dam tunneling were monitored with a stress meter that had been placed around the tunnel before commencement of the tunneling operation. At the same time, a three-dimensional FEM tunneling simulation was carried out for comparison with the observed values.

The stress on the existing dam body was also examined in the overcoring method. Figure-5 illustrates the location of a stress meter, the FEM model and both actual and analytical results.

Based on these results, a confining pressure of 0.3 MPa from the adjacent monolith was estimated, which allowed the tunneling-induced stress transient to be reproduced more appropriately. This kind of stress increment is not regarded as the tensile stress that was estimated in the early designing stages but as stress on the compressive side, since it is attributed to the confining pressure of the adjacent monolith.

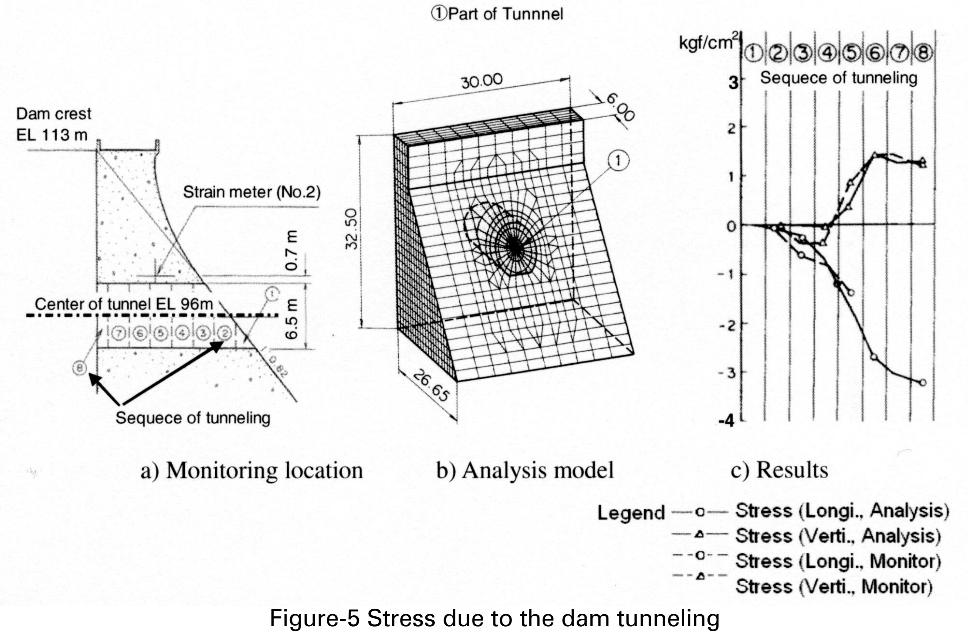


Figure-5 Stress due to the dam tunneling

4. Extension to the Okutadami hydropower station

4-1. Outline of the plan

The Okutadami hydropower station extension plan makes use of Japan's largest reservoir (600 MCM in gross reservoir capacity) on the existing Okutadami dam (PG, completed in 1960, dam height: 157 m and dam volume: 1,636,000 m^3), located in the uppermost stream of the Tadami River in central Japan. The plan was to develop a maximum output of 200 MW with the addition of the new generation facility in order to supply peak power by consuming 138 m^3/sec of water at maximum (work on the operations started in 2003)[5)-9)]. The existing Okutadami power plant takes water from the Okutadami reservoir at a maximum rate of 249 m^3/sec to generate up to 360 MW of power.

In this construction plan, as per policy, special attention was given to conservation of the natural environment, as the area is surrounded by unspoiled nature and is the natural habitat of the golden eagle, a rare bird registered in the Red Data Book. With the aim of protecting the golden eagle, the construction period was restricted to four months from July to October so as to avoid disturbing the nesting season.

4-2. Designing requirements

The intake for the extension hydropower station was installed by placing a bulkhead at the upstream surface of the existing Okutadami dam and drilling into the dam body. Because the normal operations of the existing reservoir were not interrupted during the period of construction, a steel-concrete semicircular bulkhead was constructed to withstand high water pressure at a depth of about 50 m. The structure is depicted in Figure-6.

Regarding the penstock, a volume of 1,200 m^3, 6.2 m in width and 6.2 m in height was excavated from the existing Okutadami dam body, and into this, a 32 m long penstock with a diameter of 5 m was laid. Its profile is shown in Figure-7.

Although a circular or horseshoe shape might be commonly adopted for the configuration of the tunnel, a tangential square cross section was employed in this project to reduce the stress induced by stress concentration in the existing dam. By adopting a square cross section, the flat bottom and ceiling surfaces make it easier to perform drilling operations and place the filling concrete. The validity of this structure was confirmed by a three-dimensional linear elasticity FEM analysis, in which the stress under various load conditions (e.g. seismic intensity and reservoir water level) was proved to be less than the strength of the dam concrete.

4-3. Bulkhead

The plan called for placing a bulkhead on the upstream side of the dam so that the construction work could be conducted under dry condition in a restricted execution period without interrupting the existing reservoir operations. This bulkhead had to be capable of withstanding high water pressure at a depth of 50 m in order for it to be engaged with the intake and penstock installed nearly 35 m below the full water surface. There was also a requirement for the structure to be built and removed in a short period of time.

Consequently, a steel-concrete semicircular bulkhead with a radius of approximately 8m was adopted to allow the axial force to take the water pressure. The structure was equipped with 13 box-type steel sheet piles with an arc length of nearly 2 m around the circumference and four piles in the vertical direction. The box-type steel sheet pile was filled with concrete underwater.

This structure enabled the construction of a relatively thin bulkhead with a thickness of 0.65 m that is capable of withstanding water pressure at a depth of

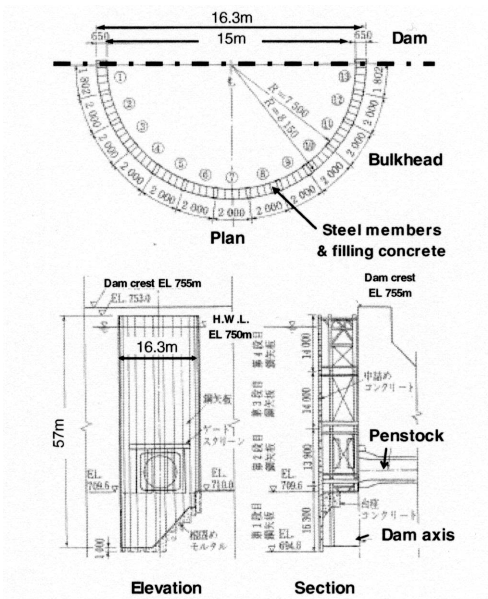


Figure-6 Bulkhead for the construction of intake, Okutadami extension HPP

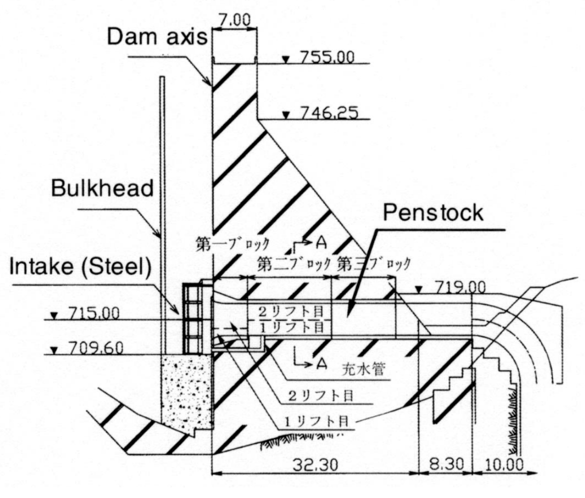


Figure-7 Profile of intake and penstock of the Okutadami extension HPP

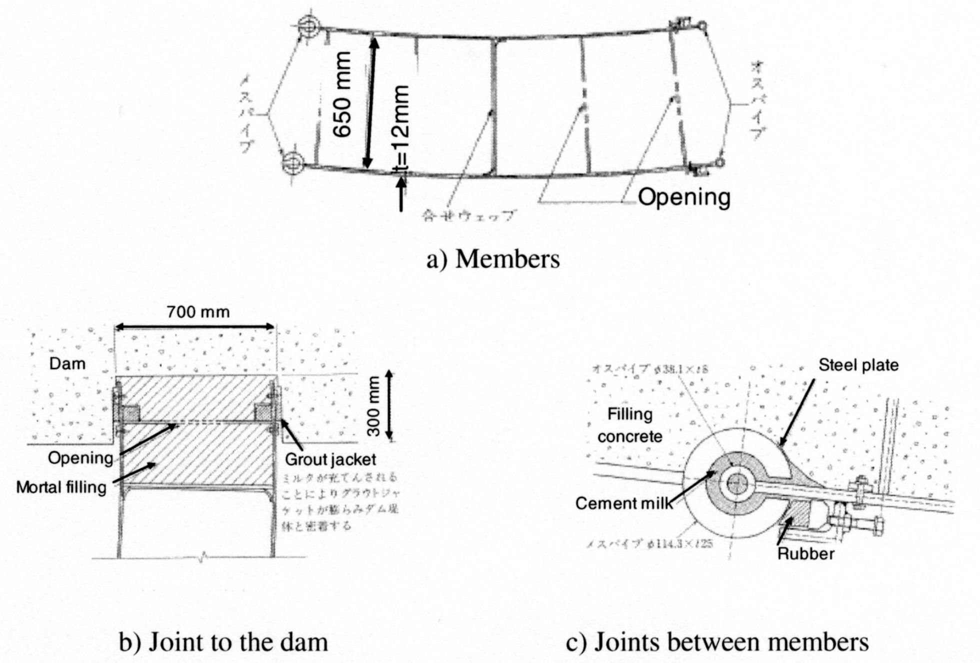


Figure-8 Details of bulkhead, Okutadami extension HPP

50 m. Figure-6 illustrates the structure of the bulkhead.

The possibility of leakage was considered at three sections: the bulkhead bottom, the joint to the dam and the joint sections of the bulkhead. To enhance the sealing capability, the following measures were taken.

(1) Bulkhead bottom

Seating concrete was laid up to a height of nearly 13 m between the lake bottom and the newly installed intake mouth. By connecting the seating concrete and the bulkhead, the sealing ability at the bottom of the bulkhead was reinforced. For the seating concrete to perform correctly underwater, anti-cracking measures had to be taken. By referring to the preliminary analytical result, precooling was carried out.

(2) Joint to the dam

The joint section to the dam was excavated nearly 0.3 m from the upstream side, where a steel sheet pile was installed to fill mortar between the pile and the dam. With the aim of enhancing the sealing ability of the joint, a grout jacket was used. The grout jacket expands under the pressure of its own weight when the milk of the grout is filled in, functioning as a packer. Figure-8 details the structure.

(3) Joint of the bulkhead

The detailed diagram of the joint of the bulkhead is shown in Figure-8.

4-4. Dam tunneling method

In determining the dam tunneling method for the Okutadami dam, reference was made to the operation record of the Akiha No. 3 hydropower station introduced in Chapter 3. A two-phase approach was chosen in order to reduce the execution period and to keep any impact on the existing dam concrete to a minimum. This method, consisting of slot drilling and breaker crushing, is similar to the one employed for the Akiha No. 3 hydropower station. Slots were drilled in such a manner that they continued around the outer edge of the tunnel section. These slots contributed to mitigating any vibration transferred to the dam and increased crushing efficiency through the creation of a free face during breaker crushing. To further enhance breaker-crushing efficiency, the coreless slots were combined. These can be seen in Figure-9.

4-5. Execution results

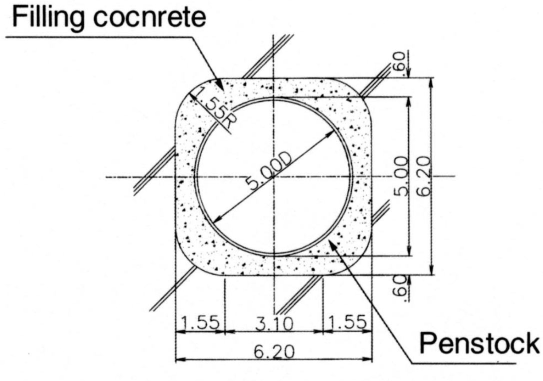
The strength of the aggregate used for the dam body was much higher than might have been expected, as the length of slot drilling in one cycle was 0.6m.

The degree of vibration transferred to the dam was monitored during drilling operations. As in the case of the Akiha No. 3 hydropower station, a vibration velocity of 2 kine (cm/sec) was set as the control criterion with the consideration of vibration-induced stress. The vibration measurements under construction were 0.2-1.1 kine at the time of slot drilling and 0.6-2.0 kine at breaker crushing, both registering within range of the control criterion.

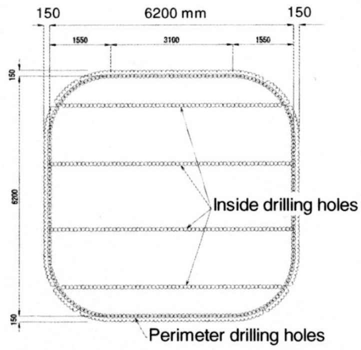
Photos-2 was taken during the execution.

The excavated section was divided into three blocks along a transverse direction to facilitate concrete filling. The two blocks on the upstream side were further divided into two lifts. The proportion of filling concrete is shown in Table-5.

The concrete was laid through a pump. Milk of cement was applied in places where the concrete was not sufficiently filled so that the dam concrete and the filling concrete would consolidate firmly.



a) Arrangement of penstock



c) Drilling arrangement

Figure-9 Section of dam tunneling of Okutadami dam

a) Bulkhead

b) Drilling machine

c) After tunneling

Photos-2 Construction of dam tunneling in Okutadami extension HPP

Table-5 Filling concrete around penstock, Okutadami extension HPP (Unit: kg)

Water	Cement	Flyash	Fine aggregate	Coarse aggregate	Admixture	
					Water reduce	Viscosity increase
180	328	231	721	828	7.27	0.18

5. Conclusion

This report introduces some technical examples for adding a new function to a dam that apply the dam tunneling method. Beside this method, several other examples have been reported in Japan, and they are evaluated as nearly-established technologies.

Recently, greater flood control capability has been required of some dams. In such cases, this method is effective from the perspectives of economical efficiency and environmental restrictions.

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