Construction of a tunnel spillway at large water depth

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ABSTRACT

To increase of the flood control capacity of the dam which has passed through the half century after completion, the large-scale tunnel spillway with a diameter of 11.5m was newly constructed at the abutment of dam under water of 33m.

The most important task was a construction of intake shaft of steel pipe sheet pile at the upper end of the tunnel which act as an intake part of new spillway and also serves as a temporary coffering, and measures to stop gush out of water at the joint part with tunnel.

For solving these engineering problems, we performed stress analysis and quantitatively grasp the stress distribution of the intake shaft in the constructing stage and joint excavation of tunnel that has been constructed from the downstream.

Based on the result of the analysis, we made monitoring plan of shaft displacement and performed countermeasures for reliable water tightness around the intake shaft and tunnel jointing part .

As a result of these countermeasures, the construction of the tunnel under the water was safely completed without suffering by large water gush out from the intake shaft.

1. INTRODUCTION

To increase the flood control capacity of a dam constructed half a century ago, a new large-cross-section spillway tunnel having an inside diameter of 11.5 m will be constructed at the dam site. This paper reports on tunnel construction work carried out successfully and safely under water pressure at a water depth of 33m.

1.1 Location and specification of Kanogawa Dam

Kanogawa Dam is located in the upper reaches of the Hijikawa River with a river basin area of 1,210km^2 and a length of 103 km that flows in the northwest of Shikoku in south western Japan. The dam was completed in 1959 to control floods and generate hydropower (Figure 1).

Figure 1. Kanogawa Dam

Table 1. Dam & Reservoir dimension

Dam dimensions			
Dam Type	Gravity Dam	Dam volume	161,000 m^3
Dam height	61.0 m	Catchment area	513 km^3
Crest length	167.9 m	Reservoir area	2.09 km^2
Crest width	13.0 m	Gross storage	48.2$\times$10^6 m^3

1.2 Overview of new tunnel spillway

1.2.1 Purpose

Over the years demand has grown for Kanogawa Dam to increase its flood control capacity, and it was decided to increase the flood control capacity by redistributing the reservoir capacity. At Kanogawa Dam, it was decided to lower the preliminary release level (the water level to which the reservoir level is to be lowered in advance for flood control purposes) by 4.7 m (H) from an elevation of 81.0 m to 76.3 m , and to increase the flood control capacity by 1.4 times. Since the elevation of crest of spillway is fixed to 76.0 m, it is not possible to attain a preliminary release rate of 600 m^3/s. Therefore, a tunnel spillway, which has discharge capacity of 1,000 m^3/s was planned to construct at a lower elevation of 53.0 m in the reservoir (Figure 2).

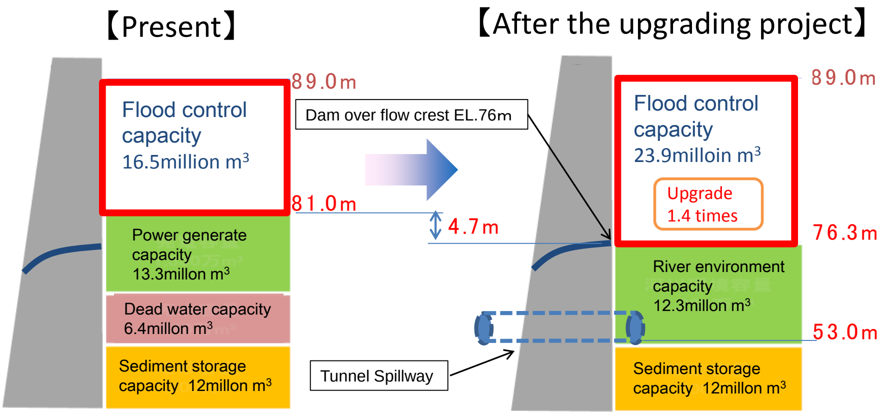

Figure 2. Reservoir operating plan (From MLIT (2016) Booklet)

1.2.2 Structure of tunnel spillway

The tunnel spillway constructed on the right bank at the dam site consists of a training channel (47 m long) located at the upstream end, an intake shaft (inside diameter 17 m), a tunnel (about 457 m long, 11.5 m in inside diameter),an outlet and an energy dissipater (Figures 3, 4and 5). The shaft in the reservoir was constructed by driving a total of 34 steel pipe sheet piles (1,500 mm in diameter, L = 44.0 m) to form a circle (in plan) having an inside diameter of 17 m, and excavating the area thus enclosed down to an elevation of 50 m while installing supports (Figure 6).

Figure 3. Overview of tunnel spillway

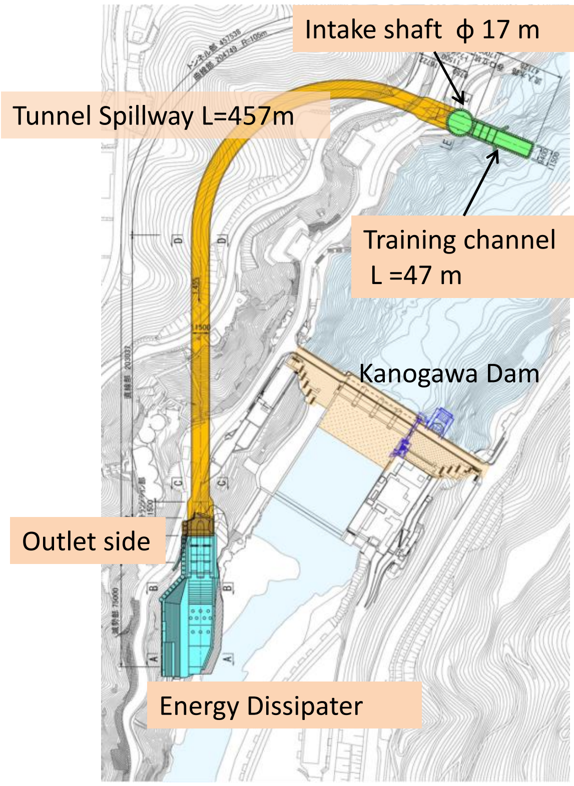

Figure 4. Layout of tunnel spillway

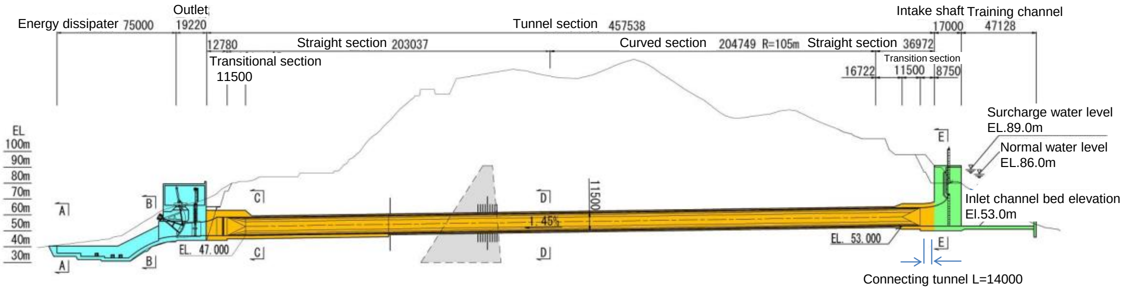

Figure 5. Longitudinal profile of tunnel spillway

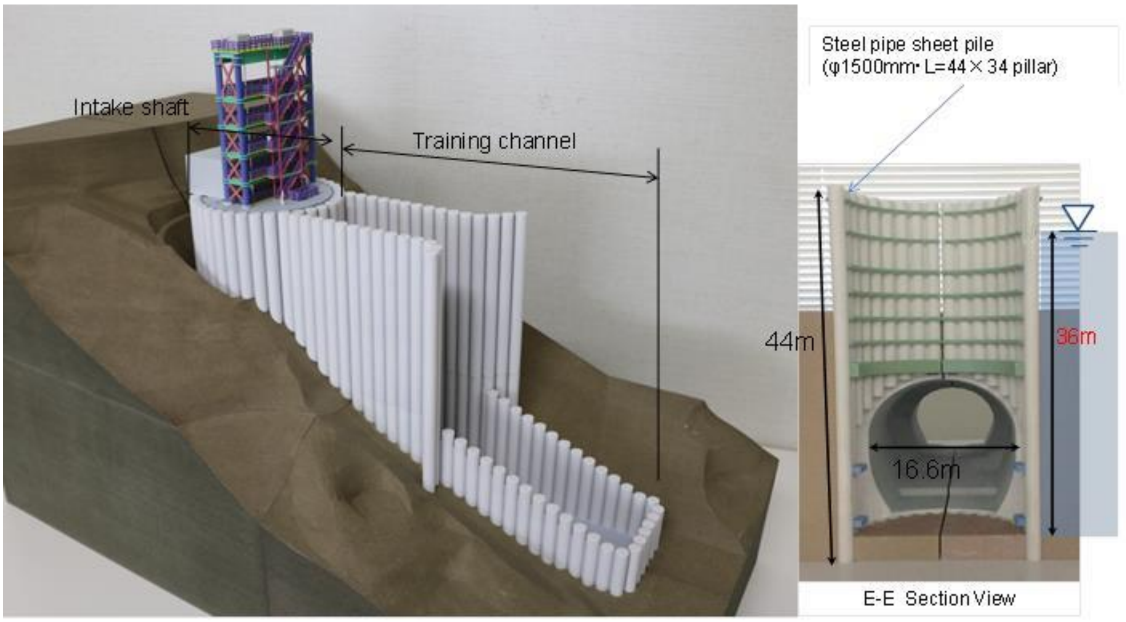

Figure 6. 3 Dimensional model of intake section upon completion

1.2.3 Construction procedure

The main steps until breakthrough in the construction of the tunnel spillway are as follows:

- Step 1: A tunnel was constructed from the outlet section toward the intake shaft in the reservoir without a 14-meter-long tunnel section to connect to the shaft ("the connecting tunnel") . (shows at Figure 5)
- Step 2: Concurrently with Step 1, intake shaft construction work was underway. Following shaft excavation, the bottom slab concrete was placed.
- Step 3: The 14-meter-long connecting tunnel was constructed by cutting through the steel pipe sheet pile wall in the area to be connected to the upstream end of the tunnel.

2. CONSTRUCTION AND SEALING OF INTAKE SHAFT

The intake section consists of the training channel, the shaft and the connecting tunnel -all of which had to be constructed at water depths greater than 30 m. Major challenges of the project included the sealing of the large intake section constructed with steel pipe sheet piles, which was almost unprecedented undertaking in Japan, and the stabilization of the shaft under construction.
The shaft in the reservoir constructed with steel pipe sheet piles is intended to double as a cofferdam while the construction work in the shaft is carried out. The difference in hydraulic head between the water surface and the bottom of the excavation was 36 m. Sealing, therefore, of the steel pipe sheet pile joints and the bottom of the excavation was important.

2.1 Construction of steel pipe sheet pile cofferdam

In order to ensure sealing of the shaft, it was necessary to drive 44-meter-long large-diameter (1,500 mm) steel pipes into the bedrock with a high degree of verticality.

2.2 Stabilization of intake shaft

During the excavation in the intake shaft, nine-level ring supports were installed in the intake shaft to control shaft deformation due to excavation. To connect the tunnel with the shaft, part of the steel pipe sheet pile wall including two levels of ring supports had be cut and removed. Since that part of the steel pipe sheet pile cofferdam was thought to become highly unstable, it was important to ensure stability of that part of the cofferdam during construction.

3. SHAFT CONSTRUCTION AND SEALING

3.1 Sealing policy

(1) Cofferdam constructed with steel pipe sheet piles

Figure 7 shows a plan view of the steel pipe sheet pile arrangement including the training channel and the intake shaft. Figure 8 shows a steel pipe sheet pile joint. Since mechanical interlocking alone would allow water to pass freely through the joint, the sections shown in blue were filled with mortar to make the joint watertight.

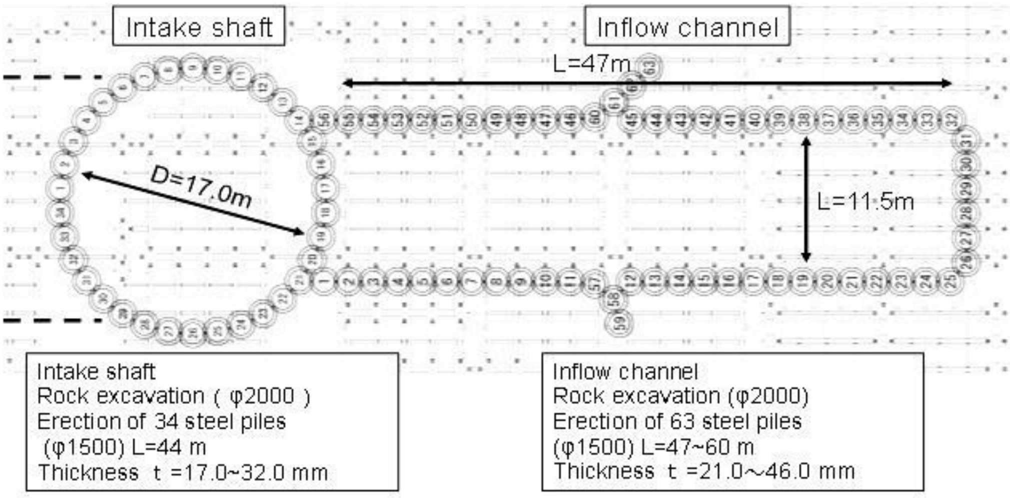

Figure 7. Configuration of steel pipe sheet piles cofferdam

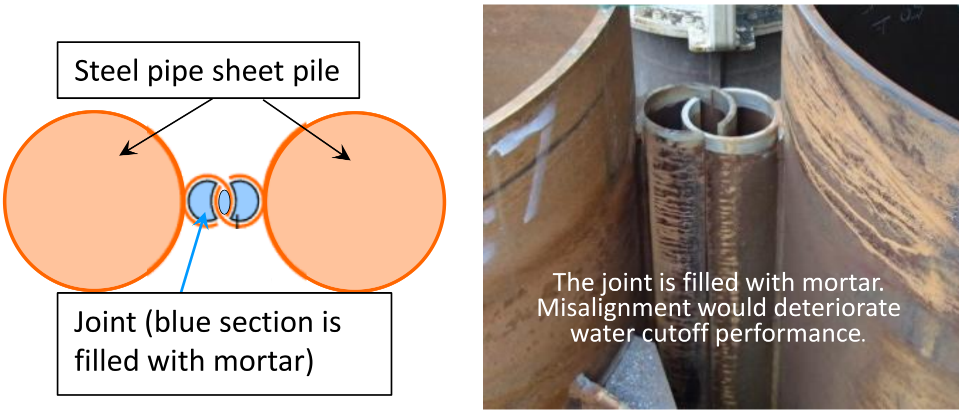

Figure 8. Joint structure

(2) Bedrock

The bedrock was grouted with cement for the purpose of sealing.

(3) Leakage observed during connecting tunnel excavation

Leakage from the steel pipe sheet pile joints of the shaft during construction was 10 to 20 L/min, and the seepage from the bedrock at the bottom of the shaft was 5 L/min. Total leakage, therefore, was around 25 L/min, indicating the effectiveness of the grouting around the shaft.

4. STEEL PIPE PILING

4.1 Verticality

Figure 8 above shows the joint structure. The steel pipes used as connectors have an inside diameter of 140 mm. In order to ensure complete end-to-end interlocking, it is necessary to achieve a verticality of approximately 100 mm/44 m, or 1/440.

4.2 Piling-related work

(1) 600 mm hole drilling prior to 2,000 mm hole drilling

The geology at the shaft site consists of an alternation of sandstone and shale, mainly containing Semi Hard and Hard bedrocks. Instead of driving steel pipe sheet piles directly into the bedrock, a series of circular holes of 2,000 mm in diameter and 35 m in average depth were drilled with a full-perimeter rotary drill in a circular pattern. Then, a steel pipe sheet pile of 1,500 mm in diameter was constructed each holes thus created (see Figure 9). At the time, the method of drilling a hole 2,000 mm in diameter and more than 30 m in depth in rock by using a full-perimeter rotary drill was almost unprecedented. There was concern, therefore, about the possibility of seizure of the drill during the drilling operation. It was decided, therefore, to drill smaller holes, 600 mm in diameter, in advance in the still-undrilled region along the 2,000 mm hole perimeter with a down-the-hole hammer (see Figure 10).

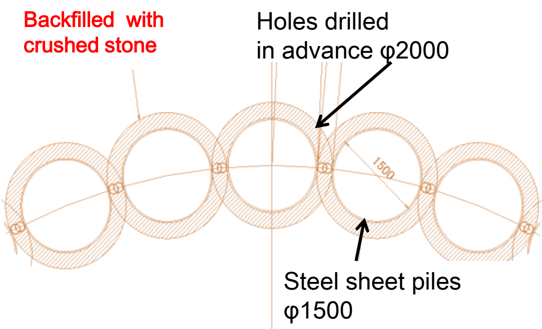

Figure 9. Holes with a diameter of 2000 mm drilled in advance and steel pipe sheet pile

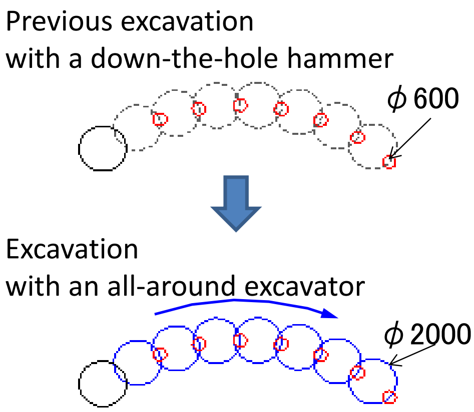

Figure 10. Rock excavation procedure

(2) Replacement with crushed stone in the 2,000-mm-diameter cavity

It had been decided to drive 1,500-mm-diameter steel pipe sheet piles following the 2,000-mm-diameter hole drilling along the shaft perimeter. In order to prevent the drilled hole walls from collapsing due to loosening of the bedrock, therefore, each hole was backfilled with crushed stone upon completion of drilling. In view of the need for backfill material that is capable of supporting the walls of the drilled holes, does not easily consolidate and is easy to work with when carrying out foot protection work or void-filling grouting because of large voids between particles, crushed stone ranging in size from 2.5 to 5.0 mm was used (refer Figure 9).

(3) Use of fixed guide platforms during erection

When placing steel pipe sheet piles, verticality was achieved by installing two guide platforms at two levels (see Figure 11). The inclination of the pile being driven was frequently measured with two electro-optical distance meters. The verticality of the steel pipe sheet piles thus driven was measured upon completion of piling with an ultrasonic measuring instrument, and the measurement results verified that the piling work was carried out with high accuracy.

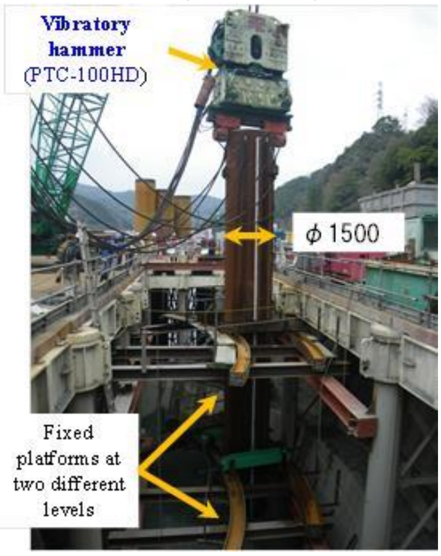

Figure 11. Erection of steel pipe sheet piles using a vibratory hammer

5. STABILITY DURING CUTTING OF STEEL PIPE SHEET PILE WALL FOR TUNNEL CONNECTION

5.1 Procedure for cutting the steel pipe sheet pile wall for tunnel connection

Figure 12 shows the steps from the excavation in the intake shaft to the cutting of the steel pipe sheet pile wall for tunnel connection.

(1) Excavation in intake shaft

Because the steel pipe embedment zone filled with single-sized crushed stone may form a water channel if no control measures are taken, anti-washout underwater cement slurry was injected before starting internal excavation. Steel ring supports were installed at nine levels from the upper end of the steel pipe sheet pile wall (elevation: 91.0 m) to the bottom slab (elevation: 50.0 m) at a depth of 41 m as the excavation surface lowered. Cement slurry was injected behind the steel pipe sheet pile wall at each construction step where large deformation of steel pipe sheet piles occurred although such injection had originally been planned to be performed after reaching the bottom of the excavation.

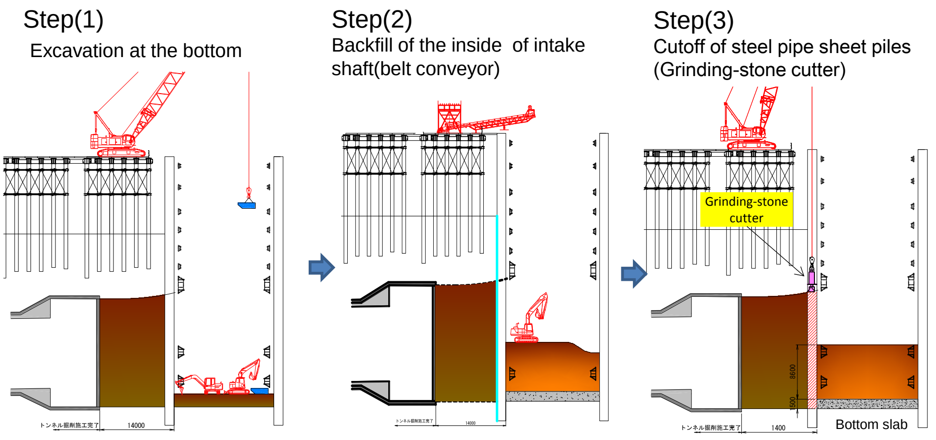

Figure 12. Steps from internal excavation at the shaft to the connecting tunnel breakthrough

(2) Placement of bottom slab concrete and construction of working platform with earth

Upon completion of the excavation, bottom slab concrete was placed to a thickness of 1.5 m, although it was eventually to be increased to 3.0 m, so that the half-depth bottom slab could be used to support the steel pipe sheet piles. The bottom slab thus placed was overlain by a 12-meter-thick layer of earth to form a working platform for removing steel pipes and constructing the connecting tunnel.

(3) Cutting of steel pipe sheet piles with grinding-stone cutters

Cement slurry was injected in advance in the area along the circumference of the circle of steel pipes that was filled with crushed stone. There was, however, concern about water channel formation at some locations. Five observation boreholes were drilled from the tunnel side before cutting steel pipe sheet piles. Cores (diameter: 52 mm. length: approximately 400 mm) were taken from steel pipe sheet pile joints in the intake shaft to verify that there was no seepage from behind the steel pipe sheet pile wall through the crushed stone zone. Before cutting steel pipe sheet piles, the intake shaft was filled with water to the level of the crown of the connecting tunnel to reduce the water level difference between the inside and outside of the shaft, and grinding-stone cutters were inserted into the steel pipe sheet piles to cut 14 steel piles in the connecting tunnel (the maximum height was 18 m).

5.2 Prediction of deformation by preliminary analysis

There was concern that the deformation of the lower part of the steel pipe sheet pile wall due to internal excavation might create gaps around the circumference of the steel pipe sheet pile wall, causing the formation of water channels connecting to the reservoir so as to induce large-scale flooding during excavation. It was therefore necessary to accurately determine the deformation and behaviour of steel pipe sheet piles, and three-dimensional FEM analysis was performed in advance. The maximum displacement upon completion of excavation was calculated to be approximately 60 mm in the region above the eighth level of supports (see Figure 13).

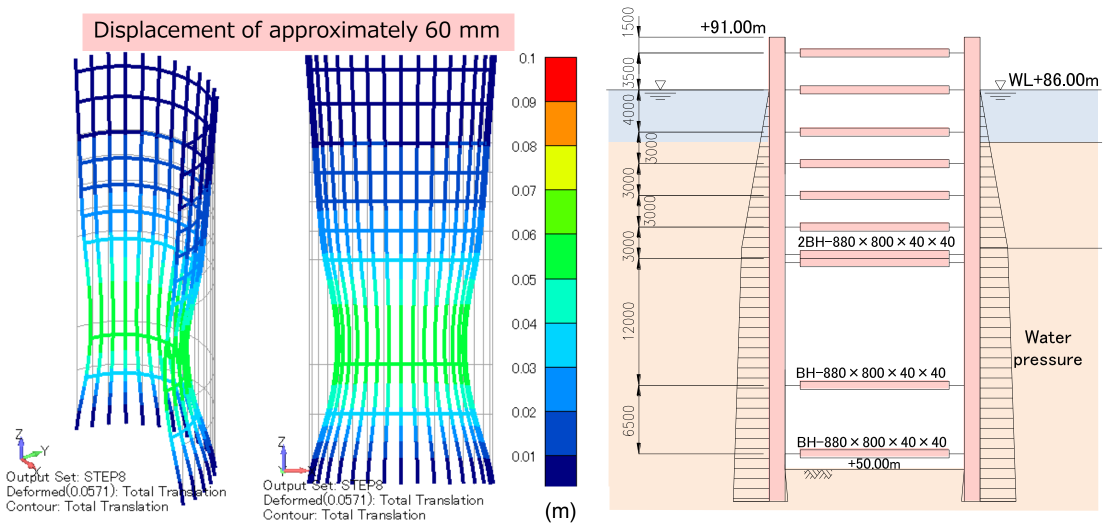

Figure 13. Results of analysis
(displacement of steel pipe sheet piles upon completion of excavation)

5.3 Deformation measurement plan

The locations of measuring instruments are shown in Figure 14. Insertion-type automatic inclinometers and strain gauges were installed in the steel pipe sheet piles, and strain gauges in the supports. Curtain grouting was undertaken to a depth of 15 m from the bottom end of the steel pipe sheet pile to prevent water intrusion from the bottom slab in the intake shaft. In order to verify the effect, pore water pressure gauges were installed in the intake shaft and outside the grouted area.

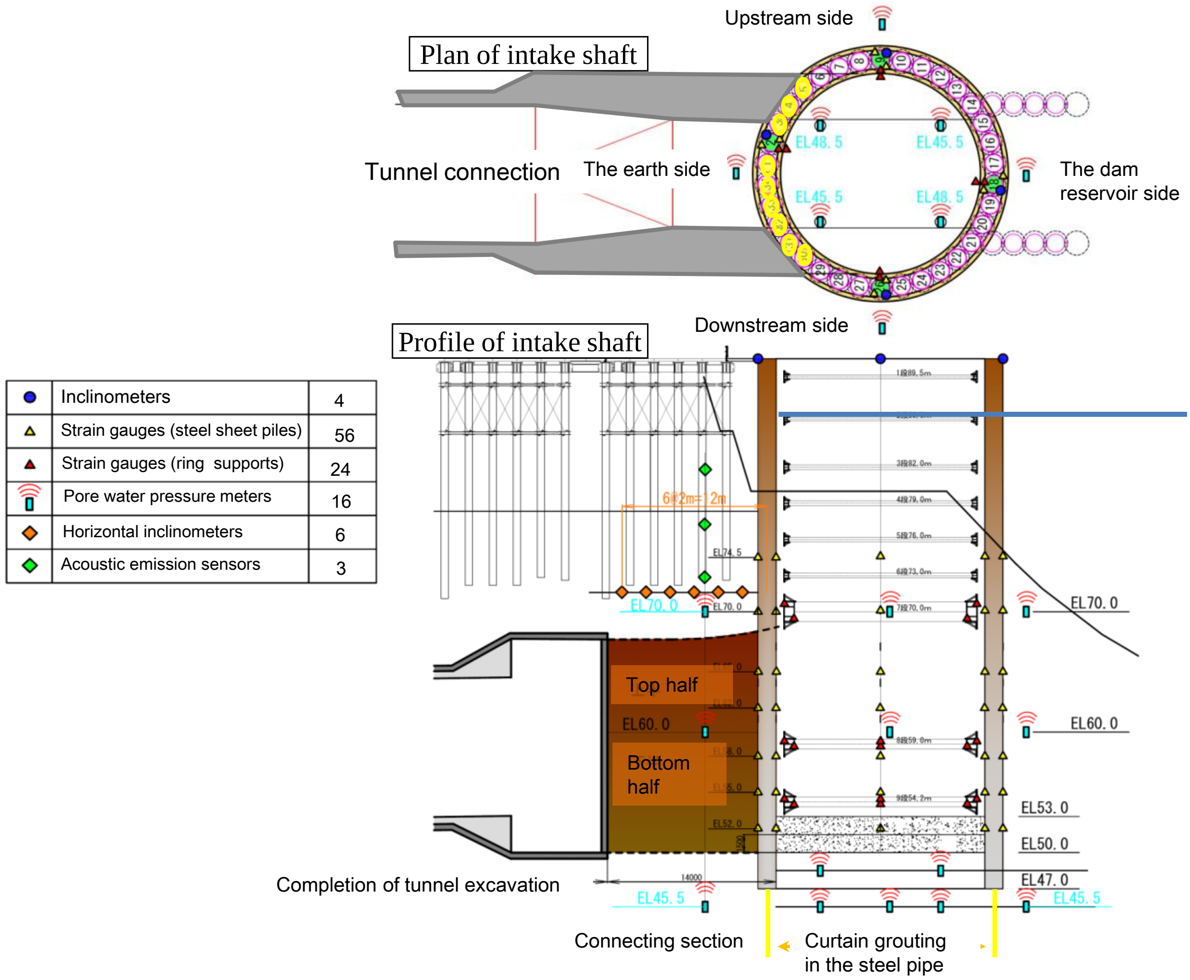

Figure 14. Locations of measuring instruments

5.4 Measured deformations

Figure 15 shows the measured deformations of a steel pipe sheet pile. It was verified that deformation was approximately 20 mm while excavation took place in the shaft, 10 mm when ring supports were removed at levels 8 and 9 and 5 mm when the steel pipe sheet piles were cut. A total inward deformation of 35 mm was verified.

The measured total deformation was smaller than the value in the preliminary analysis, and cutting open the steel pipe sheet pile wall had a smaller effect than in the analysis. The difference is ascribable to the following: (i) The reservoir level during construction was approximately at elevations 75 to 80 m, lower than that under the conditions assumed in the analysis and the external force due to water pressure was smaller than expected: (ii) Injecting cement slurry behind the steel pipe sheet pile wall after the removal of supports increased ground stiffness: and (iii) Connecting the steel pipe sheet piles on the training channel side to the intake shaft reduced deformation toward the inside of the shaft.

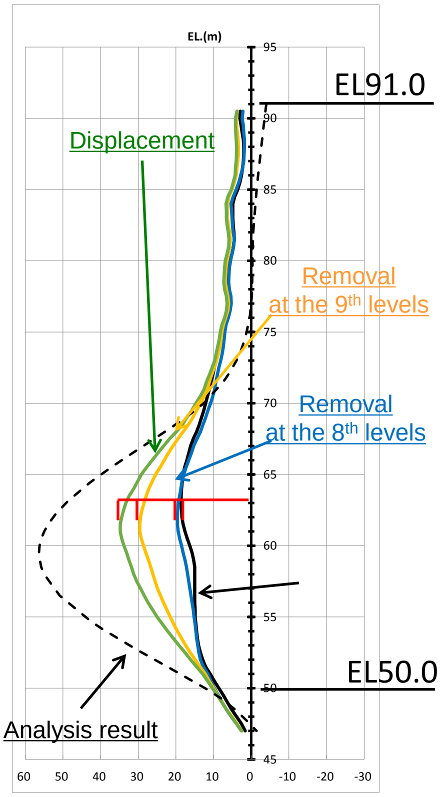

Figure 15. Measured deformation of steel pipe sheet pile

6. CONSTRUCTION OF CONNECTING TUNNEL

The inside diameter of the intake shaft was 17 m. The connecting tunnel had a large cross section with a width of 17 m, a height of 17.9 m, and the cross-sectional area of the excavation was 265 m^2. The connecting tunnel, therefore, was the most challenging part of the tunnel spillway construction work. The procedure for the construction of the connecting tunnel including the cutting of the steel pipe sheet pile wall for tunnel connection is described below.

In order to prevent the failure of crusher-runs on the rear surface of the steel pipe, steel sheet piles along the tunnel circumference were cut near the portal excavation using oxygen lance each time excavation advanced (a length of 1.0 m) (See Figure 16). The objective was to leave as many steel pipes as possible and minimize the exposure of the crusher-runs and earth behind the steel sheet piles.

Figure 16. Cutting with the oxygen lance

Injection-type forepoles with a length of 3 m were driven, two per steel pipe, near the crest before the removal of steel pipes in the rear. In addition, a total of 43 longer injection-type forepoles (12.5-m long, 114.3 mm in diameter) were also driven after the cutting of the steel pipes and before the tunnel excavation.
Deformation of steel pipe sheet piles owing to the cutting of steel pipe sheet piles for the connecting tunnel and the cutting of supports was likely to create new gaps (new water channels) between the steel pipe sheet piles and the bedrock behind them. Additional grouting, therefore, was carried out to seal off those gaps.
Construction was carried out while checking on whether seepage from steel pipe sheet pile joints was increasing or not and whether there was abnormal flooding from the connecting tunnel. Figure 17 shows the connecting tunnel, viewed from the intake shaft, upon completion of the excavation down to the invert.

Figure 17. Completion of excavation at the bottom slab

7. CONCLUSION

- Leakage during the excavation in the intake shaft and the excavation of the connecting tunnel:
  Verticality of steel pipe sheet piles was good enough to minimize leakage through steel pipe sheet pile joints. Seepage from the surrounding ground was around 25 L/min.
- Intake shaft deformation due to cutting of steel pipe sheet piles for tunnel connection: Three-dimensional FEM analysis was performed to quantitatively estimate steel pipe sheet pile deformation at different stages of construction. The estimates and the measurement results did not show any significant differences.
  Intake shaft construction as part of the tunnel spillway construction project is currently underway. Gate installation and related work and structural concrete work will begin shortly. The next step is to continue the monitoring by use of various measuring instruments and the measurement of seepage at the site including the tunnel section and conduct studies on construction methods including challenges such as underwater cutting of steel pipe sheet piles for training channel construction and analyses of steel pipe sheet pile deformation.

8. REFERENCES

Ministry of Land, Infrastructure, Transport and Tourism (2016). *Booklet of The Kanogawa dam renewal project.*