Technical features on the renewal of large-scale prestressed rock anchors in Kawamata Dam foundation

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ABSTRACT: Kawamata Dam is a concrete arch dam with 117 m high which was completed in 1966. A huge underground transmitting wall for sustaining the arch thrust force was constructed in the left bank bedrock. In addition , the world largest class prestressed (PS) anchors by total capacity in that time were installed for the purpose of tightening this wall along with too many existed nearby high-angle faults , stabilizing of the bottom of slope and prevention for the surface loosening. Additionally, big retaining walls were constructed to support PS anchors as pedestals. These structures are called bedrock PS works. However, after passing of 50 years, deterioration of PS anchors was confirmed by irregular behaviors observed in measured values, and damages in anchor heads found by integrity surveys for PS anchors. After these anomalies were checked by the technical committee, the renewal plan by the full installation of PS anchors and the repairment of the retaining wall was determined in 2013. From 2014 to 2016, additional surveys, the design of PS anchors for the renewal and detailed construction planning was implemented. The content of the renewal plan consists of a total number of 124 units of PS anchors with 2352 kN/unit of anchor load, and the repairment of the right bank retaining wall. According to this design, as the first phase renewal, 59 units of PS anchors were installed at the location of rock foundation of Kawamata Dam until 2021. The renewal works were executed under very strict site condition such as the steep and deep cliff terrain, no access ways, very hard rock foundation, frozen condition in winter and flood discharge during flood season. On the other hand, many technical developments were achieved using the latest technology, such as staging along cliff, tools and materials, corrosion protection, drilling in hard rock, tendon setting, grout mix, tensioning method, quality control, measuring instrument, maintenance method, and others. As a result, this works laid the basis of PS anchor technology for dams in Japan. We describe the judgement renewal decision-making and the main technical points of the design and construction, mainly concerning to the PS anchors reinforcing the rock foundation.

1 OUTLINE OF BEDROCK PS WORKS IN KAWAMATA DAM

1.1 *Bedrock PS works at the time of dam construction*

The bedrock PS works in Kawamata arch Dam (117m high) to reinforce the rock foundation consists of a 70m high underground transmitting wall to transmit the huge thrust force deep to the left bank, large scale PS anchors with the large-capacity of 1372～2352KN ×162 anchors and horizontal long-length of 40～70m, and two big retaining walls.

These structures were originally constructed in 1962-65. Its design method was presented at the 1965 ICOLD conference in Edinburgh by Ministry of Construction, Japanese Gov., which were acclaimed as a breakthrough method to reinforce dam foundations. The bedrock PS works include three parts of PS anchors. A part anchors penetrate and tighten the transmitting wall and many high-angle faults, B part anchors support the big retaining wall at lower elevation of the left bank, and C part that anchors prevent loosening of the right bank.

The site plan and specifications of these foundation works are shown in Figure 1.

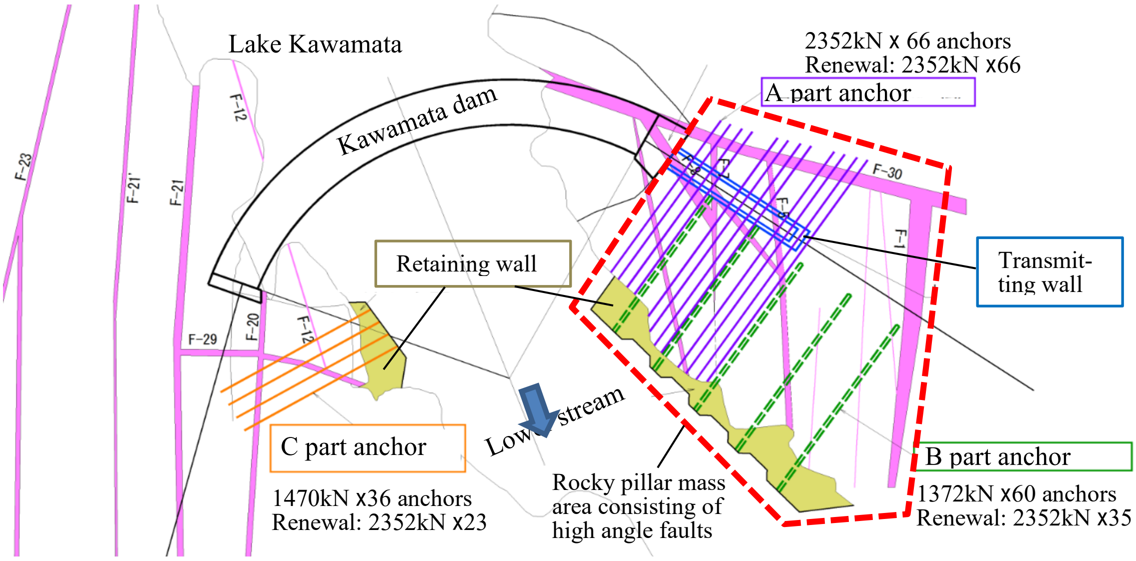


Figure 1. Plan of Kawamata Dam, transmitting wall and PS anchors in rock foundation

1.2 *Renewal of bedrock PS works*

Several measurements such as displacements in the bedrock foundation were continued for about 10 years after the dam completion, and no anomalies were found. However, due to concerns about deterioration over time, in 2004 when 40 years passed after the dam completion, rock displacement sensors were re-installed at 12 sites (8 at left bank and 4 at right bank).

After several years, some measurement values revealed stair-like behaviors of displacement in the bedrock near the transmission wall, which was interpreted as the gradual break of a tendon with six PC steel bars. Corresponding to this, the integrity surveys were conducted in 2011-2012, it was found that some tendons of PS anchors were rather deteriorating by corrosion, and three horizontally long cracks in the right retaining wall were opening.

Thus, the technical committee for Kawamata bedrock PS works was held in March 2013 and judged the renewal by full installation of PS anchors and the repairment of the right bank retaining wall. The renewal PS anchors are a total number of 124 units of PS anchors with design anchor load 2352 kN/unit of and anchor length of 40~70 m.

From 2013 to 2016, additional surveys, anchor renewal design and field tests by prior anchor installations were carried out. As a result of the detailed consideration on PS anchors, as shown in Figure 2, the renewal anchors are placed in the center of elevation to existing anchor rows. Also, on the premise that the existing anchors will deteriorate in the future, the renewal anchors were decided to set the same total load as at the time of construction for each section of A part, B part, and C part. Further, in order to improve construction efficiency, all design loads were unified to 2352 kN/unit, of which drilling diameter is 216 mm.

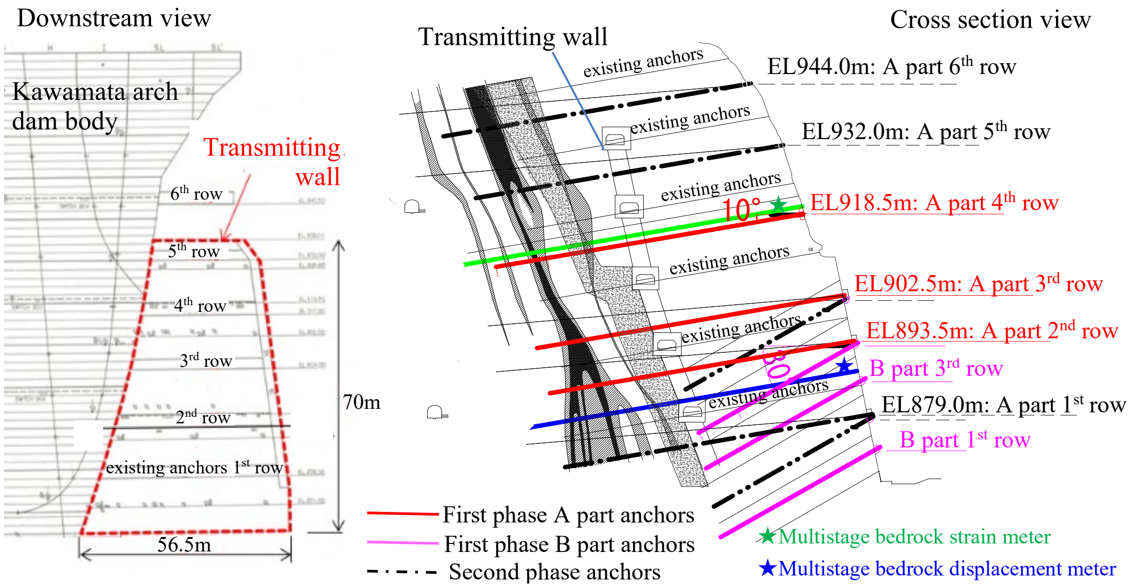


Figure 2. Downstream view and Cross section view of left bank on PS anchors and transmitting wall

Figure 3. Situation of Kawamata Dam under the renewal works in 2019

In the renewal design, the design load was decided at 2352 kN/unit which is the same as the construction time, to balance with the existing PS anchors. The first phase renewal was executed from 2017 to 2021, and 59 PS anchors, about half of the total 124 anchors, were renewed. Figure 3 shows the working situation on the downstream of the dam. Main materials and machineries were transported by a 4.5-ton cable crane.

On the left bank, due to the steep topography, large-scale temporary construction platforms were installed at each elevation of the PS anchor stage using a sub-tower crane. The right bank was not as extensive as the left bank, but taller scaffolds were erected. Then, very large amount of cement milk(Figure 8) was injected to fill the gap below the back of wall before the anchor works. This bonding of the wall and rock was very effective to stabilize the steep cliff.

1.3 *Anti-corrosion protection on tendon*

The tendon as an anchor unit consists of 14 PC steel strands with the diameter of 15.2mm.

As for anti-corrosion, targeting 100 years of durability, the full-bonded type which fills all length of tendon by grout was adopted, and it was combined with ECF (Epoxy Coated and Filled) strands (Figure 5) as the double anti-corrosion structure.

After 60 years of the Kawamata Dam construction, the integrity surveys showed obviously that the full-bonded type was more durable, because the corrosion of the full-bonded type adopted to existing anchors was quite less than other anti-corrosion measures.

In anticipation of long-term durability, the quality of grout is also very important. Therefore, a new non-shrink grout was developed for the renewal of PS anchors.

About grout injection, it requires a long distance of 80m pumping with a height difference 90m due to construction site conditions, and there were concerns about segregation and cracking. So, to achieve both high fluidity and non-shrinkage, a composition with combination of grout milk, high-performance AE water-reducing agent and expanding agent for the grouting material was used. The trial was repeated to derive the optimum addition amount and it was completed as shown in Figure 4.

Internal filling type epoxy resin coated PC strand

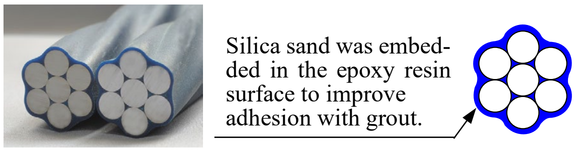


Table of grout composition

Ordinary Portland cement	High efficiency Air Entraining water reducing agent	Bulkage admixture	C:W
1,423kg／m^3	22.5kg／m^3	74.9kg／m^3	1:0.35

Figure 4. Anti-corrosion protection by ECF strand and super high-quality grout

2 INTEGRITY SURVEY ON ANCHORS

Various integrity surveys such as the one summarized in Table 1 were conducted and confirmed that some PS anchors have significantly deteriorated. In particular, the deterioration of the unbonded anchors on the right bank was progressing, and a decrease in tension was also observed.

On the other hand, the deterioration of left bank anchors at the full-bond type was limited, but pitting corrosion leading to delayed fracture was observed (Fig. 5), the measured values of rock displacement showed step-like movements, and 60 years had passed since anchor installation. Considering these together, a policy of full renewal of the PS anchors was decided in 2013.

Table 1. Results of integrity surveys to existing anchors

1. Left bank A part (PC steel bar, bonded type) a. Drilling visual inspection and ultrasonic measurement (on steep slope surface): Deterioration could not be visually confirmed. Detected there were voids around the steel bar by ultrasonic measurement on steel bar head. b. Anchor exposure in GG6 pit: Confirmed traces of water infiltration in the mortar around the steel bar. Confirmed partial surface rust and pitting corrosion on the surface of the steel bar confirmed.
2. Left bank B part (PC steel wire, bonded type) a. Visual and endoscopic: Confirmed significant head defects at the bottom place near the water level.
3. Right Bank C part (PC steel wire, unbonded type) a. Visual and endoscopic: Confirmed breakage of the highest row anchor and progress of corrosion of PC steel wires in the hole. Confirmed significant deterioration of the head cover concrete in several anchors. b. Lift-off test (20 anchors): Confirmed serious reductions in tensile load, several anchors showed softening.
4. Fracture surface of PC steel wire or bar a. Observation of PC steel wire: Confirmed the main causes of fracture are the cross-sectional area reduction b. Observation of PC steel bar in the other dam: Confirmed delayed fracture due to corrosion Tensile test: Confirmed a significant decrease in elongation capacity of PC steel bars

Figure 5. Pitting corrosion on a tendon at Grout tunnel and surface looks in an existing anchor

3 DESIGN FOR REINFORCEMENT OF ROCK FOUNDATION

3.1 *Stability check of rocky pillar mass*

In left bank of Kawamata Dam, there are many high-angle faults called rocky pillars (hereinafter RP), which needed to be reinforced as the massive rock foundation of the Arch Dam.

At the time of construction, two-dimensional model experiments were conducted using gypsum and photoelasticity, and it was found that a transmitting wall (hereinafter TW) was effective in enlarging the shear sliding zone, and that the stress near TW was reduced. However, since it was shown that tensile stress almost perpendicular to the TW occures widely, strong tensioning in the wide area was needed to tighten and integrate the whole of RP mass including TW.

Figure 6 is the simplified 3D model separated by F30 and F1 including TW and PS anchors to reproduce the stability calculation at the time of construction. By using this model, the importance of TW and integration of RP mass by PS anchors was reconfirmed.

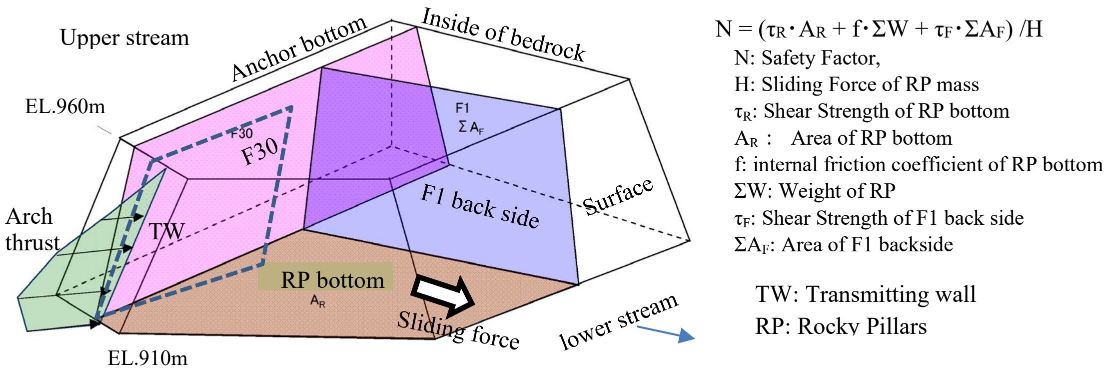


Figure 6. 3D model for Stability calculation of Rocky Pillar mass in Kawamata Dam left bank

3.2 *Confirmation of Prestress in bedrock inside*

Figure 7 shows the results of pseudo-three-dimensional analysis of three elevations on the left bank. As the characteristic of PS anchors, prestress (compression stress) strongly occurs around the head and bottom, but prestress around the center is weak. So, the PS anchors were densely arranged in rows so that the prestress around TW was kept high by the group anchor effect.

However, since the prestress is dissipated on the tip of TW, an intermediate load removing method to generate strong prestress developed. This method to increase prestress can suppress the formation of a gap between the tip of TW and the bedrock.

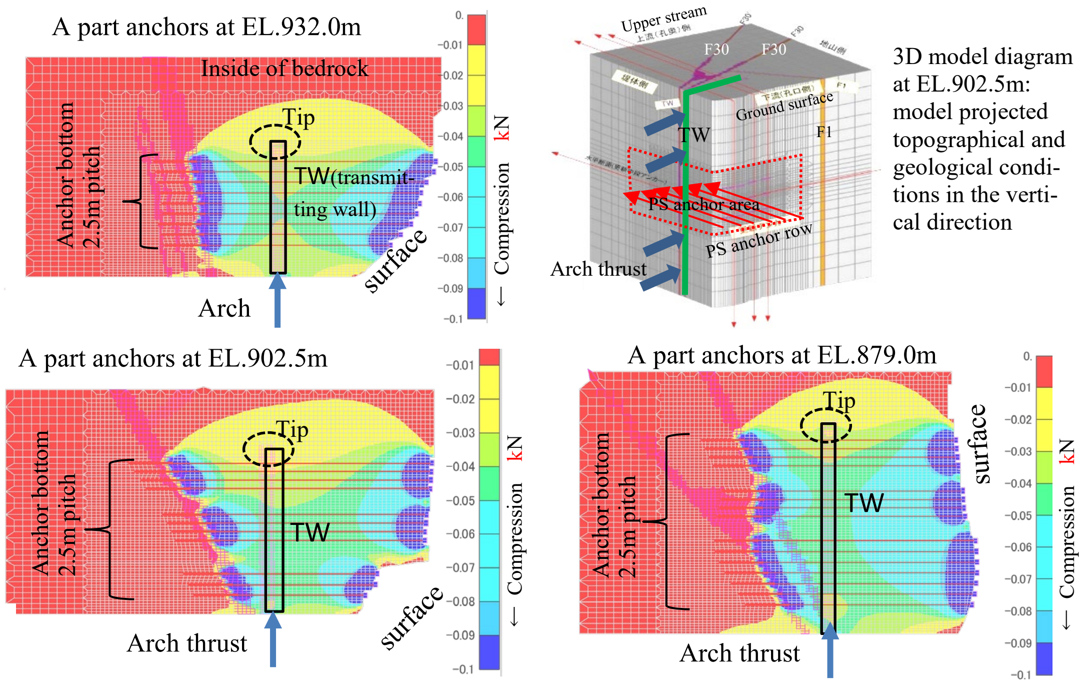


Figure 7. Compression stress distribution on slice plan by 3D FEM analysis of Rocky Pillar mass

4 MAIN SPECIFICATIONS OF RENEWAL PS ANCHORS

By the design of renewal PS anchors, design load, ultimate and acceptable strength, PC material, number of PC steel strands per tendon, bond length, diameter and so on were decided.

Table 2 shows the calculated results according to the design. La is calculated by τ_u which means ultimate bond strength between grout and rock, and τ_u was determined to be 1.0 N/mm^2 according to the results of the field pull-out test at the Kawamata Dam site. Lb is calculated by τ_{ba} which means ultimate bond strength between grout and tendon, and τ_{ba} was determined to be 1.0 N/mm^2 from a corresponding value to the grout compressive strength of 30 N/mm^2 in the design standards in Japan. Eventually, larger value of La and Lb is adopted as the bond length.

Table 3 shows specification of anchors or building-use anchors in Japan. Though these manuals are made for the soil anchor, we applied them, also referring to overseas manuals on PS anchors. Actually, the rock anchor manual in Japan was issued in 2021 right after the first phase renewal.

Table 2. Necessary bond length (m) by calculation result of the renewal anchors

Construction point	Left bank A part	Left bank B part and Right bank C part
Number of PC steel strands per tendon	14	14
U: Perimeter around tendon (m)	287	295
La: Necessary bond length (m) to τ_u	9.646	7.074
Lb: Necessary bond length (m) to τ_{ba}	8.362	8.136
Larger value of La and Lb (m)	9.646	8.136
Round up value of bond length (m)	10.0	8.5
Grout design standard strength(N/mm^2)	30	

Table 3. Specification of anchors: Number, Design Load, Bore diameter, Bond length, etc.

Construction point		Left bank A part	Left bank B part	Right bank C part
Number of Anchors		66	35	23
Design Load (KN)		2,352 (same as original load 240tonf x 9.8)		
Safety factor(Fs)		3 (safety side value same as building ground anchor in Japan)		
Anchor placement	Pitch of anchors(m)	2.5	6.0	2.5 or 3.0
	Declination angle (°) in drilling hole	Horizontal angle:0 Vertical angle: 10	Horizontal angle:0 Vertical angle: 30	Horizontal angle:10 Vertical angle: 20
Bore diameter (mm)		216 (actual maximum size in Japan's anchors)		
Maximum anchor length (m)		72.9	34.2	50.0
Drilling method / Machine type		Down-the-hole hammer (pneumatic type) / RPD skid type		

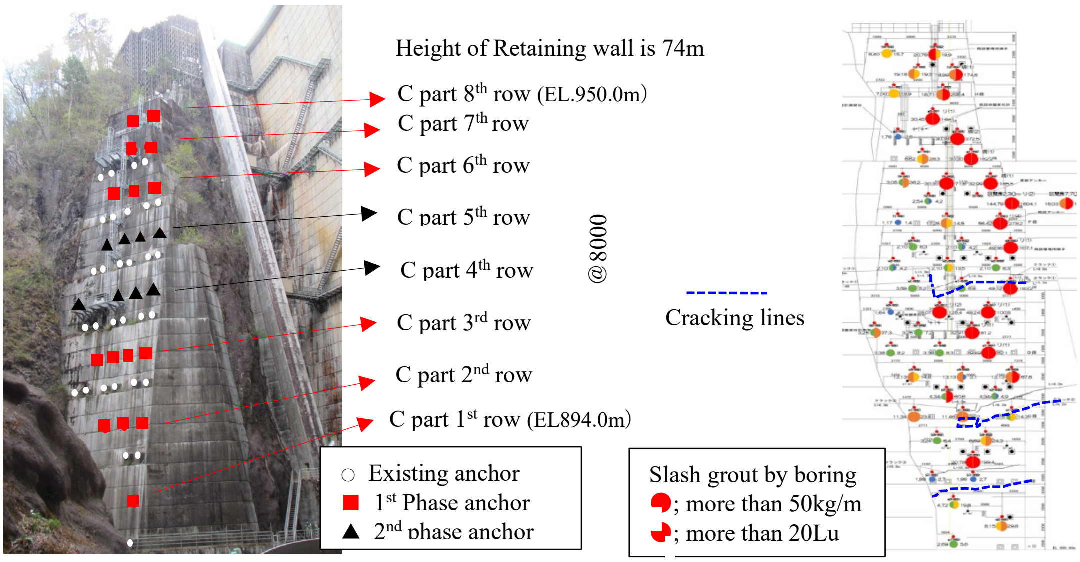


Figure 8. Front view of Right bank C part anchors, crack lines and quantity of grout injection

5 RENEWAL WORKS OF PS ANCHORS

5.1 *Repairment of the right bank retaining wall*

Figure 8 shows the front view of the right bank of C part anchors, the crack lines confirmed by visual inspection, and quantity of grout injection.

There are three horizontal cracks in the middle to low elevations of the right bank retaining wall, and a boring survey confirmed that there were gaps between the retaining wall and the bedrock. So, Large amount of slush grouting (10m depth in bedrock) was conducted to the entire backside of the retaining wall to integrate the bedrock and the retaining wall. This works along with slope protection works and prior to the PS anchor works were done from October 2017 to July 2018.

From August 2018 to August 2020, 6 stages (15 anchors) out of 8 PS anchor stages (23 anchors) were installed in the first phase renewal. Also, since there were no drainage holes, 10 drainage holes were installed around the renewed anchors on the middle and lower elevations.

Eventually, these works greatly improved the safety of the right bank.

5.2 *Construction of large-scale staging on steep cliff*

A large-scale work staging platforms covering a steep cliff were erected to install PS anchors. Regarding the structure of the left bank work platform, the first and third rows of the low-elevation parts are less impact of water discharge from dam and in order to install the anchor during the non-flood season when construction is possible, A bracket structure in which each row of work platforms are independent, was adopted.

The system scaffolding was set up from the third stair bracket work platform. The structure of the right bank work platform is a system scaffolding, and the scaffolding was set up from lower to upper when slash grouting was performed before installing anchor. At the time of anchor work, the system scaffolding was dismantled for each anchor work step (8m).

Figure 9 shows the staging by work platforms on both banks, respectively.

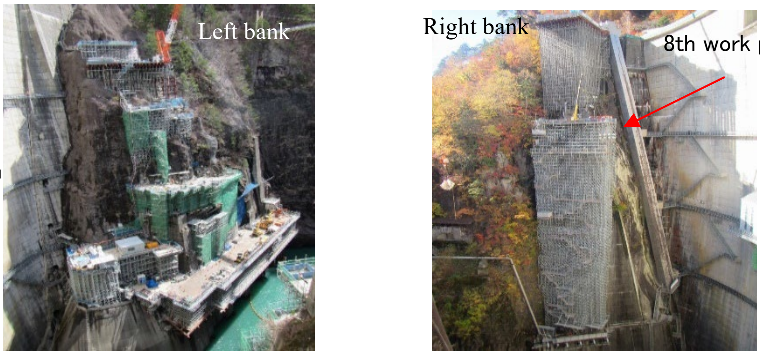


Figure 9. Large-scale Staging by work platforms on the left bank and right bank

5.3 *High accuracy of solid rock drilling*

The drilling diameter of the anchor for this work is as large as 216 mm, and the maximum drilling length is 72.9 m. Since the in-situ bedrock were very hard ranging from C_H to B class, A down-the-hole hammer (hereinafter DTH) capable of high-speed drilling on workability, and a skid type improved for easy decomposability to transport by a 4.5-ton cable crane was chosen. In particular, we took the following technical measures to achieve high-precision drilling during high-speed drilling for anchors of large-diameter and long.

5.4 *Ingenious initial drilling*

At the initial drilling that affects the drilling accuracy, by using the DTH from the beginning, it becomes difficult to secure drilling accuracy due to thrashing of the bit tip at the beginning of drilling. Therefore, a 2.6m long rod was pre-drilled with a non-impact rotary boring machine that was less prone to blurring and misalignment and used as a guide hole for drilling by DTH.

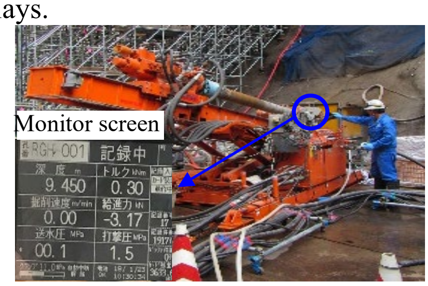
The measurement results at 2.6m and 5.0m from the hole mouth with the drilling angles at A part, B part and C part (see Fig.1) of 0.27°, 0.13°, and 0.23° on average, respectively and only a slight increase in the drilling angle, were analyzed. The initial drilling accuracy, which greatly affects the final hole bending accuracy, is ensured just by doing so. In addition, assembling work for the down-the-hole hammer drilling machine had been going smoothly.

5.5 *Drilling management*

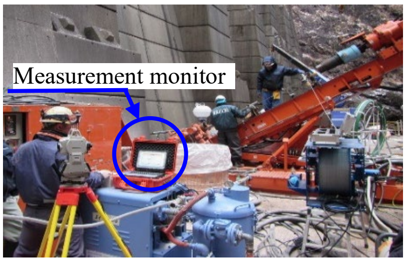
In the largest hard rock drilling in Japan, to obtain dynamic information during drilling immediately, ground exploration sounding device was attached to the drilling machine. And then, we obtained data quantitatively such as machine rotation torque, striking pressure, water pressure and drilling speed in real-time and grasped the characteristics of bedrock (Fig. 10a).

The drilling accuracy of all holes was confirmed at the middle point of drilling, using during drilling measurement device with a gyro and an acceleration sensor. In addition, the full-length measurement was also carried out for 10% of installed anchor (Fig. 10b).

Table 4 shows the measurement results of hole bending. Accuracy confirmation during drilling enables early detection of an increase in hole bending and countermeasures against defects. Therefore, it was a useful means of construction management based on the suppression of process delays.



a.Drilling situation by ground exploration technology



b.Measurement circumstance of hole bending

Figure10. Drilling and measurement

Table 4. Hole bending measurement results Unit:m

Horizontal distance	5.0	10.0	15.0	20.0	25.0	30.0	35.0	40.0	45.0	50.0	55.0	60.0	65.0	69.0
Vertical downward measurement result (Difference from design)	0.10	0.14	0.19	0.25	0.32	0.40	0.50	0.61	0.72	0.83	0.97	1.10	1.25	1.36
Increment per m		0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03

5.5.1 *Observation in the underwater borehole*

After completion of drilling, the underwater hole wall was directly observed by a camera system, which was developed to capture clearer photographs even under turbid water. These accurate geological characteristics were reflected in the form of 3D information of geological map. Using obtained geological map, we aimed at reducing hole bending by controlling the drilling speed based on the geological data. Figure 11 shows the geological map by the camera observation.

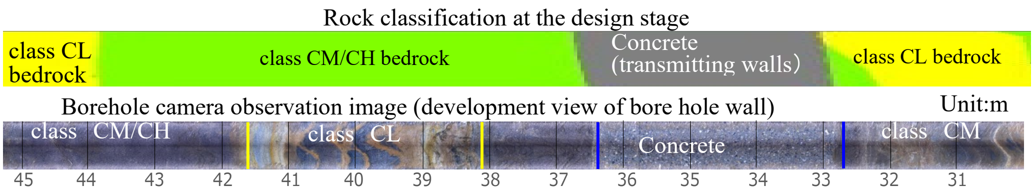


Figure 11. Bore hole wall confirmation diagram by underwater borehole camera system

5.5.2 *Drilling management by CIM*

The centralized data management was performed using CIM (Construction Information Modeling) such as drilling information and hole bending data acquired by ground exploration technology, borehole wall observation and so on. It achieved high-accuracy drilling by reflecting the drilling data of peripheral holes. Eventually, it enabled more accurate drilling to avoid interference with other underground structures (Fig. 12).

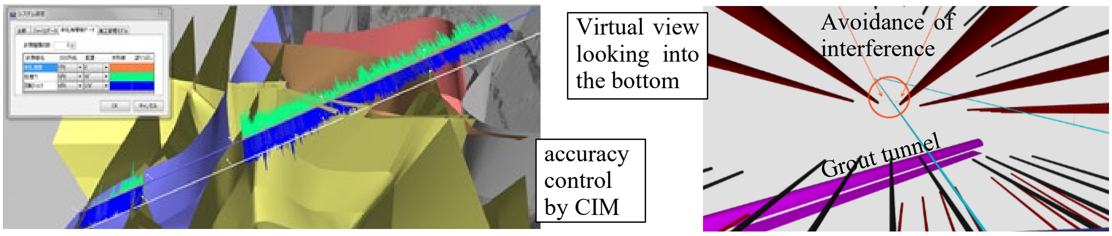


Figure 12. Quality control on drilling by information modeling system

5.6 *Tensioning management*

In tensioning work, when the amount of elastic displacement is large, the stroke of the jack is insufficient with a conventional single tensioning jack, and replacement work is required.

Therefore, a large jack coupling system was devised that couples 2 or 3 jacks according to the anchor length, enabled to tension work without replacing the tension jack. In addition, we confirmed that the measurement results of the load-displacement in real time using the tension control system. We achieved high-accuracy tension control by combining these technologies (Fig. 13).


Figure 13. Triple coupled large tension jacks and tension control system

5.7 *Lifting equipment for transportation of long-size tendons*

Tendons must be transported in such a way that the twisted, sharply bent, adhered with harmful substances, or damaged in anticorrosive materials, which are not damaged. The tendon of this project is about 50m long and weighs about 1 ton, so its handling is not easy.

In addition, the site condition is not suitable for tendon transporting by hanging from its assembly yard. Therefore, in transporting tendons, we developed a semi-circular characteristic hanging tool that makes the tendon curve smoothly so that no concentrated load is generated on the suspension part, and the tendons were transported by folding it in two or three (Fig. 14).

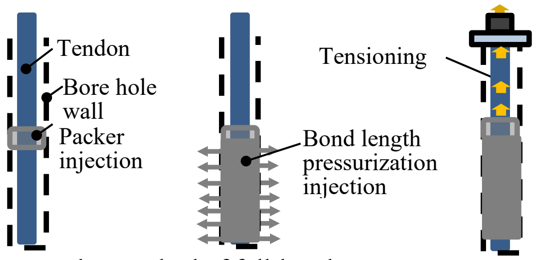
Figure 14. Tendon transport lifting tool

5.8 *High-pressure resistant cloth packers*

A packer is an indispensable tool, because of enough injection to the bond length in grout injection under pressure, and suitable tension fixing of a tendon after grout hardening (Figs. 15a). Because the above-mentioned intermediate unloading method requires two packers for a short section, it was desired to make it significantly lighter than the conventional steel rubber packer. However, product cloth packers were only available up to a diameter of 165mm, so we developed a cloth packer with a large diameter and high-pressure resistance.

For development, we confirmed its performance that abrasion resistance and pressure resistance due to differences in material quality. Further, installation method, performance tests, wearing tests, practicality confirmation tests, etc (Figs. 15b) were conducted.

In the on-site pull-out test at Kawamata Dam, a cloth packer was used, and there was no problem such as grout leakage even under high pressure. In addition, though the pull-out resistance increased greatly, it was presumed that these values were affected using the cloth packer. Namely, when grout is injected, the grout in the cloth packer is concentrated by removing only water through the special fabric as pressure increases, resulting in high strength.



a. packer method of full-bond type

b. High pressure resistant cloth packer

Figure 15 Development of cloth packer on full bonded type anchor

6 HIGH-PERFORMANCE MEASUREMENT FOR SAFETY

As for measurement of anchors and bedrock, many instruments such as “anchor load; 17 (25) units, bedrock strain; 5 (9) units, and rock displacement; 3 (4) units” were installed by the first phase renewal. Numbers inside of parentheses show the total number of the units.

Anchor load is particularly important, but until now, its measurement in full bonded type anchors has been considered difficult. However, in Kawamata Dam, we developed “axial force measuring strand” which is a steel strand in a sheath and has small load cells on the anchor head. This instrument is placed inside the tendon and has so far stably captured anchor loads linked to the change of seasonal temperature and reservoir water level.

Next, as for bedrock strain, the A part anchor has an important role in introducing prestress around the transmitting wall. So, "strain measuring anchor" was developed that is installed very close to the targeting anchor and can measure a slight strain change in the rock mass. This instrument proved the effectiveness of the intermediate load-removing method by measuring very slight strain changes and residual prestress generated by anchor tensioning. Further, the depth-dependent rock displacement meter measures the rock displacement according to five depths, and it is considered to be effective when displacement occurs due to anchor fractures or earthquakes.

These measurements are planned to continue until 100 years from now. So, the long-term durable measurement methods such as the vibrating string type were adopted.

7 CONCLUSIONS

After passing of 50 years, deterioration of PS anchors was confirmed by irregular behaviours in measured values, and damages in heads were found by integrity surveys for PS anchors. So, the renewal project by the full installation of PS anchors and the repairment of the retaining wall was started in 2013. The renewal plan consists of the installation of total 124 unit of PS anchors and the repairment of the retaining wall. In the first phase renewal until 2021, 59 units of PS anchors were installed and the right bank retaining wall was stabilized by grout injection.

Through the experiences of Kawamata Dam and others, “Design and construction manual of PS anchors for dam” was issued in 2021.9. At the present, the second phase renewal is under consideration, and further improvements by this manual will be made as appropriate.

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