Development of new maintenance program for scouring measures at downstream of dam

Shingo Takagi[1,a], Mai Sato[1,b], Yuichi Kitamura[2,c]

[1]*Funagira Constraction Office, Electric Power Development Co., Ltd. (J-POWER), Shizuoka, Hamamatsu, Japan*

[2]*Chigasaki Research Institute, Electric Power Development Co., Ltd. (J-POWER), Kanagawa, Japan*

[a]shingo_takagi@jpower.co.jp
[b]mai_sato@jpower.co.jp
[c]yuichi_k@jpower.co.jp

ABSTRACT

Energy dissipations at downstream of dam have to be sufficient to reduce the stream power and to pass the flood discharge safely. The scouring at downstream foundation of dam and spillway structure is especially a major topic in presence of hydraulic structures for flood control.

By utilizing the obtained information, we will further and continuously make our all efforts to securely carry out the existing erosion measures and long-term measures at downstream of dam to stabilize the dam, to thoroughly keep and control the environment including the dam and the river, and to respond to the problems found as the results of the measures. They are including checks and reviews for the maintenance and control standards, plans, and countermeasures.

In this paper the new maintenance program was explained and introduced the process of setting up by the experimental study with the field observation, mathematical model tests, and the hydraulic scale model tests. The program was appropriately to be examined through the various observation and tests about the topics of during construction of scouring measures and maintenance for the existing dam.

1. INTORODUCTION

The Funagira Dam owned by J-Power has repeatedly experienced large-scale floods from immediately after completion to recently and been subjected to intermittent progress of degradation of riverbed. In order to secure stability of the Dam, accordingly, consideration was made from viewpoint of both "structural stability" and "hydraulic stability" to start downstream scouring control measures from October 2015.

On the other hand, past maintenance has been conducted on a corrective maintenance basis which takes an action when the structures such as the Dam and banks are affected by a scouring phenomenon. This time, based on the knowledge obtained through investigation of the scouring phenomenon by a field survey and hydraulic scale model experiment, and study of the countermeasures, the concept of preventive maintenance has been introduced to build a new maintenance system. Specifically, this is to (1) monitor a stream regime, riverbed and scouring control measures, (2) evaluate by control standards, (3) conduct protective measures and additional countermeasures as required, and (4) review maintenance system in an appropriate manner, referring to the report of J-POWER (2014).

This paper outlines the cause of downstream scouring at the Funagira Dam and countermeasures therefor, and describes the actual operational situation and future issues of the constructed maintenance system for the downstream scouring control measures.

2. SCOURING PHENOMRNON AT FUNAGIRA DAM AND LONG-TERM COUNTERMEASURES

2.1 Scouring Phenomenon at Funagira Dam

The Funagira Dam is a concrete gravity dam constructed at the most downstream of the Tenryu River in 1977. Its profile is as shown in Table 1. The design flood discharge of the Funagira Dam is 11,130 m^3/sec. At downstream of the Dam, a hydraulic jump type energy dissipator has been adopted to construct bed protection work.

The following summarizes the progress of riverbed scouring immediately after completion of the Dam and the recent progress of scouring based on the analysis results of riverbed fluctuations from after completion of the Dam to the present time and changes of the stream regime at immediate downstream of the Dam and the water level at downstream of the Dam over years, and the verification results by the hydraulic scale model experiment.

Table 1. Profile of Funagira Dam

Start of Construction	Nov./1972.	High water level		EL.57.00 m
Commisioning	Apr./1977	Low water level		EL.54.80 m
Type of Dam	Concrete gravity type	Preliminary discharge level		EL.50.60 m
Height of Dam	24.50 m	Spillway gate		9 roller gates
Length of Dam	220.0 m	Design flood discharge		11,130 m^3/s
Volume of Dam	54,000 m^3	Generation	Turbine discharge	270m^3/s
Catchment area	4,895 km^2		Maximum output	32,000 kW

2.1.1 Riverbed scouring immediately after completion of the Dam

2.1.1.1 Layout of bed protection blocks and situation of riverbed scouring

For the downstream section upon completion of the Dam, bed protection blocks had been installed in the immediate downstream area of the No. 1 to No. 5 gates (gravel riverbed), but no bed protection blocks have been installed in the immediate downstream area of the No. 6 to No. 8 gates where bedrocks are exposed (bedrock exposed area). In short, a bed protection block installation range was not uniform in the river crosswise direction (Figure 1). However, the bedrock exposed area was scoured and the bed protection blocks were moved by a flood immediately after completion of the Dam (June 1977, maximum discharge rate = 2,134 m^3/sec.), scouring the gravel riverbed.

2.1.1.2 Factors of riverbed scouring

The following analyzes the factors of riverbed scouring immediately after completion of the Dam.

- The bedrock exposed area was unexpectedly greatly scoured by the flood.
- Near the boundary of the bed protection block area and no-block area, the end blocks were moved by a complicated action of stream regime caused by a difference in roughness of both areas and scouring of the bedrock exposed area.
- The moved bed protection blocks failed to prevent scouring of the nearby gravel riverbed and reduced an engagement effect of adjacent blocks. As a result, block move widely spread, expanding riverbed scouring.

2.1.2 Recent progress of riverbed scouring

2.1.2.1 Situation of riverbed scouring

There occurred large-scale floods over a long period in 2010 to 2011 (maximum discharge rate = 6,396 m^3/sec., total flood period = 153 days), and scouring particularly progressed in the foundation bedrock area immediately below the No. 3 and No. 4 gates. For this reason, bed protection blocks (tetrapods, 12.5-ton type) were constructed at immediate downstream of the No. 1 to No. 5 gates as an emergency countermeasure. However, the riverbed was scoured and bed protection blocks moved again, centering on the downstream area of the No. 4 gate due to the floods by the typhoons in 2013 (No. 18 typhoon with the maximum discharge rate of 4,864 m^3/sec. and No. 27 typhoon with the maximum discharge rate of 1,960 m^3/sec.).

2.1.2.2 Factors of progressed riverbed scouring

It is conceived that the progress of riverbed scouring was greatly increased by a swirling flow associated with water discharge and the lower water level at downstream of the Dam.

a) Effect of the swirling flow

- Immediately after completion of the Dam, its gates had adopted a discharge style like pyramid (hereinafter called “pyramid style open”) and a partial equivalent discharge method (hereinafter called “partial equivalent style open”). With these methods, however, all the gates are opened only when a flood reaches a considerable scale (Figure 2).
- In the downstream areas of the non-discharge gates on the right and left banks (dead water areas), planar swirling flows are generated, forming an obliquely downward creeping flow at the confluence of the swirling flow and gate discharge water. These swirling flows are harsh stream regimes to riverbed scouring; particularly the one in the left-bank area was large.

b) Effect of the lowered water level at downstream of the Dam

- When discharged from the gates of the Dam, an outflow mode depends on the water level at downstream of the Dam. The outflow mode transitions from underwater flow to submerged flow, free flow and to drop flow. The drop flow is the harshest outflow mode to riverbed scouring (Figure 3).
- A riverbed level at downstream of the Dam (approx. 350 m downstream of the dam) has been lowered approx. 5 cm annually from the completion time of the Dam. Because the lower river water level at downstream of the Dam tends to generate a drop flow which is highly likely to affect riverbed scouring, the lower downstream riverbed level is one of the factors (Figure 4).

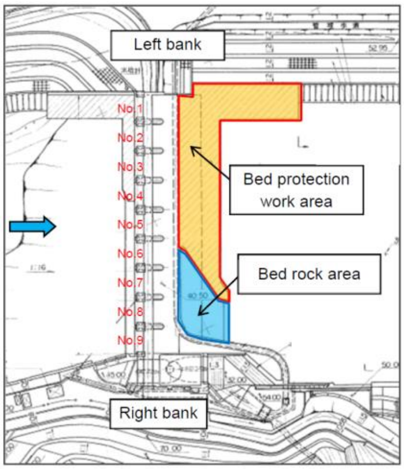


Figure 1. Area of original bed protection

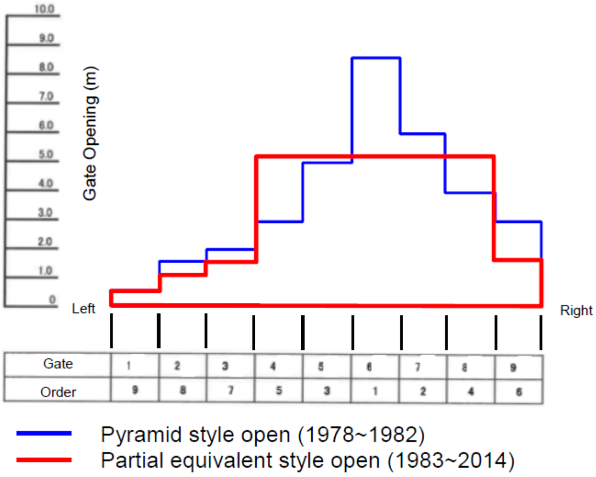


Figure 2. Comparison of flow condition with gate operations

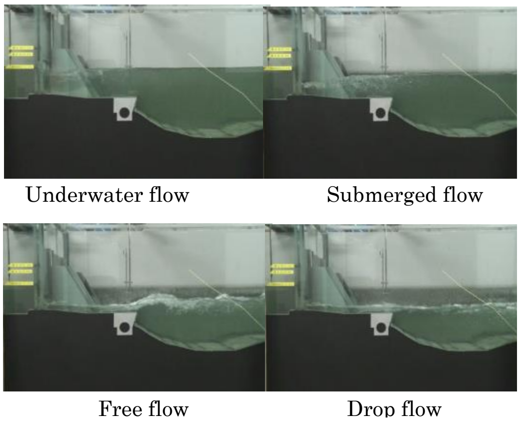


Figure 3. Condition about types of hydraulic jump in front of Gate 7 with different downstream water level

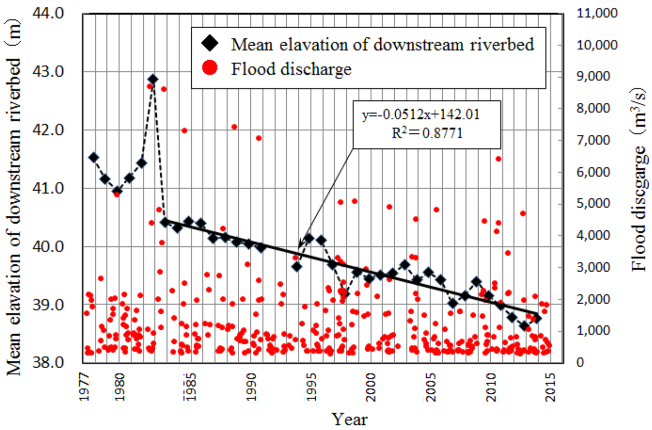


Figure 4. Annual change of mean riverbed level and maximum discharge at cross section about 350 m downstream from Funagira Dam downstream water level

2.2 Overview of Long-term Countermeasures

In light of the above-mentioned, it was decided to implement the following items as long-term downstream scouring control measures.

2.2.1 Change of the water discharge method

In order to inhibit generation of the swirling flow which is a harsh stream regime to riverbed scouring, the water discharge method is changed from "partial equivalent style open" to "fully equivalent style open." The method sequentially opens each gate on the basis of 50-cm opening. Although it depends on the water level of a regulating reservoir, all the gates will be opened when a total discharge rate reaches slightly less than 1,000 m^3/sec. because the rate at 50-cm opening is generally 100 m^3/sec.

2.2.2 Scouring control measure for the right-bank bedrock area

In view of the past record of scouring, it is necessary to take a scouring control measure for the right-bank bedrock area at immediate downstream of the Dam, as with the gravel area. Also, it is effective to install the control measure of the same structure in the crosswise direction of the river in order to equalize the stream regime in the crosswise direction. The most effective layout of concrete blocks was considered based on the hydraulic scale model experiment (Figure 5). It was decided to use tetrapods weighing 16.5 to 32 tons each as concrete blocks and cover the overall downstream of the Dam for the purpose of maintaining the present riverbed level.

2.2.3 Protection against riverbed lowering at downstream of the Dam

If the downstream water level drops along with lowering of the riverbed at downstream of the Dam, the stream regime becomes harsh to riverbed scouring. Accordingly, it was planned to construct protection work against riverbed lowering shown in Figure 6 at 350 m downstream of the Dam. The protection work against riverbed lowering replaces the present gravels with huge stones (rocks) in order to minimize an effect of scouring at downstream of its installation site; its design has emphasized the bending properties. Considering a current velocity (design current velocity = 5.0 m/sec.) at the installation site, it was decided to use rocks weighing 500 to 1,000 kg each.

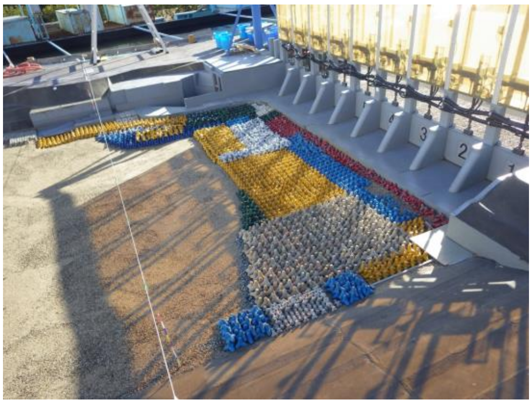


Figure 5. Long-term measure by hydraulic scale model experiment

Figure 6. Protection work against riverbed lowering by hydraulic scale model experiment

3. MAINTENANCE SYSTEM

3.1 Overall Flow of Maintenance System

A maintenance system for downstream scouring should be designed to observe a situation changing according to the flood condition and take a preventive maintenance measure as required instead of a corrective maintenance measure which is taken only when the structures such as the Dam and banks are affected by a scouring phenomenon.

Based on the knowledge obtained through the investigation of the scouring phenomenon by the field survey and hydraulic scale model experiment conducted so far, and study of the countermeasures, the new maintenance system was built. Specifically, this is to (1) monitor a stream regime, riverbed and scouring control measures, (2) evaluate by control standards, (3) conduct protective measures and additional countermeasures as required, and (4) review maintenance system in an appropriate manner. Figure 7 shows an overall flow of the maintenance system.

3.2 Formulation of Maintenance Plans

Important monitoring items are the (1) river regime (water level, flow direction), (2) riverbed level associated with understanding of the downstream scouring condition, and (3) bed protection work, (4) protection work against riverbed lowering associated with understanding of the countermeasure condition. Table 2 lists classification, items, location & range, methods and frequencies of monitoring. The frequencies were basically monitored before a flood season (around the end of May) and after a flood of approx. 2,000 m^3/sec. or more.

3.2.1 Stream regime

The water level is observed with a water gauge near the installation site of the lower riverbed control work and the flow direction is filmed with Industrial Television (ITV) camera and Unmanned Air Vehicle (UAV).

3.2.2 Riverbed level

To measure the riverbed level, multibeam measurement is mainly used for below the water surface, and single beam measurement, Global Navigation Satellite Systems (GNSS) measurement and Total Station (TS) measurement are used for the shallow areas to complement. For observation above the water surface, the UAV is used to film and synthesize. The measurement scope of the riverbed level was set to be from a dam axis to the installation site of the protection work against riverbed lowering before the flood season, and an area of approx. 150 m from the dam axis after the flood of 2,000 m^3/sec. or more.

3.2.3 Bed protection work

Movement of the concrete blocks is observed by riverbed measurement. For observation above the water surface, the UAV is used to film at a fixed point to complement visual observation.

3.2.4 Protection work against riverbed lowering

Deformation of rocks is observed by riverbed level measurement. For observation above the water surface, a digital camera is used to film at a fixed point.

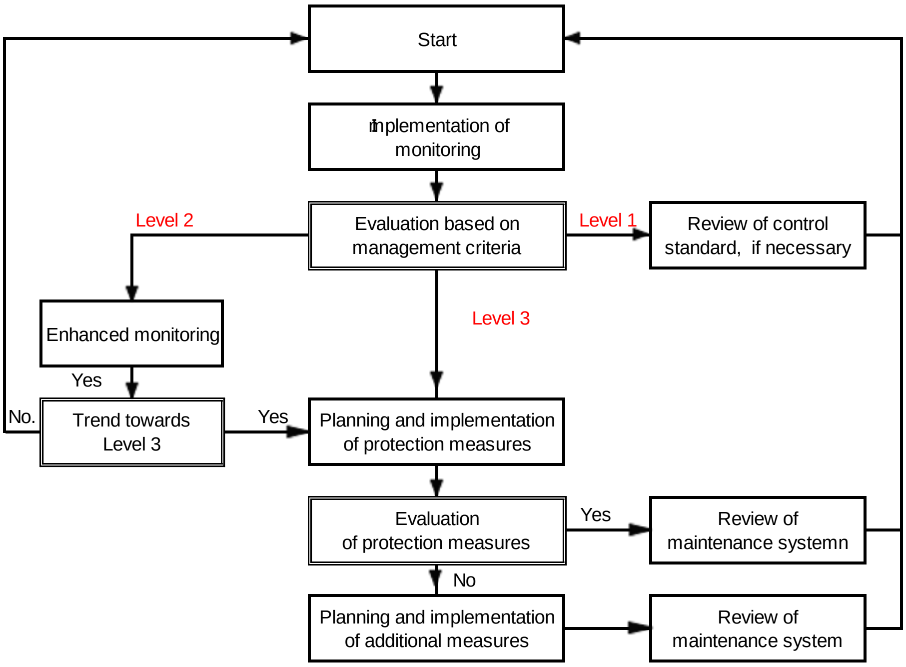


Figure 7. Overall flow of maintenance system

Table 2. Contents of monitoring

Classification	Items	Location & range	Method	Frequency of monitering
River regime	Water level	Vicinity of protection of riverbed lowering	Water level gauge	At a flood of approx. 2,000 m^3/s or more
	Flow direction	Area of 200m downstream from the dam axis	Visual observation Photo & movie	At a flood of approx. 2,000 m^3/s or more
Riverbed	Riverbed level	Vicinity of protection of riverbed lowering	Riverbed survey	Before flood season (May)
		Area of 150m downstream from the dam axis		At a flood of approx. 2,000 m^3/s or more
Bed protection	Concrete block	Covering Concrete Block area installation and surrounding riverbed	Riverbed survey Fixed point photo	Before flood season (May) At a flood of approx. 2,000 m^3/s or more
Protection of riverbed lowering	Rock	Covering protection area of riverbed lowering and surrounding riverbed	Riverbed survey Fixed point photo	Before flood season (May) At a flood of approx. 2,000 m^3/s or more

3.3 Setting of Control Level

Some monitoring items are difficult to set their control standards. The following summarizes the basic concept of control levels (Table 3) and sets the control standards individually as to the items, if possible.

Table 3. Basic concept of control levels

Level	Status	Description
1	Regular control level	There are hardly changes to the stream regime, riverbed and countermeasure at downstream of the Dam, and safety is secured.
2	Caution level	There are partial changes to the stream regime, riverbed and countermeasure at downstream of the Dam, and stability may be being lowered. Care should be taken for maintenance such as enhancing monitoring.
3	Warning level	There are changes to the stream regime, riverbed and countermeasure at downstream of the Dam, and stability is being lowered. It is necessary to take a protective measure or additional measure.

3.3.1 Stream regime

Monitoring items on the stream regime are a relation change between a discharge rate and the water level at downstream of the Dam, generation of the swirling flow, local drift and hydraulic jump near the structure, and so on. Of them, the control standards for the stream regime have set the control levels shown in Table 4 and Figure 8, using the water level at the installation site of the protection work against riverbed lowering. A boundary between Levels 1 and 2 is the water level obtained by a backwater calculation based on the riverbed height data of the section to a point approx. 5 km from the Funagira Dam, and that between Levels 2 and 3 is a drop water level obtained by the hydraulic scale model experiment.

Table 4. Control standards for water level at downstream of dam

Level	Status	Description
1	Regular control level	Compared with when the concrete blocks were installed, the riverbed level has been maintained or elevated.
2	Caution level	Compared with when the concrete blocks were installed, the riverbed level has been lowered.
3	Warning level	Compared with when the concrete blocks were installed, the riverbed level has been further lowered, and the water level has been lowered, resulting in a drop flow at the lower end of an apron.

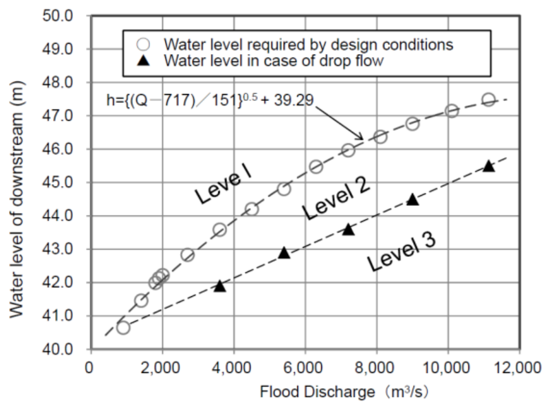


Figure 8. Water level vs. Flood discharge

3.3.2 Riverbed

Monitoring items on the riverbed are fluctuation of the riverbed (scouring, sedimentation), difference between the right- and left-bank riverbed levels, and so on. The downstream riverbed level changes greatly depending on a flood discharge volume and a downflow sediment volume from upstream. For this reason, the control standards for the riverbed have been set using the average level of the crosswise riverbed level at 150 m downstream from the dam axis as shown in Table 5. and Figure 9.

Table 5. Control standards for riverbed level at downstream of dam

Level	Status	Description
1	Regular control level	The average crosswise riverbed level is less than EL. 36 m.
2	Caution level	EL. 36 m or more and less than EL. 42 m.
3	Warning level	EL. 42 m or more.

*. The average crosswise riverbed level is calculated at 150 m downstream from the dam axis.

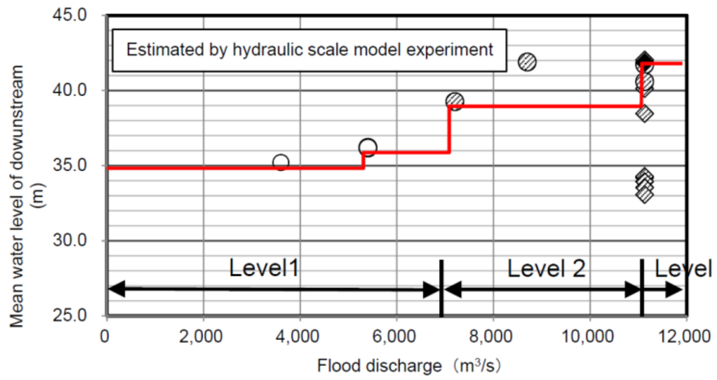


Figure 9. Change of average crosswise riverbed at 150 m downstream from dam

3.3.3 Bed protection work

Monitoring items on bed protection work are displacement of concrete block (planar change, subsidence), movement of concrete blocks near the structure, transition of the nearby riverbed level, and so on. Of them, the control standards for bed protection work have set the control levels listed in Table 6, focusing on deformation of the concrete blocks. Evaluation criteria are as shown in Figure 10.

Table 6. Control standards for concrete clocks

Level	Status	Description
1	Regular control level	The concrete blocks have been hardly moved and the nearby riverbed has not been scoured. A guide for evaluation is that they have been moved up to about the 3rd row at the end of the installation range.
2	Caution level	The concrete blocks have been moved beyond the range of Level 1, but coverage of the riverbed has been maintained. They have been moved near the structure, but the bed protection function has been maintained.
3	Warning level	The concrete blocks have been moved at the end of the installation range and coverage of the riverbed has not been maintained. They have been moved considerably near the structure.

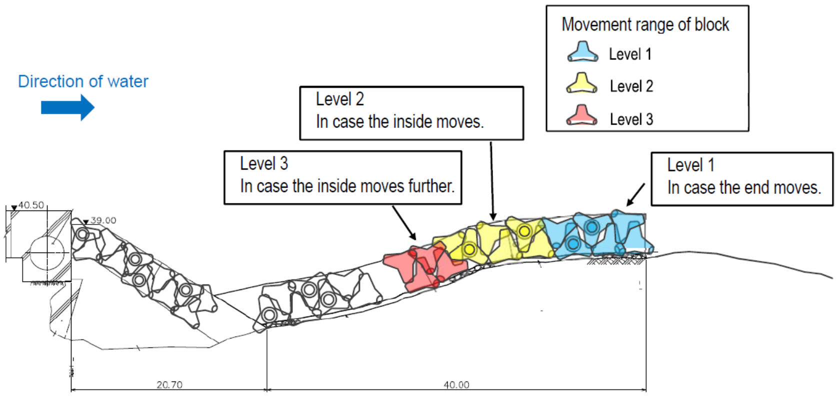


Figure 10. Deformation image of concrete blocks

3.3.4 Protection work against riverbed lowering

Monitoring items on protection work against riverbed lowering are deformation of rocks (degree of deformation), deformation of the installation part, scouring and sedimentation of the upstream and downstream riverbeds, and so on. Of them, the control standards for protection work against riverbed lowering have set the control levels shown in Table 7.

Table 7. Control standards for protection work against riverbed lowering

Level	Status	Description
1	Regular control level	Rocks have been hardly moved. The upstream and downstream riverbeds have been hardly scoured.
2	Caution level	Rocks have been moved, but the shape of the main body has been held. The upstream and downstream riverbed levels have been lowered, but the effect still remains in the bed protection area at upstream and downstream of the main body, not reaching the main body.
3	Warning level	Rocks have been moved and the shape of the main body has not been held. The upstream and downstream riverbed levels have been greatly lowered, reaching the main body.

4. PRESENT SITUATION OF MONITORING

Among the long-term countermeasures, for (1) Change of the water discharge method it has been changed from partial equivalent discharge to fully equivalent discharge since July 2014. For (2) Scouring control measure for the right-bank bedrock area and (3) Drawdown control measure at downstream of the Dam, their work has been started as a 3-year plan since October 2015 as long-term scouring control work at downstream of the Funagira Dam.

In the meantime, the maintenance system has started its operations since April 2015. At the end of December 2016, the maximum discharge rate is 1,987 m^3/sec., a low level compared with a design precipitation of 11,130 m^3/sec. All the monitoring items described in Chapter 3 are at the regular control level. On the other hand, the monitoring data with no set control standards can be also analyzed in different ways. The following describes transition analysis of the riverbed level and stream regime analysis.

4.1 Fluctuation analysis of the riverbed level

Figure 11 shows transition of the riverbed level.

- A. May 2014 - This is riverbed level data before changing to fully equivalent discharge. Scouring (green-color area) is confirmed crosswise immediately below the Dam. It has been expanded to downstream of the No. 5 and No. 6 gates. On the other hand, riverbed gravel material has been deposited (red-color area) at downstream of the No. 1 to No. 3 gates as a whole.

- B. Jun. 2015 - This is the riverbed approx. 1 year after changing to fully equivalent equivalent discharge. The riverbed height has changed greatly due to a change to fully equivalent equivalent discharge. First, soil has been deposited (red-color area) across the width immediately below the Dam, showing a sedimentation trend at downstream of the No. 5 and No. 6 gates, and sand deposition trend at downstream of the No. 1 to No. 3 gates. Furthermore, a scouring trend is clearly confirmed immediately below the right-bank discharge port. Along with the change of the water discharge method, it is confirmed that gravels deposited at downstream of the Dam have been reconfigured.
- C. Sep. 2015 - This is the riverbed approx. 1 year and 4 months after changing to fully equivalent equivalent discharge and immediately before installation of the concrete blocks. It has a similar trend to the riverbed in B, but there is a change to the scouring and sand deposition areas.
- D. May 2016 - This is the riverbed after 1-year construction work and the left-bank riverbed is immediately after installation of the concrete blocks. A blue-color area indicates a construction road using round stones and the concrete blocks are installed in a yellow-color area.

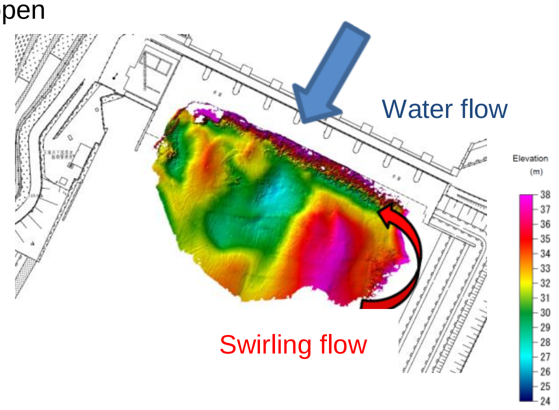
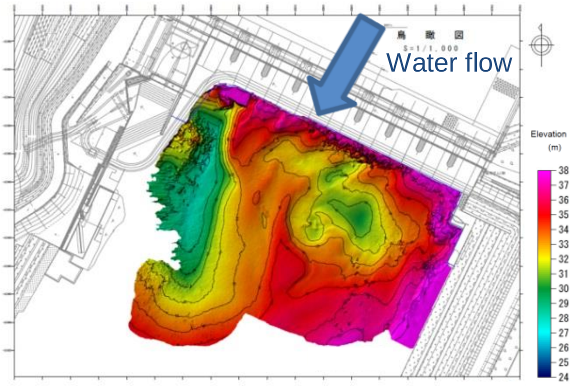
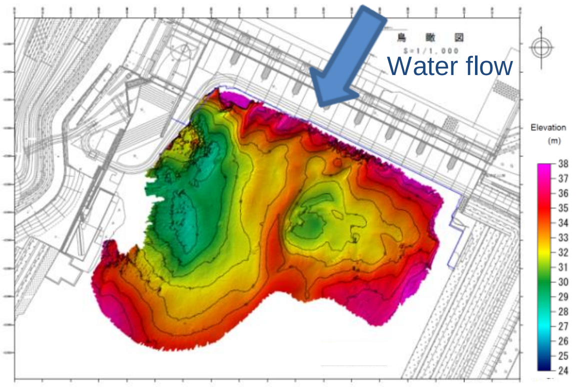
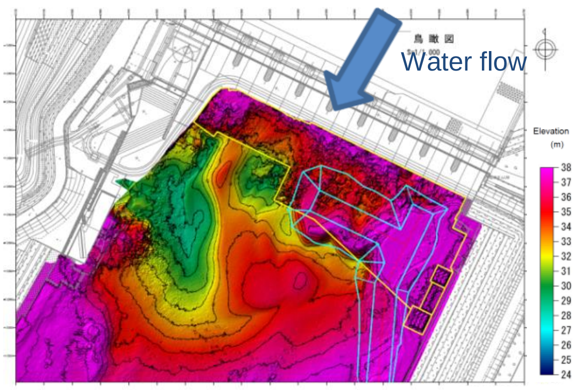
A. 2014. May Riverbed before changing to full equivalent style open	C. 2015. Sep Riverbed before setting concrete block
	
B. 2015. Jun Riverbed at the time about 1 year passed after changing to full equivalent style open	D. 2016. May Riverbed after setting concrete block
	

Figure 11. Fluctuation of riverbed level

4.2 Analysis of the stream regime by UVA video data

Figure 12 shows the results of streamline analysis, using the animation data filmed by the UAV. Filmed on Sep. 4, 2015, a total discharge rate is 474 m^3/sec. and 6 gates of No. 4 to No. 9 are opened. It is confirmed that a distinct swirling flow has been generated.

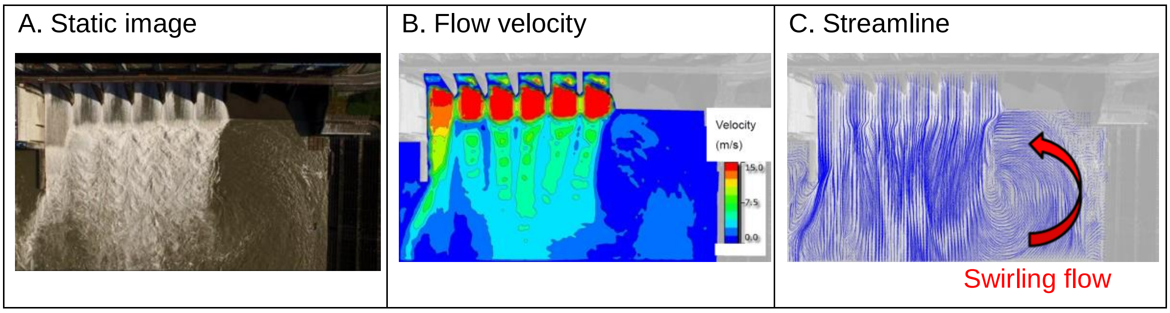


Figure 12. Streamline analysis with UAV video data

5. CONCLUSION

The maintenance system for downstream scouring was constructed in order to secure stability of the Dam and surrounding structures over a long period after completion of downstream scouring control work. Presently, countermeasures are being conducted and the maintenance system has not been fully equivalent operated yet, only starting part of monitoring. Monitoring data leaves some to be reviewed as to their methods and accuracy, but have been utilized for drawing up a countermeasure construction plan by making use of the results. The following summarizes the future issues.

(a) The control standards for each monitoring have been set based on numerical analyses and hydraulic scale model experiments, but there may occur locally different phenomena at actual facilities. It is necessary to compare the control standards with the monitoring results and check the validity to review them accordingly.

(b) Of the monitoring items, the riverbed level fluctuation is very significant data. On the other hand, its measurement is conducted under the restrictions imposed by the river condition at that time. Specifically speaking;

- Measurement is always conducted under power-generating water discharge; it is difficult to measure in the immediate outlet discharge.
- The gates of the Funagira Dam are opened to discharge water for approx. 90 days on the annual average; measurement may be conducted with the gates opened to discharge water.

It will be necessary to consider how to maintain constant quality (accuracy) while securing safety of measurement work.

6. REFERENCES

- J-POWER (2014). *Report on scouring of Funagira Dam at down-stream*. J-POWER & technical review board committee.