Study on scouring phenomena at downstream of dam during flood control

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ABSTRACT

Funagira Dam was built at the most downstream of the Tenryu River in 1977. The spillway facilities were designed to handle the design discharge of up to 11,130 m3/s under gross head of 10m to 18m. The energy dissipation at downstream of the dam was designed as the hydraulic jump-type on the bed protection blocks.

The dam has been experienced several large flood events during the last about 40 years after the completion. The protection blocks were damaged and the scouring downstream foundation of the dam was begun in the early stage, and up to 6,300 measure blocks were continually put on. In recent time, nonetheless, the flood events in 2011, was larger and longer period of flood with maximum flood about 6.396 m3/s, and the scouring increased to the severe condition at the foot and stability of dam.

In this paper the experimental study results and knowledge with the field observation, mathematical model tests, and the vertical 2-dimensional and the fully 3-dimensional hydraulic scale model tests were introduced to evaluate the scouring processes and to determine the long-term measures.

1. INTRODUCTION

Energy dissipation downstream of the dam has to be sufficient to reduce the stream power and to pass the flood discharge safely. Various dissipation methods are used in places where the excess hydraulic energy could cause such damage as erosion of tail water channels, abrasion of hydraulic structures, generation of tail water waves, or scouring. Scouring downstream of dam and spillway structures is a major topic in relation to hydraulic structures that foresee the production of flood discharge, referring to Breusers (1991).

Funagira Dam was built at the most downstream area of the Tenryu River in 1977 (Figure 1). The dam is a concrete gravity dam, and is 24.5 m high and 220 m long, with 9 large spillway gates (Figure 2). The spillway facilities were designed to handle the planned discharge of up to 11,130 m^3/s under a gross head of 10 m to 18 m. For energy dissipation, the area downstream of the dam was designed as a hydraulic jump type dissipater using bed protection blocks (Figure 3). It is shown in the four reports of J-POWER (1972) and J-POWER (1977).

The dam has experienced several large storm events during these 40 years after completion. The protection blocks were damaged and the scouring downstream of the dam began soon after completion. About 6,300 tetrapods were added in stages to the bottom. In recent times, however, flood events were more intense and of longer duration, with maximum spillway releases of up to approximately 6,396 m^3/s. This resulted in increased scouring at the foot of the dam. Emergency measures were built just downstream of the dam apron from 2011 to 2013. The scouring process is caused by several variables, such as water discharge, water level downstream, bed protection, bed materials, sediment transport, morphological riverbed conditions, and gate operations.

In this paper, an experimental study with field observations, mathematical model analysis, and vertical 2-dimensional (hereinafter 2D) and fully 3-dimensional (hereinafter 3D) hydraulic scale model tests were carried out to examine the scouring processes and to determine mitigation measures.

Figure 1. Location map of Funagira Dam

Figure 2. Funagira Dam

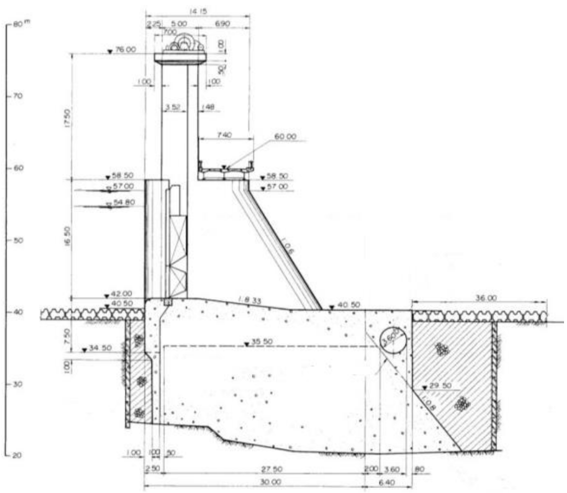


Figure 3. Standard cross section of Funagira Dam

2. SCOURING SITUATION AND MEASURES

In June 1977, just after completion of the dam, the first flood was discharged using a few of the gates, with a maximum outflow rate of 2,134 m^3/s, which was not so large. However, almost all the grasp blocks (5-t blocks) forming the downstream bottom at a height of 40.5 m were damaged during the flood discharge. The riverbed at Gate 6, just downstream of the dam, was scoured by a volume of approximately 90,000 m^3, with a maximum depth of approximately 10 m. Table 1 and Figure 4 show how the riverbed was scoured and how mitigation measures against scoured parts have been taken until now, since the completion of Funagira Dam (1977).

Table 1. History of scouring and its measures for Funagira Dam

Period	Scouring and its measures
1978-1992	* Placed 6,300 m^3/s tetrapods (5-t, 6.3-t) as bed protection work * Switched discharge operation from pyramid style to semi uniform opening gate * Largest discharged floods: 8,700 m^3/s in 1982, and 8,613 m^3/s in 1983 * Additional tetrapod (6.3-t) in jointed manner with cables between 1990 to 1992 * Changed discharge operation to partially equal style (Gates 4 to 8 with semi uniform opening until the flow rate of 3,000 m^3/s)
1992-2003	* Stable with slight morphological changes in each year and no particular measure
2003-2011	* Scoured riverbed gradually in front of dam spillway * 15m of riverbed scoured locally near dam foundation in front of Gates 3 and 4 due to the large and long period of discharge (153 days and 6,396 m^3/s).
2003-2013	* Filled with underwater concrete with filter-unit above scoured foundation (Gates 3 and 4) between September 2011 and May 2012 * Additional measures with 836 tetrapod (12.5-t type) in front of Gates 1 to 5 between August and October 2012 and March and April 2013
2013-2015	* Reviewed long-term measures for selection and control methods in the technical review board committee on scouring downstream of the Funagira Dam and the follow-up committee
2015-	* Started long-term measures works in October 2015. * Planned construction works to be completed in May 2018

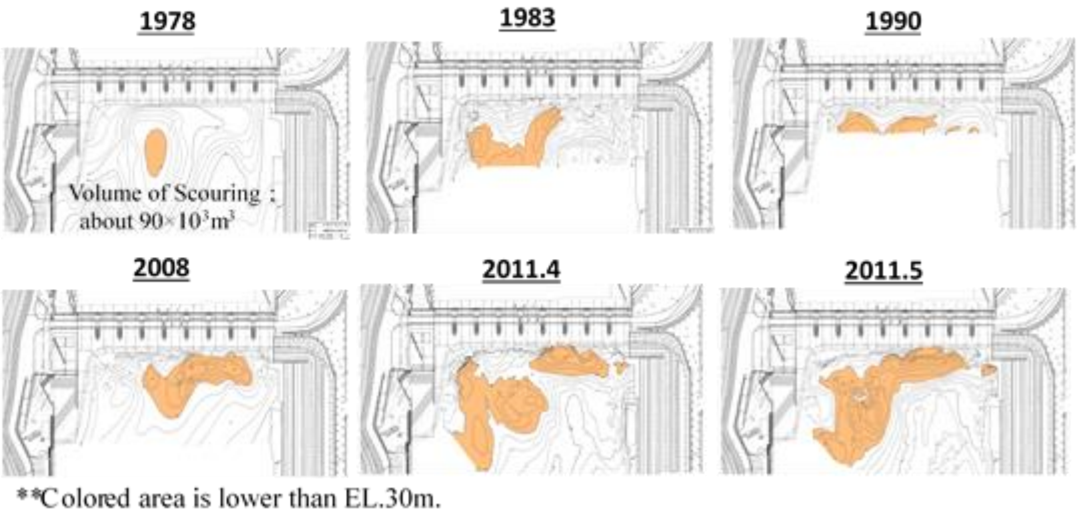


Figure 4. Morphogical change in front of Funagira Dam

Between 2010 and 2011, a large flood (6,396 m^3/s in September 21, 2011) was discharged continuously and for a long period (153 days). The riverbed was scoured near the conduit foundation bedrock just downstream of Gates 3 and 4. The mitigation work was carried out at the conduit foundation in response to this. In addition, bed protection blocks (12.5-t tetrapods) were placed as emergency measures on the left bank at just downstream of Gates 1 to 5 in May 2013 (see Figure 5). The downstream area of the dam in 2011 was scoured by a volume of approximately 230,000 m^3 with a maximum depth of approximately 13 m for a riverbed height of EL 39.0 m.

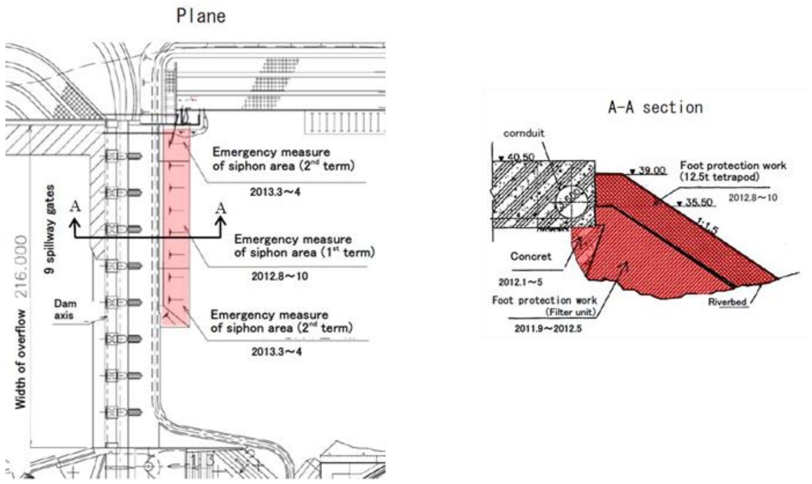


Figure 5. Plane and cross section of emergency measues

3. STUDY OF SCOURING FACTORS

We have studied to investigate why and how the riverbed downstream of Funagira Dam was scoured. The study used field observations, mathematical model analysis, and hydraulic scale models tests, referring to Suga (1990). The several hydraulic scale models were mainly applied to examine the morphological changes in the riverbed and the scouring processes, and to determine the long-term measures. It was applied vertical 2D partial models (Figure 6) with a scale of 1/50. It was also a fully 3D model with a scale of 1/50 of the movable riverbeds at and around the dam 1.5 km upstream and downstream (Figure 7). As a result, we have identified the factors that caused scouring close to the dam was completed and why the riverbed was scoured further, referring to the report of J-POWER (2014).

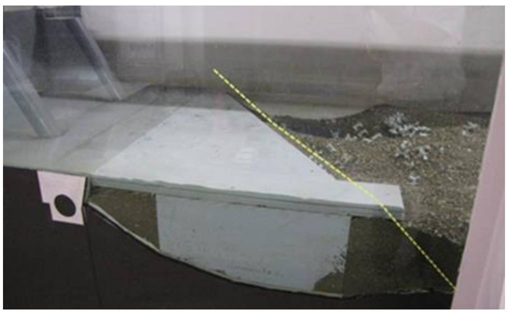


Figure 6. Vertical 2D hydraulic scale model

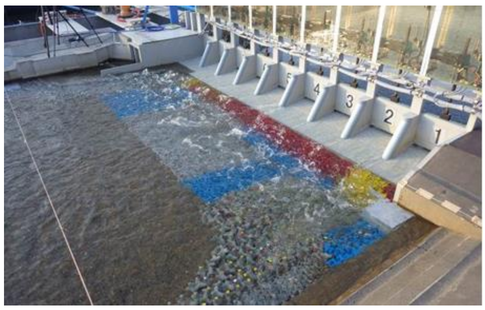


Figure 7. Fully 3D hydraulic scale model

3.1 Scouring of bedrock

While Funagira Dam was constructed, bed protection blocks were placed as a measure against scouring on the riverbeds, where gravel was present. They were installed close to downstream of Gates 1 to 5. Meanwhile, with no fear of scouring, no such blocks were placed close to downstream of Gates 6 to 8 near the right bank, where the bedrock (black schist) was exposed. However, according to the results of the depth measurements conducted in 1978, the exposed bedrock on the right bank was significantly scoured. It happened by discharged water just after the dam was completed.

Even though the scoured bedrock could not be assessed quantitatively, it can be thought that it was caused by fluid forces and stones that hit and scratched the jointed bedrock.

3.2 Removal of bed protection blocks and scouring of gravel bed

As described above, the bed protection blocks were not uniformly placed across the river, but placed along areas of gravel where bedrock was not apparent (Figure 8). The boundary of exposed bedrock and gravel with bed protection blocks had different roughness. It had unstable hydraulic jump which were caused by an uneven riverbed. Therefore, it can be thought that the bed protection blocks placed along the edges of the bedrock area were removed.

The tests with the vertical 2D hydraulic scale model showed that the bed protection blocks were stable in the case of uniformly placed blocks. On the other hand the blocks were removed in the front of Gate 7 where blocks were decreasing along exposed bedrock. A large morphological change was observed in the model (Figure 9).

The testes showed that some blocks were removed at the edge of bed protection blocks just after the completion of the dam. The gravel around them then began to been scoured. This would reduce the engaging effect of adjacent blocks. The blocks were further removed in a wide area, eventually losing the function of protecting the bedrock with the blocks at the end.

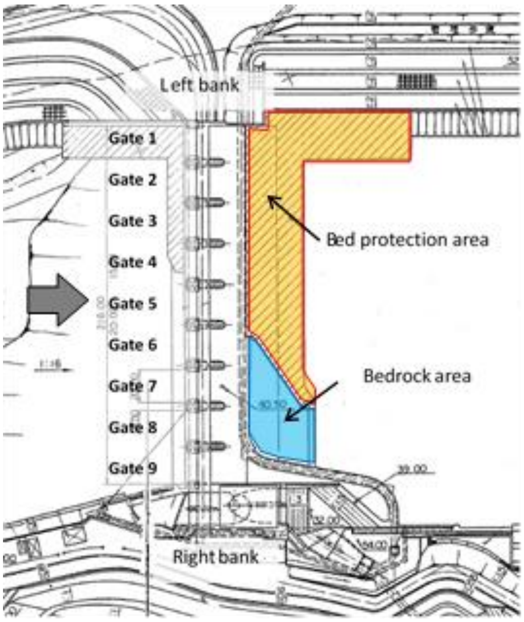
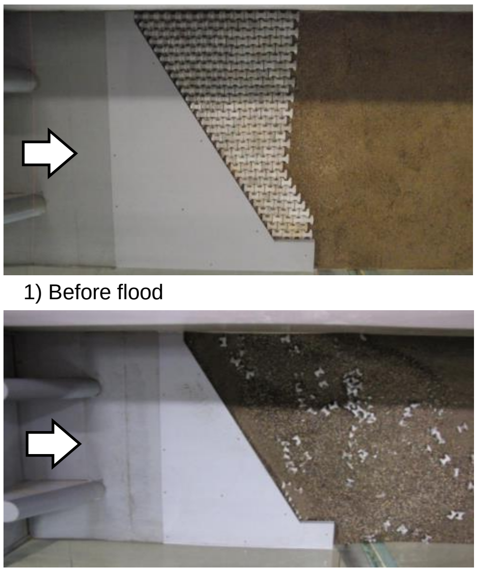


Figure 8. Area of original bed protection measures



1) Before flood

2) After flood

Figure 9. Model test on satbility of original bed protection in front of Gate 7

3.3 Effect of horizontal swirl flow

Several floods were discharged from the gates after the dam was completed. The discharging style was like a pyramid style opening gate (hereinafter pyramid opening) during 1978 and 1982. After two large floods, we changed the gate operation in a semi uniform opening in 1983 (Figure 10). Even in the case of following this semi uniform opening, the rates of water discharged on both left and right sides differed. This opening still generated a plane horizontal swirl flow in both the left and right areas downstream of the gates from which no water were discharged (dead water region). We did not take account this phenomena at that time referring to the report of J-POWER (1990).

Downstream of Funagira Dam, in particular, the horizontal swirl flow around the left bank was larger than around the right bank. Figure 11 shows the flow conditions downstream of Funagira Dam computed by a 3D free surface mathematical model. The semi uniform opening gate generates a huge horizontal swirl flow around the left bank of the dam.

The tests using the 3D model showed that the horizontal swirl flow proceeded upstream towards the left bank, changed direction at the lower edge of the apron. Then it became parallel to the dam axis (Figure 12). It formed a diagonally downward flow after joining the flow of water discharged from the gates. It finally created a critical flow for the protection blocks and scoured on the riverbed unlike a normal hydraulic jump. The velocity at the downstream with semi uniform opening gate became larger than the fully uniform one. The velocity at downstream of opening gate became especially high velocity and the direction of flow became toward downstream (Figure 13).

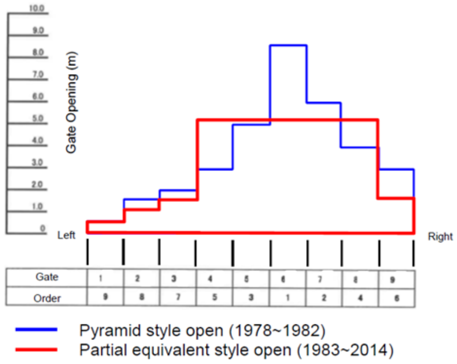


Figure 10. Pyramid and semi unifrom opening gate for until 3,000m^3/s

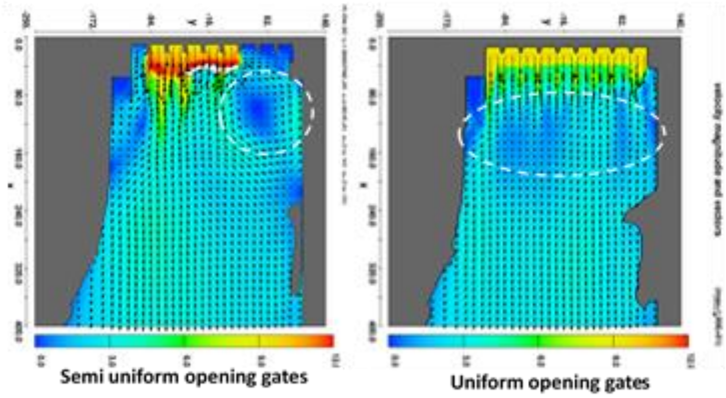


Figure 11. Comparison of flow condition with different opening gates

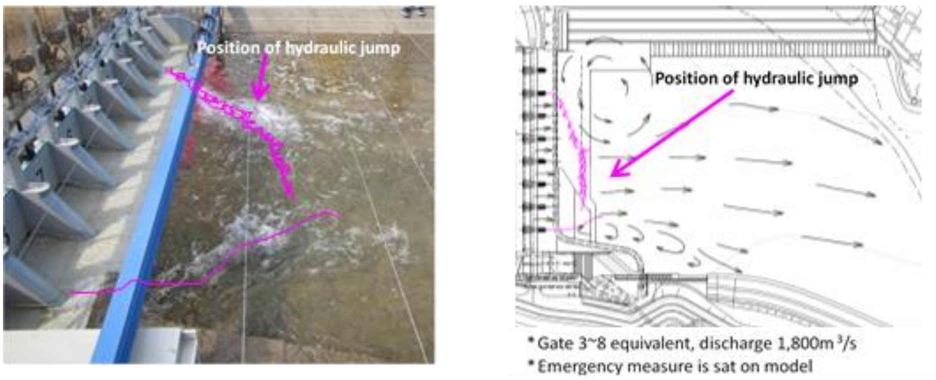


Figure 12. Flow regime of semi uniform opening gate operation

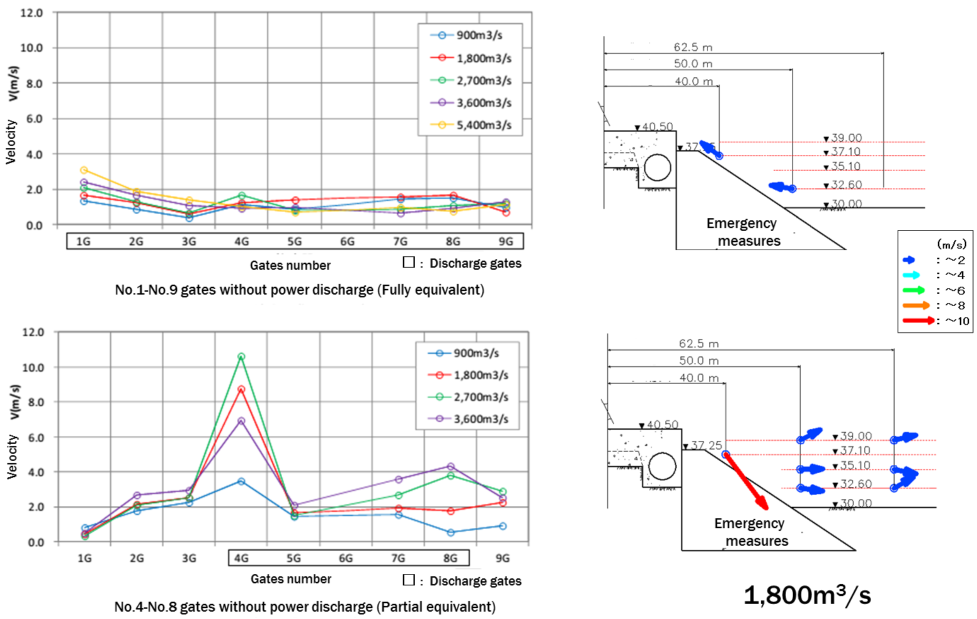


Figure 13. Difference of velocity conditions with different gate operations for 1,800m^3/s (Uniform and semi uniform opening gate operations)

3.4 Effect due to the water level downstream of the dam

The vertical 2D hydraulic scale model tests allowed to investigate the relationship between the discharged water from the gates and the downstream water level. Figure 14 shows that different types of hydraulic jump are formed according to the downstream water level. They are (1) an underwater flow, (2) a submerged flow, (3) a free flow, and (4) a drop flow (overflow) for a constant discharge rate. The underwater flow is mostly appearing during the design discharge, and the other flows are appearing until middle class discharge. The drop flow will generate the high velocity near bottom.

Figure 15 shows the different types of hydraulic jump as a function of the downstream water level and as a function of the Gate 6 discharge rate. It shows that the lower the downstream water level, the more different types of hydraulic jump are appearing. Also, drop flow appears in the case of the lowest downstream water level.

The flood of 2,134 m^3/s in 1978 and the largest flood of 8,700 m^3/s in 1982 generated similar types of hydraulic jump until 800 m^3/s discharge of Gate 6 in the Figure 15. It means that the downstream water level is low at the beginning of discharge with any class of flood discharge, and that it facilitates scouring of the riverbed at the initial discharge operation. It is the reason that Funagira Dam was seriously scoured during the small flood in 1978.

Furthermore from the completion of the dam in 1977 until the end of 1985, the water level lowered by approximately 10 cm per year. The water level still keeps on lowering, even though its rate is moderated, approximately few centimetres per year since the 1990. Therefore reduction of the downstream water level can also cause discharge flow as a drop flow, which can facilitate scouring of the riverbed. It is one of the factors that generates scouring in the riverbed downstream of the dam.

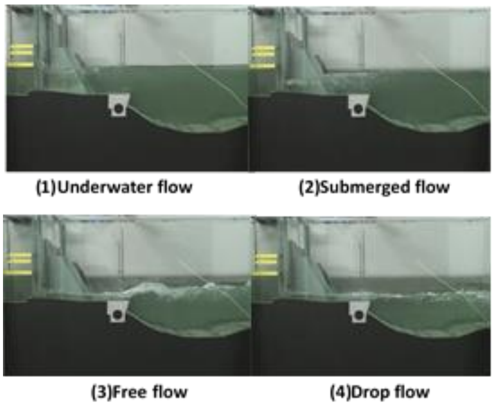


Figure 14. Types of hydraulic jump in front of Gate 7 with different downstream water levels

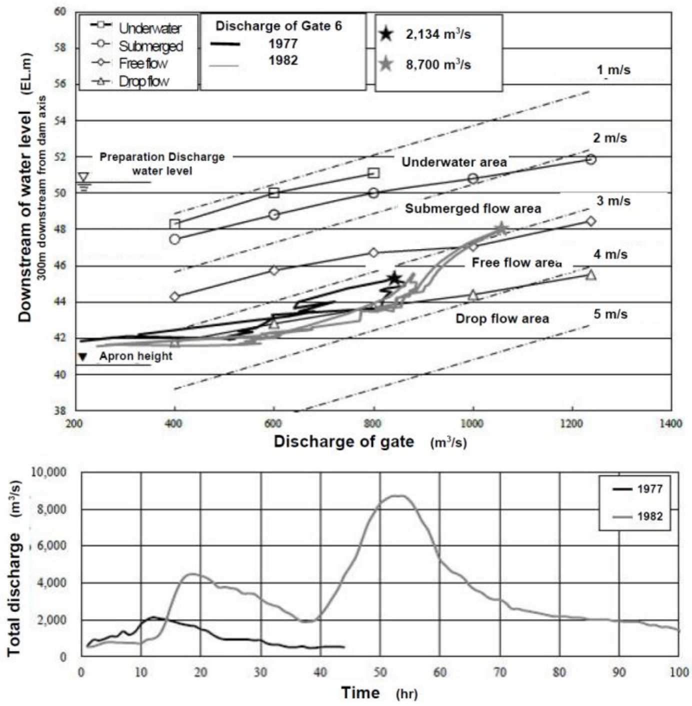


Figure 15. Transition of hydraulic jump in front of Gate 6 with discharge and water level

4. EMERGENCY MEASURES AND LONG-TERM MEASURES

4.1 Stability of emergency measures in 2013

We have investigated the stability of the emergency measures (12.5-t type tetrapods) taken from 2012 to 2013. Study was conducted through the results of monitoring and 3D hydraulic scale model tests. We found that some tetrapods were moved after flood with a semi uniform opening gate both in the field and in the model. On the other hand, when discharging using a uniform opening gate, sand was built up and kept relatively stable with a discharge in a range from approximately 7,200 m³/s to 8,000 m³/s in the model. However, the discharge exceeded 8,000 m³/s that leads free flow with all the gates full opening. It is shown in the discharge operation of Funagira Dam in Figure 16. This period lead the scouring in front of Gates 1 to 4 and of Gate 9 at the foot of emergency measures. Particularly, the left and right banks were largely scoured (downstream of Gates 1, 2, and 9) (Figure 17), referring to the report of J-POWER (2014).

In the situation with emergency measures, the left and right banks can be scoured when water is discharged, even in a uniform opening gate, at a rate of a minimum of 8,000 m³/s. So we have determined that some permanent mitigation measures (hereinafter referred to as “long-term measures”) must be implemented as quickly as possible to obtain the restoration protection.

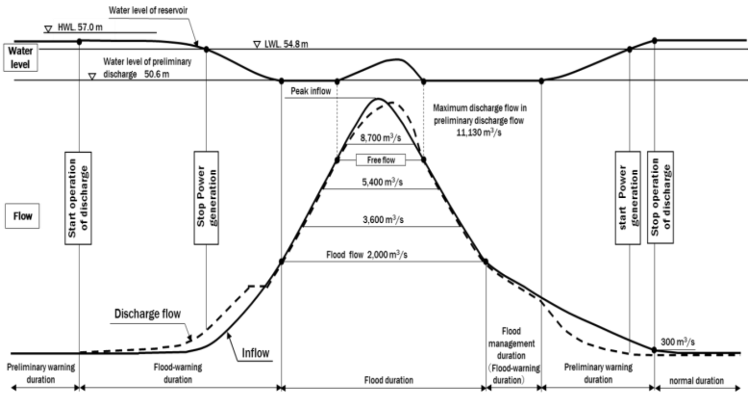


Figure 16. Flood operation of Funagira Dam

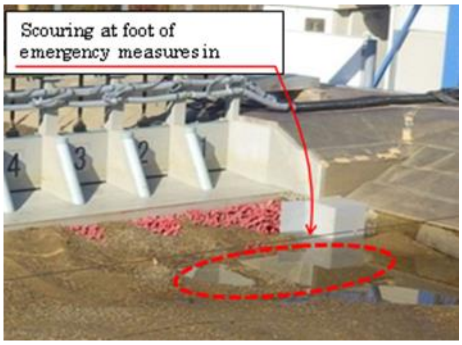


Figure 17. Stability test of emergency measures after design flood with fully equivalent gate operation

4.2 Design of long-term measures

The following shows the design for establishing long-term measures, based on an enhancement of the stability of the emergency measures through various hydraulic scale model tests.

- To reduce possible horizontal swirl flow that can facilitate scouring on the riverbed, switch the gate discharging operation from “semi uniform opening gate” to “uniform opening gate.”
- To carry out measures for preventing scouring on the bedrock on the right bank, above the bedrock, to obtain the same bottom roughness in the lateral direction and to allow laterally uniform flow.
- To take some measures to prevent the riverbed downstream of the dam from being lowered and scoured for a long period.
- To switch the uniform opening gate of gate operation, to be sure to take some measures as required so that the flow of water along the left and right banks and the shape of the riverbed do not change.

5. STUDY OF LONG-TERM MEASURES

5.1 Properties of long-term measures

We have studied to establish long-term measures. They were two measures. One is a “riverbed recovery plan (hereinafter recovery plan)” that is putted back to the original riverbed with bed protection blocks. The other is a “riverbed maintenance plan (hereinafter maintenance plan)” that is carried out reinforcement by blocks on the current riverbed after the emergency measures were taken. Through the study, we took into account the present situation where the downstream water level is lowered. We focused on how the long-term measures can be comprehensively satisfied including management. Figure 18 shows the recovery plan and the maintenance plan.

According to the results of the tests, both plans reduced scouring potential during medium flood. They led to stable results for the safe against scouring close to downstream of the dam. During free flow discharge, the water flow was biased toward the left bank by the sedimentation on the right bank, resulting in local scouring along the left bank. Therefore, although the blocks placed along the left bank downstream of the dam were partially removed, it was considered that the impact was local and did not expand further.

In the tests with a design flood, the recovery plan had an oscillating hydraulic jump instead of a steady jump. The more sediment was deposited along the right bank in this plan. This plan showed some scouring in front of left side of gates, and removal in the protection blocks and the implemented consolidation blocks placed along the left bank (Figure 19).

By the way the maintenance plan also had a morphological change in downstream of the dam. But this plan had a steady hydraulic jump because the present riverbed led as a stilling basin. This plan showed a superior effect during design flood. (Figure 20).

The maintenance plan has finally been chosen as a long-term measure. This plan planned also the shorter construction period, too. The construction has started in October 2015, and second period has started in September 2016 and it will be finished in May 2018.

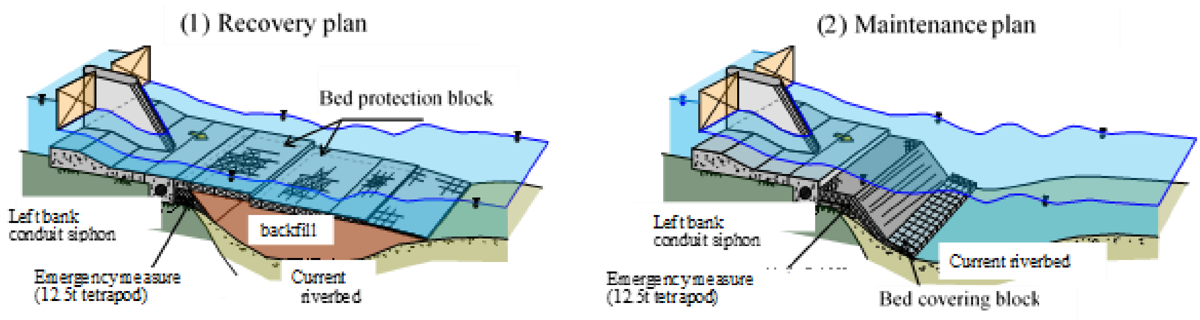


Figure 18. Recovery plan and maintenance plan of long term measures

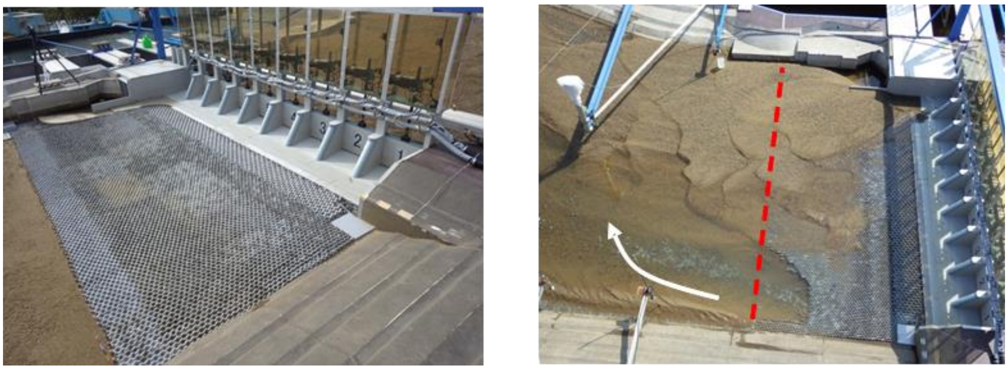


Figure 19. Stability of recovery plan after design flood 11,130m^3/s

Figure 20. Stability of maintenance plan after design flood 11,130m^3/s

5.2 Management of long-term measures

The results of the tests pointed out, for both the recovery plan and the maintenance plan, that sediments were deposited along the right bank. They created a water passage along the left bank, and morphological changes occurred in the implemented consolidation blocks.

The maintenance plan showed especially instability in hydraulic jump positions due to sediment deposits along the right bank. The hydraulic jump positions were shifted upstream and downstream, and caused the water flow to accelerate during discharge reduction. Then the deposits have to been removed to respond to these issues, and the blocks have to been reinforced. Some additional measures have to be taken to comply with this measure as followers:

- To establish of management standards stipulating those including allowable of sediment along the right bank, and height of the riverbed around the river wall along the left bank
- To control of the riverbed by removing of sediment excessively deposited along the right bank, supplying sediment around the river wall on the left bank
- To displace of the river wall itself with implementation of regular inspections, and to reinforce of the river walls on the both side of banks by increasing the width of the consolidation work

The tests were carried for establishing of management standards, and the maintenance plan was modified to be more stable. Figure 21 shows the latest long-term measure design. The field observations of morphological changes is important at the downstream of the dam. Figure 22 shows the morphological change of the riverbed in front of Funagira Dam after starting the uniform opening gate of water discharge on June 2014, referring to the report of J-POWER (2016).

Figure 21. The latest long-term measures in front of Funagira Dam

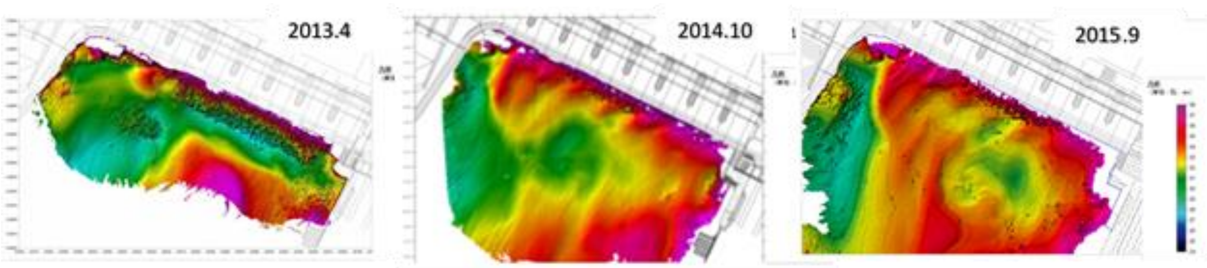


Figure 22. Field observation of morphological changes with multi-beam sonar

6. CONCLUSION

The present paper describes the results of the study on the scouring phenomena that has occurred since Funagira Dam was completed, as well as describes the planned long-term measures that will be taken at the present. To successfully implement the measures, the following points are considered important:

- The hydraulic scale model tests indicate that the scouring was caused by the horizontal secondary swirl with non-equivalent released discharges, and it carries high velocity near riverbed close to downstream of the dam.
- The tests especially indicate that severe scouring would occur not only during the extreme design discharge, but also during small discharges. It is changing the types of hydraulic jump with water level at downstream of the dam.
- The design for establishing long-term measures is to reduce possible horizontal swirl flow by uniform opening gate. It is to carry out measures for preventing morphological riverbed changes for a long period at the riverbed downstream of the dam.

After the measures are taken, it is necessary to review measures, longitudinal changes in the water level downstream of the river, and including the work against the reduction of the water level. If there is a problem to be found, appropriately conduct measures including drastic modifications and reinforcements. This includes checks and reviews for management program and countermeasures.

7. REFERENCES

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