Determining the Depth of Local Scouring in a Downstream Energy Dissipation in the Physical Model Test

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Abstract. Karangnongko Weir is planned to be located in the Bengawan Solo River (Lower Solo River Basin) about 15 km downstream of the confluence of Bengawan Solo River with the Madiun River in Ngelo Village, Margomulyo Sub-District, Bojonegoro Regency, and Ngrawoh Village in Kradenan Sub-District, Blora Regency. This study aims to determine the Depth and pattern of scouring in downstream energy dissipation through physical model tests based on initial planning. Downstream protection of energy dissipation in the original design model combines 50 m of riprap rocks and 50 m of riprap concrete for a total length of 100 m of protection. The maximum scouring pattern occurred at elevation + 17.64 m, where the scouring was 4.36 m deep, from the planned essential height of Height 00 m. Thus, the downstream protection of energy dissipation was extended to 112 m in riprap concrete blocks for the final design model. Scouring at the end of riprap was 3.04 m, the original elevation of the river bottom of + 22.00 m, down to + 18.96 m. It is concluded that the protection is effective in reducing scouring by up to 30.27%.

Keywords: scouring, riprap protection, physical model test

1. Introduction

The problems faced in the design of a spillway are concern the safety of the large flow of water, the source into the uptake, and the energy dissipation [1]. Protection is expected in the design, considering that the dam's construction is funded by capital and has a high chance for good fiscal and social expression [2]. And harm by the kinetic energy of flowing water stored up in the Spillway, which should prevent scouring of the downstream riverbed and failure of downriver structures. The energy dissipation downstream usually is intended to disperse energy from the weir and slow the speed of flowing water to protect downriver watercourse channels from erosion. Thus, the basin is intentionally created to spread the kinetic energy of water stored up to the point of a hydraulic jump. Analysis of the mechanics of the model is needed to examine, judge the form that flow takes from energy dissipation of the weir to the method of escape as it channelizes in the downstream area.

Karangnongko Weir has the planned location of being on the Bengawan Solo River (Lower Solo River Basin) about 15 km downstream of the confluence of the Bengawan Solo River in Madiun, in
Ngelo Village of Margomulyo Sub-District, Bojonegoro Regency, and Ngrawoh Village of Kradenan Sub-District, Blora Regency. As one of the efforts to establish a construction of a weir that is technically feasible, especially in the analytically planned hydraulic aspect, it is necessary to perform a test of the Hydraulic Model Test in the laboratory. By examining the Model Test, it is expected to obtain a weir design that, according to hydraulics, provides the best hydraulic performance from the technical aspect. This model is becoming the underlying objective of this study, as the “Testing the Model Test for the Karangnongko Weir (Off-Stream)”. The Model Test for Karangnongko Weir had gone through various stages of testing, as the preliminary running test for calibration and verification of the model, testing of the Series 0 model (original design), and development test to look for alternative refinements through the stages of the model. The execution of scouring pattern experiments for the Model Test for Karangnongko Weir examined the patterns of basic scouring and sediment deposition that occurred. A large scouring pattern on the section of energy dissipation can cause damage to the structural floor of the energy dissipation. Thus the execution of work on the Model Test is needed to determine the scouring pattern and sediment deposition downstream of the energy dissipation.

The Implementation of testing the Model Test is to determine the scouring pattern in the downstream energy dissipation of the Karangnongko Weir (off-stream). The experiment began with discharge flows of Q2yr, Q5yr, Q20yr, Q50yr, Q100yr, and Q1000yr. The provision of inflow sediment for the execution experiment flows with the stipulation of a flow time of 20 minutes in the model or 3.0 hours in the prototype scale is 1:80. Both outcomes established that existing design approaches might be conservative when practical to significant scour representations, highlighting the need for further inquiry on scale and model results. Moreover, this structure additionally removes the scour protection and decreases Depth. It is ascertained that the flow damages the protective elements of the riverbed [3]. Because the flow depth over time brings out unprotected rocks on the edge of the river, indicating the difficulties of varying flow frequencies and ground protection capacities [4]. Thus, riprap protection for the flow usually is essential. Two ways of installing protective elements are suggested by [5]. One way is to lay rocks to fix the scouring pattern before the apron. The other is to apply stones to improve the scouring pattern after the apron to maintain an equal depth. The problem thus brings out issues related to the design of stable flow protection. In river engineering, the failure of flow protection due to rough structural work is discussed in [6–8].

2. Materials and Methods

2.1. Spillway Hydraulics

The discharge through the gated-radial Spillway can be calculated with the following equation:

\[ Q = \frac{2}{3} \sqrt{2g.b} \cdot C_d \cdot (H^{3/2} - H_1^{3/2}) \]  

(1)

Where:
- \( Q \) = Spillway discharge (m\(^3\)/s)
- \( C_d \) = Coefficient of discharge (m\(^{1/2}\)/s)
- \( L \) = Effective width of the spillway gates (m)
- \( H \) = height of energy on the spillway overflow (m)
- \( H_1 \) = \( H - a \)
- \( a \) = Height of gate openings (m)

2.2. Energy dissipation

The flow phenomenon on the Spillway is that the flow velocity is very high, with the flow condition being supercritical. Therefore, before the water flow is directed to the river, the flow should be slowed down and transformed into the sub-critical flow to prevent scouring that damages the geometry river at its bottom and the river cliffs.
The optimum design for energy dissipation has a greater slope, lower height, aHeightater steps number. Stefan and Hubert [18] studied a moderate slope stepped weir (1 V:2H), and five stepped configurations. The outcomes indicated that the rate of energy dissipation was similar for uniform and nonuniform stepped configurations. However, the nonuniform stepped configurations induced some flow instabilities in the case of low flow rates.

The hydraulic formula utilized as the basis for planning energy dissipation is derived from the principles of the law of conservation of energy with the phenomenon of forces that work on channel nodes for a flow state changing from supercritical flow to subcritical flow.

2.3. Depth of River Flow Scouring in Downstream Energy dissipation
Theoretical calculations and measurements in the hydraulic Model Test on the potential for scouring that occur in the river flow downstream of the energy dissipation are essential to protect the morphology of the river downstream of the energy dissipation. As the object of study in this research, measurements and calculations of scouring potential downstream of the energy dissipation were carried out with various empirical formula approaches, as the following:

Lacey Formula:

\[ R = 0.47 \left( \frac{Q}{f} \right)^{1/3} \]  

Where:
\( R \) = Depth of scouring below the surface of floodwater (m)
\( f \) = Lacey Factor = 1.76 \( D_m \) 0.5
\( D_m \) = Diameter of the mean value for the material of the river bottom (mm)

For the turbulence of unstable flow, \( R \) is increased by 1.5.

Schotlisch Formula (1932):

\[ d_s = S + hd = 4.75 \left( H \cdot 0.2 \cdot q \cdot 0.5 / D_90 \cdot 0.32 \right) \]  

Where:
\( d_s \) = Distance from the deepest point of the scouring hole toward the surface of downstream water (m)
\( S \) = Depth of scouring hole (m)
\( H.D. \) = Depth of downstream water (m)
\( q \) = Discharge unit width (m³/sec/m)
\( D_90 \) = Size of granules where 90% of the material is held (mm)
\( H \) = Vertical Distance of the energy line and the base of energy dissipation (m)

2.4. Riprap
Riprap is implemented where there is the concern that local scouring would occur on the riverbed, taking into account the condition of the riverbed and the resulting flow in both the upstream and downstream, as well as safe construction against flows and will have an energy-dissipating effect. Riprap is consistently implemented on the downstream apron to prevent riverbed scouring. The scouring is due to the removal of deposited silt or the vertical inflow compensation of the local dissipation of water energy.

Bed scouring is a phenomenon resulting from the interaction of the water and soil in the vicinity of hydraulic structures. Its expansion may lead to the destruction and inefficiency of these structures [4]. Given the importance and complexity of this phenomenon, it has been studied by many researchers to identify the affecting parameters, accurately predict the scour Depth, obtain an appropriate measure to control and reduce this phenomenon, and consequently, enhance the safety of the hydraulic structures [15]. The downstream of ski-jump spillways (S.J.S.) is one of the essential parts, where scour control is of great importance. Until now, there have been many reports on the damages of a few ski-jump spillways due to bed scouring.
2.5. Length of Riprap A on the Downstream Side

The length of riprap A downstream should be made to a height that reduces the energy of the flowing water with assured dissipation of power by the apron, which forces the hydraulic jump to occur by the riprap. The hydraulic jump phenomenon is different in form depending on changes in the flow rate, the riverbed slope, and the gap. The perfect hydraulic jump that creates a giant vortex imparts a large force to the riverbed. Therefore, riprap section A should be more significant in length than a perfect hydraulic jump considering the hydraulic phenomenon. In the case of a rapidly flowing river, because the hydraulic jumping length is longer. It is possible to install an assisting structure that dissipates energy and distributes the dynamic water pressure, thereby reducing the Size of riprap section A by the apron, which forces the hydraulic jump to occur (Fig. 1).

![Figure 1. Riprap Detail](image)

2.6. Calculation method for fixed weir

The following formula calculates the length of riprap section A:

\[ L = L_1 + L_2 \]  \hspace{1cm} (4)

Where \( L_1 \) is the hypercritical flow section from the dropping point of the stream to the initial point of the hydraulic jump, and \( L_2 \) is the section where the hydraulic jump occurred.

a. Calculation of water depth at the weir base

\[ \frac{V_c^2}{2g} + \Delta z + h_c = \frac{V^2}{2g} + h_{1a} \]  \hspace{1cm} (5)

Where:
- \( V_c \) = velocity of critical depth (m/sec) = \( q / h_c \)
- \( g \) = acceleration of gravity (m/sec\(^2\))
- \( h_c \) = critical depth (m) = \( (q^2/g)^{1/3} \)
- \( h_{1a} \) = water depth at the dropping point from overflowing (m)
- \( V_{1a} \) = velocity at the weir base (m/sec)
- \( \Delta Z \) = height between crest and apron (m)
- \( q \) = unit width of flood discharge (m\(^3\)/sec/m) = \( Q_d / W \)
- \( Q_d \) = planned flood discharge (m\(^3\)/sec)
- \( W \) = river width (m)

b. Calculation of water depth at the initial point of the hydraulic jump

\[ \frac{h_{1b}}{h_2} = \frac{1}{2} (\sqrt[3]{1 + 8F_r^2} - 1) \]  \hspace{1cm} (6)

Where:
- \( h_{1b} \) = water depth at the initial point of the hydraulic jump
- \( h_2 \) = downstream water depth
- \( F_2 \) = downstream Froude’s number
- \( V_2 \) = downstream velocity

c. Comparison with \( h_{1a} \) and \( h_{1b} \)

- \( h_{1a} = h_{1b} \)
In this case, the hydraulic jump occurs from the dropping point from Overflow. It is assumed that the length of the hydraulic jump section is approximately 4.5 - 6 times the downstream water depth, and the following formula calculates the length of riprap A.

\[ L = L_2 = (4.5 \text{ to } 6) \times h_2 \]

- \( h_{1a} > h_{ib} \)
  - In this case, it is not necessary to install riprap A because the hydraulic jump is submerged. However, it is better to make riprap B longer because jet flow can occur on the riverbed.
- \( h_{1a} < h_{ib} \)
  - In this case, as the initial point of the hydraulic jump moves downstream, it is better to make riprap A longer. Therefore, the length of riprap A is calculated by the following formula.

\[ L = L_1 + L_2 \]

2.7. Structural Engineering of the Riprap

The riprap blocks must resist the force flow and are stable. The Size of each block should satisfy the formula below desirably.

\[ W > 3.75 \frac{AV^2}{2g} \]  

(7)

Where:
- \( W \): weight of each block (t)
- \( A \): area of collision with flowing water (m²)
- \( v \): velocity of the flowing water that collides (m/sec)
- \( g \): acceleration of gravity (m/sec²)

3. Results and Discussions

The Model Test for Karangnongko Weir had gone through various stages of testing, which are the preliminary running test for calibration and verification of the model, testing of the Series 0 model (original design), and development test to seek alternative refinements through the stages of the model. The proposed Final Design Model (off-stream) refinement the Final Design Model (in-stream). The Final Design Model can control and regulate flow conditions following the Planning Guidelines for Hydraulic Structures on various discharge flows (\( Q_{2yr} \), \( Q_{5yr} \), \( Q_{20yr} \), \( Q_{50yr} \), \( Q_{100yr} \), \( Q_{1000yr} \), and \( Q.P.M.F. \)). The intent is for the flow to enter the original river directly.

Karangnongko Weir is an overflow gate with nine gates (B = 11.00 m, \( \max = 11.20 \) m). Gates operation diagram as shown in Figure 2.

Table 1 represents various discharge flows (\( Q_{2yr} \), \( Q_{5yr} \), \( Q_{20yr} \), \( Q_{50yr} \), \( Q_{100yr} \), \( Q_{1000yr} \)) and maximum upstream elevation when the gates are opened.

| Return Period (year) | Flood Discharge (m³/sec) | Max Upstream Elevation (m) | Height of Radial Gate Opening (m) |
|----------------------|--------------------------|---------------------------|----------------------------------|
| Q2                   | 1,564                    | + 40.16                   | 1.52                             |
| Q5                   | 1,876                    | + 40.21                   | 1.76                             |
| Q20                  | 2,260                    | + 40.13                   | 2.40                             |
| Q50                  | 3,992                    | + 39.41                   | 4.96                             |
| Q100                 | 4,324                    | + 39.60                   | 5.52                             |
| Q1000                | 5,584                    | +40.29                    | 7.00                             |

Notes: Maximum Opening = 11.20 m – Gate Condition: Generator Gate Open and Drain Gate Closed – Source: Measurement Results
Operation pattern of the 9 Gates of the Weir (Q.P.M.F.) Alternative 1: Gates 1, 2, 3, 4, 5, 6, 7, 8, 9 operated.

![Diagram of Gate Operation](image1)

**Figure 2.** Diagram of Gate Operation

**Original Design Model Test**

Original Design Model Test (Series 0) weir is a physical model based on the same model scale for vertical and horizontal scales (undistorted model) with a ratio of 1: 80. This model is based on the original design prototype according to the planning drawings. Downstream protection of energy dissipation in the original design model combines 50 m of riprap rocks and 50 m of riprap concrete for a total length of 100 m of protection. Downstream protection of energy dissipation in the original design model is shown in Figure 3.

![Energy Dissipation In The Original Design Model](image2)

**Figure 3.** Energy Dissipation In The Original Design Model

**Scouring Patterns Downstream of the Energy dissipation (Original Design Model)**

The Implementation of the model test determines the scour pattern downstream of the Karangnongko Weirs. Experiments carried out were starting from the flow of discharge $Q_{2yr}$, $Q_{5yr}$, $Q_{20yr}$, $Q_{50yr}$, $Q_{100yr}$, $Q_{1000yr}$, by providing sediment inflow (table 1), which flowed with details of the flow time for 20 minutes in the model or 3.0 hours in the prototype with a scale of 1: 80. The test results of the scour pattern downstream (original design model) are as follows:

| No | Return Period (year) | Depth of Scouring (m) | Elevation of Scouring (m) | Height of Sedimentation (m) | Elevation of Sedimentation (m) |
|----|----------------------|----------------------|--------------------------|---------------------------|-------------------------------|
| 1. | $Q_{2}$ = 1564 m$^3$/sec | 1.16 m               | + 20.84 m                | 2.68 m                    | + 24.68 m                    |
| 2. | $Q_{20}$ = 2260 m$^3$/sec | 3.88 m               | + 18.68 m               | 0.60 m                    | + 22.60 m                    |
| 3. | $Q_{50}$ = 3992 m$^3$/sec | 3.48 m               | + 18.52 m               | -                         | -                             |
| 4. | $Q_{100}$ = 4324 m$^3$/sec | 4.36 m               | + 17.64 m               | -                         | -                             |
| 5. | $Q_{1000}$ = 5548 m$^3$/sec | 5.00 m               | + 17.00 m              | -                         | -                             |
It is necessary to do an analysis related to the calculation of riprap length requirements. Table 2 shows that the maximum scouring pattern occurs at an elevation of + 17.64 m, where the scour that happens is as deep as 4.36 m, from the design base elevation of + 22.00 m. In this condition, it can be concluded that the scour Depth is relatively large, so there is a need for protective buildings to anticipate the possibility of scouring.

**Analysis of the Riprap Length Requirements**

Analysis of the riprap length requirements concrete blocks aims to prevent scouring downstream of the energy absorber apron. The following is the related data:

- Elevation of the Overflow Spillway = 29.00 m
- Elevation of the Bed of the Energy dissipation = 20.00 m
- Spillway Width without Pillars = 99.00 m
- Spillway Width with Pillars = 127.00 m
- \( Q_{100th} \) = 4324.00 \( \text{m}^3/\text{sec} \)

Based on the results of the calculations:

\[
L_j = 60.48 \text{ m} \\
L_A = 63.83 \text{ m} \\
L_B = 47.82 \text{ m} \\
L_j + L_A + L_B = 172.13 \text{ m}
\]

Thus, the necessary length of the riprap according to the calculations becomes:

\[
L_A + L_B = 63.83 + 47.82 \text{ m} \\
= 112.00 \text{ m}
\]

**Analysis of Concrete Block Dimensions**

The following is the calculation of the Size of the concrete blocks with the Ishash equation for the movement of rocks in flowing water:

\[
W > 3.75 \cdot \frac{v^2}{2g} \\
> 3.75 \cdot 4.86^2/2 \cdot 9.81 \\
> 4.51 \text{ tons} \rightarrow 4.50 \text{ tons}
\]

The following is the summary of calculations for the sizes of riprap concrete blocks with the Ishash equation for the movement of rocks in flowing water:

| Return Period (year) | Flow Speed at the End of the Apron (m³/sec) | Water Depth (m) | Froude Number | Weight (tons) | Length of Concrete Blocks (m) |
|---------------------|---------------------------------------------|----------------|---------------|--------------|------------------------------|
| \( Q_2 \)           | 1.57                                        | 6.45           | 0.20          | 0.47         | 0.60                         |
| \( Q_5 \)           | 3.00                                        | 6.88           | 1.72          | 1.72         | 0.90                         |
| \( Q_{20} \)        | 3.08                                        | 7.79           | 0.35          | 1.81         | 1.00                         |
| \( Q_{50} \)        | 4.59                                        | 9.49           | 0.48          | 4.03         | 1.20                         |
| \( Q_{100} \)       | 4.86                                        | 9.79           | 0.50          | 4.51         | 1.30                         |
| \( Q_{1000} \)      | 5.96                                        | 10.45          | 0.59          | 6.80         | 1.50                         |

Based on the above calculations, the required blocks are concrete cubes with a side length of 1.30 m or a weight of 4.50 tons. Concrete Block Riprap Length = 112 m (calculated from the end of the apron)
Scouring Patterns Downstream of the Energy dissipation of Karangnongko Weir (Final Design Model)

The purpose of executing the experiment of scouring patterns for the Model Test of Karangnongko Weir is to study the occurring patterns of basic scouring and sediment deposition. A large scouring pattern on the energy absorber section can cause damage to the structural floor of the energy dissipation. Thus the execution of work on the Model Test is necessary to determine the scouring pattern and sediment deposition downstream of the energy dissipation.

The execution of testing the Model Test was to determine the scouring pattern downstream of the energy dissipation of Karangnongko Weir (off-stream). The conducted experiment began with discharge flows of $Q_{2yr}$, $Q_{5yr}$, $Q_{20yr}$, $Q_{50yr}$, $Q_{100yr}$, and $Q_{1000yr}$, with inflow sediment for the execution of experiment flows, specifically for flow time 20 minutes in the model or 3.0 hours in the prototype with the scale of 1:80. The following are the utilized discharge flows for the Implementation of scouring patterns downstream of the energy dissipation of Karangnongko Weir:

| Return Period (year) | Discharge Prototype ($m^3/sec$) | Discharge Model (l/sec) |
|----------------------|---------------------------------|-------------------------|
| $Q_2$                | 1,564                           | 27.32                   |
| $Q_5$                | 1,876                           | 32.77                   |
| $Q_{20}$             | 2,260                           | 39.48                   |
| $Q_{50}$             | 3,992                           | 69.74                   |
| $Q_{100}$            | 4,324                           | 75.54                   |
| $Q_{1000}$           | 5,584                           | 97.55                   |

The following are the results of experiments of scouring patterns downstream of the energy dissipation for the final design model:

| No | Return Period (year) | Depth of Scouring (m) | Elevation of Scouring (m) | Height of Sedimentation (m) | Elevation of Sedimentation (m) |
|----|----------------------|-----------------------|---------------------------|-----------------------------|-----------------------------|
| 1  | $Q_2 = 1,564 m^3/sec$ | 0.16                  | + 21.84                   | 1.12                        | + 23.12                     |
| 2  | $Q_5 = 1,564 m^3/sec$ | 0.20                  | + 21.80                   | 1.60                        | + 23.60                     |
| 3  | $Q_{20} = 1,564 m^3/sec$ | 0.48                 | + 21.52                   | 2.32                        | + 24.32                     |
| 4  | $Q_{50} = 1,564 m^3/sec$ | 1.76                 | + 20.24                   | 5.20                        | + 27.20                     |
| 5  | $Q_{100} = 1,564 m^3/sec$ | 3.04                 | + 18.96                   | 5.60                        | + 27.60                     |
| 6  | $Q_{1000} = 1,564 m^3/sec$ | 4.40                | + 17.60                   | 6.56                        | + 28.56                     |

Local scouring that occurred at the end of riprap for $Q_{100yr}$ was 3.04 m, by which the original elevation of the bottom of the river of + 22.00 m decreased to + 18.96 m. In this condition, it can be concluded that the occurring Depth of scouring needs to be anticipated with a protective structure in the form of a ground sill with a depth cutoff of at least 5.00 m (Fig. 5), with the elevation of the groundsill threshold being the same as the river bottom elevation of + 22.00 m.

In the present study, the fundamental parameters affecting the scour hole and its Distance from the Spillway were first defined. Important parameters include jet mean flow velocity leaving the Spillway ($V$), tailwater Depth ($Y$), the head difference in water level between the upstream and the downstream of the Spillway ($H$), gravity acceleration ($g$), maximum scour Depth (D.S.S.), the maximum scour Depth...
up to the tailwater level (D), and the Distance of the Spillway to the deepest point of the scour hole (L) (Fig. 4).

**Figure 4.** Diagram of Scouring Depth on the Model Test

**Figure 5.** Diagram of Sediment Height on the Model Test

**Figure 6.** Diagram of Protective Structure in the form of a Groundsill
4. Conclusion
Downstream protection of energy dissipation in the original design model was a combination of riprap rocks of a length of 50 m and concrete riprap of a distance of 50 m, for a total protection length of 100 m. The maximum scouring pattern that occurred was at elevation + 17.64 m. The scouring occurred to a depth of 4.36 m from the planned base elevation of + 22.00 m. Thus, for the final design model, downstream protection of energy dissipation is extended to 112 m in the form of riprap concrete blocks (with a side length of 1.30 m or a weight of 4.50 m). The local scouring that occurs at the end of the riprap is 3.04 m. The original elevation of the river bottom of + 22.00 m decreases to + 18.96 m. The conclusion is that the protection is effective in reducing scouring by up to 30.27 %.

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