Investigation of spillway rating curve via theoretical formula, laboratory experiment, and 3D numerical modeling: A case study of the Riam Kiwa Dam, Indonesia

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Abstract. The spillway rating curve of the Riam Kiwa Dam was investigated via theoretical formula, laboratory experiment, and 3D numerical modeling. It is an ogee type with two uncontrolled and five gated spillways with a total length of 77.5 m. The experiment was performed with a scale of 1:50, while the numerical modeling was conducted using FLOW-3D software. Several discharge values (16.67–2,652.7 m³/s) were tested and observed for two different scenarios of gate openings. For the low discharge in Scenario 1, the theoretical formula and FLOW-3D computed the rating curve less accurately with the error values greater than 10%. A similar phenomenon was observed in Scenario 2, where both theoretical formula and FLOW-3D predicted the rating curve accurately with error values less than 10% for the higher discharge. The discharges tend to be overestimated for the water depth values greater than 2 m giving the average discharge deviation of 6% for the PMF condition. FLOW-3D was found to calculate water depth for all scenarios accurately. It shows a promising approach between numerical simulation and physical modeling, to minimize laboratory model construction costs.

Keywords: 3D numerical modeling, construction cost, spillway

1. Introduction

The Riam Kiwa Dam will be built on the Riam Kiwa River in Indonesia to control the flood and support the irrigation and drinking water systems. The Riam Kiwa Dam is an earthen dam with a total length of 377.8 m and a maximum height of 40 m (from the crest to the downstream toe). The hydraulic structures of the dam consist of two uncontrolled and five gated ogee spillways (with a total length of 77.5 m), intake structure, chute channel, and stilling basin. The dam is designed for the probable maximum flood (PMF) discharge of 1,900 m³/s. The layout of the dam is given in figure 1.

The detailed design study of the Riam Kiwa Dam was conducted in 2018. Based on [1], the detailed calculations for the Riam Kiwa Dam were carried out mostly using the theoretical/empirical equations, e.g., flow over a spillway, discharge through a gate, etc. Fundamentally, such theoretical/empirical equations were developed in a laboratory, thus may be devised with some simplifications. For example, the flow equation over the spillway was developed assuming 1D flow. In other words, the equation does
not consider the effects of expansion and contraction on the water flowing over the spillway. That may exist in the real condition. 
Another example is that the empirical equation does not account for the effect of the turbulence on a stilling basin that may affect the flow condition over the spillway. Therefore, using only the theoretical/empirical equations to design and build a dam in real conditions. Thus, this way should only be considered as a basic engineering design of a dam.

![Figure 1. The layout of the Riam Kiwa Dam (dimension in meter).](image)

In evaluating and optimizing such a basic design, a physical model test has become a standard. Possible mistakes that are not considered by the theoretical/empirical equations can be anticipated. A physical model may be a tool to represent a real-world prototype in finding technical and economical solutions to hydraulic engineering problems. Typically, a physical model is constructed in a laboratory based on dimensional analysis. It indicates a model is similar to the prototype in terms of geometric, kinematic, and/or dynamic similitude. Note that it is not physically possible to obtain a fully dynamic similitude between the model and prototype, especially when using the same fluid. It is therefore important to select the most relevant ratio between the model and prototype [2]. The Froude similitude is typically used in the physical modeling of hydraulic structures because of the significant effect of the gravity force.

In Indonesia, it is obligatory to conduct a physical model test in a laboratory during the design phase of a dam project [3–4]. In the scope of physical modeling, a real-world prototype of a dam is downscaled to a certain value in a hydraulic laboratory. Commonly, such a scale value depends on the availability of the laboratory space, as the main criterion among the others. In other words, the other factors, e.g., the effect of turbulence, may not be considered in selecting the scale value. Because of the scaled model, some different results may be produced due to the scale effects; the lower the scale, the higher the scale
effects, and vice versa [5]. Such scale effects are dissonances emerging from the inequality of the force ratio between the model and prototype, and they cannot be entirely eradicated. Indeed, studies on the investigation of the scale effects in hydraulic physical modeling have not been progressed significantly yet in the past ten years; see some previous works [5–9].

The main objective of this paper is to present a comparison of the results between the theoretical formula, laboratory experiment, and 3D numerical modeling with a focus on the spillway rating curve of the Riam Kiwa Dam. The novelty of this research is the comprehensive investigation of the limitation and benefits of using a 3D numerical model for designing a spillway. Where it is still rarely investigated synchronously with physical modeling conducted in the laboratory. Because it is compulsory to conduct the physical modeling for dam projects in Indonesia, simultaneously performing the numerical and physical modeling is beneficial to optimize the designing phases of the projects.

The theoretical formula employed is the empirical equation of flow over a spillway that has been used in many textbooks. This equation is a function of the effective length of the spillway, the water depth above the spillway crest, and the discharge coefficient. For numerical computations, the FLOW-3D model is used to predict flow behavior. With the recent advances in computer processing power, this model can simulate the flow over the spillway on a prototype scale. Furthermore, it provides the flow properties, i.e., water depth and velocity, for the entire domain. It helps the users study the flow behaviors in detail, even for several different scenarios. This study will reveal a promising approach to combine a numerical simulation with physical modeling to investigate the flow behaviors over hydraulic structures. It can minimize the laboratory model's construction cost.

2. Materials and methods
This section describes the materials and methods used in this paper, such as the details of the physical model, empirical formula, and FLOW-3D model.

2.1. Physical model
The undistorted fixed model of the spillway was constructed in the hydraulic laboratory of the Experimental Station for Hydraulic and Geotechnics, Ministry of Public Works, and Housing Indonesia. The sketch of the physical model configuration is shown in figure 2. The model was built based on the dimensional analysis that aims to compute the dimensionless quantity. Adopting the Froude similarity, the laboratory model was constructed with a scale of 1:50 due to the space availability. The scaling used in the physical modeling is written in table 1. Note that the variable \( n_h \) denotes the base scale factor for the height.

| Hydraulic Parameters | Notation | Factor |
|----------------------|----------|--------|
| length, height       | \( L, h \) | \( n_L = n_h = 50 \) |
| velocity             | \( v \)   | \( n_v = n_h^{1/2} = 7.07 \) |
| discharge            | \( Q \)   | \( n_Q = n_h^{5/2} = 17,677.67 \) |
| Manning coefficient   | \( n \)   | \( n_n = n_h^{1/6} = 1.92 \) |
| volume               | \( V \)   | \( n_V = n_h^{3} = 125,000 \) |

In this study, two scenarios were applied. Scenario 1 is where all the gates are closed, while Scenario 2 is where all gates are open. Based on [1], the technical data and flood discharge designed for the Riam Kiwa Dam are given in table 2 and table 3, respectively.
Figure 2. The physical model of the spillway of the Riam Kiwa Dam.

Table 2. Technical data of the Riam Kiwa Dam.

| Feature                          | Value                        |
|---------------------------------|------------------------------|
| Length of dam                   | 377.8 m                      |
| Height of dam                   | 40 m                         |
| Width of the dam crest          | 8 m                          |
| Spillway type                   | ogee                         |
| Spillway crest elevation        | +145.5 m (5 gated) and +150 m (2 ungated) |
| Length of spillway              | 77.5 m                       |
| Bottom elevation                | +106 m                       |
| Downstream sill elevation       | +110 m                       |

Table 3. Design discharge.

| Return Period | Discharge (m³/s) |
|---------------|------------------|
| 2 years       | 15.1             |
| 25 years      | 74.5             |
| 50 years      | 104.7            |
| 100 years     | 141.4            |
| 1000 years    | 823              |
| PMF           | 1,900            |
2.2. Empirical formula
The flow over a spillway can be sketched in figure 3. The discharge through the spillway is estimated using the empirical equation as follow

\[ Q = CBH^{1.5} \]  

where \( Q \) is the flow discharge (m\(^3\)/s), \( C \) is the discharge coefficient (2.1), \( B \) is the spillway length (m), and \( H \) is the total energy head (m).

![Figure 3. Sketch of flow over a spillway.](image)

2.3. Numerical model: FLOW-3D
FLOW-3D is used in this study as it can simulate the complicated 3D fluid flow behaviors with complex geometries. FLOW-3D was developed to solve the Navier-Stokes equations for free surface flows using the volume of fluid (VOF) technique. In general, this model computes numerically the motions of fluids that are of 3D transient problems. Such motions are described as non-linear second-order differential equations. By using the algebraic expressions, the solutions of such differential equations are approximated for various terms. The modeling processes are typically started from building the computational mesh. It is a very important step in maintaining the accuracy of the numerical model. The physical space is divided into small volumes with several nodes. These nodes are assigned to store the flow values, i.e., pressure, temperature, and velocity.

The Renormalization Group (RNG) method in the FLOW-3D module was chosen to simulate the turbulence properties. This method is categorized into the Reynolds-averaged Navier–Stokes (RANS) turbulence model. It spatially and temporally does not disintegrate the turbulent structures. However, it uses the turbulent kinetic energy approach. Therefore, this model is limited by the adverse pressure gradient. It will not perform well when such a gradient becomes larger. For the sake of brevity, the details of the governing equations and the numerical approaches used in FLOW-3D are not discussed here; thus interested readers may refer to [10–13].
3. Results and discussions

The hydraulic structures investigated in the physical modeling consist of the spillway, chute channel, stilling basin, and downstream river bathymetry. A pump with a total capacity of 7.6 l/s was used in the laboratory. A v-notch weir was used to measure the discharge flowing to the reservoir. Along the chute channel, both depth and velocity measurement data were collected. The flow depth was measured with an analog point gauge, whereas the flow velocity was measured with a laboratory digital current meter. It can be ensured that the accuracy of the measurement instruments was less than 1 mm and 0.007 m/s for the depth and velocity data, respectively. It corresponds to 0.05 m and 0.049 m/s in the prototype. For all the results, the error is computed as:

\[
\text{Err} (%) = \frac{|Q_a - Q_b|}{Q_b}
\]

where the variable \( \text{Err} \) is the error, \( Q_a \) is the discharge obtained either by using the empirical formula or FLOW-3D, and \( Q_b \) is the observed discharge.

A 3D geometry file involving the spillway, chute channel, and stilling basin was extracted from the CAD drawing for the numerical model. In general, a CAD model consists of different types of topological entities such as solids, faces, edges, and vertices. A rectangular fixed grid was generated in the meshing process. Rectangular cells are used for all simulations in this study as they are easy to generate. In addition, it is easy to store the computational results using rectangular cells due to their structured nature. This study used a total of 2,061,329 cells with 0.1 m size for the numerical simulations. The Riam Kiwa Dam design discharges were set as the upstream boundary condition, while for the downstream boundary conditions, the water levels of the downstream river were employed. Note that FLOW-3D was only employed in this work for the prototype simulations; thus the scale effects are not considered (as they are not the main objective of this work). The model setup in FLOW-3D is sketched in figure 3. Note that the cells shown in figure 3 are of a 2 m size, only for the sake of visualization.

![Figure 4. Mesh setup in FLOW-3D.](image)

Two scenarios are applied in this work. First, it is a condition where all gates are closed. In other words, the water flows only over two uncontrolled spillways with a crest elevation of +150 m. The discharge values tested in this scenario were up to 500 m$^3$/s. The second scenario is a condition where all gates are open. In this scenario, the water flows over the two aforementioned uncontrolled spillways and five controlled spillways with a crest elevation of +145.5 m, where the discharge values tested were
up to 2,500 m$^3$/s. The discharge rating curves obtained from the experiment, theoretical formulas, and numerical results of FLOW-3D are shown in figure 5 for all scenarios. The computation summary is given in table 3 and table 4 for Scenario 1 and 2, respectively. Note that the values for the experiment are shown for the prototype.

![Scenario 1 (all gates are closed)](image1)

![Scenario 2 (all gates are open)](image2)

Figure 5. Discharge rating curve for Scenario 1 and Scenario 2.

As shown in figure 5 and table 3, in Scenario 1, the theoretical formula computes the discharge value of 14.85 m$^3$/s for the water level of 150.5 m, corresponding to an error value of 11%. Meanwhile, for the same water level, FLOW-3D calculates the discharge value of 18.77 m$^3$/s, which indicates an error of 13%. For the water level of 152 m, the theoretical formula gives the discharge value of 118.79 m$^3$/s, while FLOW-3D yields 119.69 m$^3$/s. It corresponds to a similar error value, 22% and 23%, for the theoretical formula and FLOW-3D, respectively. For the water level of 155 m, the theoretical formula
computes the discharge value of 469.57 m³/s, while FLOW-3D gives 528.04 m³/s. It leads to 6% and 2% error values for the theoretical formula and FLOW-3D, respectively. From table 4, one can also see that for Scenario 1, the theoretical formula and FLOW-3D become more accurate in simulating the higher discharges, indicated by the average error values of 11% and 10%, respectively.

Table 4. Summary of Scenario 1.

| Water level (m) | Discharge (m³/s) | Error |
|----------------|------------------|-------|
|                | Experiment | Theoretical | FLOW-3D | Theoretical | FLOW-3D |
| 150.0          | 0         | 0           | 0       | 0           | 0       |
| 150.5          | 16.67     | 14.85       | 18.77   | 11%         | 13%     |
| 151.0          | 34.64     | 42.00       | 41.81   | 21%         | 21%     |
| 151.5          | 61.21     | 77.16       | 73.36   | 26%         | 20%     |
| 152.0          | 97.65     | 118.79      | 119.69  | 22%         | 23%     |
| 152.5          | 152.67    | 166.02      | 164.45  | 9%          | 7%      |
| 153.0          | 209.76    | 218.24      | 215.56  | 4%          | 3%      |
| 153.5          | 270.73    | 275.01      | 277.24  | 2%          | 2%      |
| 154.0          | 331.70    | 336.00      | 337.67  | 1%          | 2%      |
| 154.5          | 388.00    | 400.93      | 401.88  | 3%          | 4%      |
| 155.0          | 442.30    | 469.57      | 449.14  | 6%          | 2%      |
|                | MAX       | 26%         | 23%     |
|                | MIN       | 1%          | 2%      |
|                | AVG       | 11%         | 10%     |

Table 5. Summary of Scenario 2.

| Water level (m) | Discharge (m³/s) | Error |
|----------------|------------------|-------|
|                | Experiment | Theoretical | FLOW-3D | Theoretical | FLOW-3D |
| 145.5          | 0         | 0           | 0       | 0           | 0       |
| 146.0          | 23.43     | 31.55       | 32.06   | 35%         | 37%     |
| 146.5          | 63.46     | 89.25       | 84.91   | 41%         | 34%     |
| 147.0          | 134.06    | 163.96      | 151.19  | 22%         | 13%     |
| 147.5          | 220.00    | 252.44      | 226.01  | 15%         | 3%      |
| 148.0          | 320.00    | 352.79      | 329.70  | 10%         | 3%      |
| 148.5          | 425.00    | 463.76      | 433.39  | 9%          | 2%      |
| 149.0          | 540.38    | 584.40      | 546.68  | 8%          | 1%      |
| 149.5          | 674.96    | 714.00      | 673.90  | 6%          | 1%      |
| 150.0          | 809.54    | 851.98      | 804.79  | 5%          | 1%      |
| 150.5          | 982.30    | 1,012.69    | 977.74  | 3%          | 1%      |
| 151.0          | 1,173.08  | 1,193.20    | 1,150.70| 2%          | 2%      |
| 151.5          | 1,400.00  | 1,388.86    | 1,376.84| 1%          | 2%      |
| 152.0          | 1,650.00  | 1,597.83    | 1,609.58| 3%          | 2%      |
| 152.5          | 1,900.00  | 1,818.95    | 1,870.02| 4%          | 2%      |
| 153.0          | 2,150.90  | 2,051.40    | 2,157.87| 5%          | 1%      |
| 153.5          | 2,401.80  | 2,294.51    | 2,445.71| 4%          | 2%      |
| 154.0          | 2,652.70  | 2,547.75    | 2,733.56| 4%          | 3%      |
|                | MAX       | 41%         | 37%     |
|                | MIN       | 1%          | 1%      |
|                | AVG       | 10%         | 6%      |

In figure 5 and table 5, one can see in Scenario 2 that for the water level of +146 m, the theoretical formula calculates the discharge value of 31.55 m³/s that corresponds to an error value of 35%. FLOW-3D, for the same water level, computes a slightly higher discharge value of 32.06 m³/s, corresponding
to an error value of 37%. Interestingly, for the water level of +147.5 m, FLOW-3D becomes significantly more accurate than the theoretical formula, where the values of 226.01 m$^3$/s and 252.44 m$^3$/s are produced by FLOW-3D and the theoretical formula, indicating the error values of 3% and 15%, respectively. For the higher water level of +154 m, the theoretical formula computes a lower discharge value of 2,547.75 m$^3$/s, whereas FLOW-3D calculates a higher 2,733.56 m$^3$/s. It leads to 4% and 3% error values for the theoretical formula and FLOW-3D, respectively. The results of Scenario 2 in table 4 show that FLOW-3D is generally more accurate than the theoretical formula, indicated by the average error values of 6% and 10%, respectively. Figures 6 and 7 show the flow view over the spillway crest in the experiment (Scenarios 1 and 2) and the FLOW-3D numerical. Visually, the numerical results show similar flow characteristics to the experimental ones.
Figure 7. Scenario 2: View of flow over the spillway crest: experiment (upper) and FLOW-3D (lower)

Scenario 1 indicates that for low discharge values (the water depths above the spillway crest of up to 2 m), neither theoretical formula nor FLOW-3D is quite accurate in predicting the discharge rating curve. It is indicated by an error greater than 10%. Surprisingly, the theoretical formula and FLOW-3D become more accurate in predicting the discharge rating curve for the water depths above the spillway crest greater than 2 m by producing less than 10% errors. The results in Scenario 2 show a similar characteristic to the ones in Scenario 1. It is especially for low discharge values (the water depths above the spillway crest of up to 1.5 m). None of the theoretical formulas and FLOW-3D can accurately predict the discharge rating curve, with less than 10% errors. FLOW-3D becomes significantly more accurate than the theoretical formula for the water depth above the spillway crest within the range of 1.5–4.5 m. Afterward, both theoretical formula and FLOW-3D show similar characteristics that accurately predict the discharge rating curve for the water depths above the spillway crest greater than 4.5 m, with errors below 10%. The results may perceive that FLOW-3D is not sufficiently accurate for the flow simulation over the spillway. However, in another perspective, the inaccuracy can be caused by the scale effects not considered yet in the physical model.
The values measured in the experiment are of the model scale and directly upscaled to the prototype one proportionally with the scale determined. It may constitute inequality of the force ratios between the prototype and model. Hypothetically, these scale effects exist in the Froude similitude applied to the physical model so that the flow variables must be limited to a certain value. Another reason may be the accuracy and limitations of the analog point gauge used as the measurement tool in the experiment. However, all these assumptions have not been studied yet in this work and thus need to be investigated further.

4. Conclusion
A study investigating the comparison of the rating curve via theoretical formula, laboratory experiment, and 3D numerical modeling has been presented for a case study of the Riam Kiwa Dam, Indonesia. The physical model was built in the laboratory with a scale of 1:50, adopting the Froude similarity. Two scenarios were considered, i.e., all gates were closed and open. For the low discharge in Scenario 1, the theoretical formula and FLOW-3D computed the rating curve less accurately with the error values greater than 10%. For the higher discharge, both the theoretical formula and FLOW-3D could accurately predict the rating curve with less than 10% error values. A similar phenomenon was observed for the low discharge in Scenario 2, where both theoretical formula and FLOW-3D predicted the rating curve less accurately with the error values greater than 10%. However, for the higher discharge, FLOW-3D became significantly more accurate than the theoretical formula. The scale effects cause the inaccuracy for the upscalling calculation from the model scale to the prototype one. However, needs to be investigated in the future study. A simpler-yet-accurate non-hydrostatic shallow water model developed in [14] will also be used for future studies.

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