

Designing Labyrinth Spillways for Less than Ideal Conditions

Real World Application of Laboratory Design Methods

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Abstract – Complications are often encountered when applying empirical laboratory design methodologies for labyrinth spillways to real-world applications. In particular, real-world applications often do not replicate the ideal flow conditions created in laboratory models and must account for irregular conditions such as curved approaches, bridge decks and piers, non-prismatic channels, and unusual tailwater conditions. These irregular conditions can have significant adverse impacts on the performance of the spillway. By applying a combination of published laboratory design data, engineering judgment, and detailed hydraulic computer modeling, economical and reliable labyrinth spillway designs can be achieved.

The purpose of this paper is to share lessons learned and an approach to apply empirical laboratory design information for labyrinth spillways to unusual real-world applications. The recent design of the labyrinth spillways at Lake Scranton Dam and Lake Isabella Dam will be used as examples to illustrate the process. The authors will also share recommendations for designers considering labyrinth spillways in less than ideal conditions.

I. INTRODUCTION

Complications are often encountered when applying empirical laboratory design methodologies for labyrinth spillways to real-world applications. In particular, real-world applications often do not replicate the ideal flow conditions created in laboratory models. Designs must account for irregular conditions such as curved approaches, bridge decks and piers, non-prismatic channels, and unusual tailwater conditions. These irregular conditions can have significant adverse impacts on the performance of the spillway.

II. MODERN SPILLWAY DESIGN TOOLS

Engineers have a variety of tools that can be used in conjunction with empirical laboratory methods to account for these irregular conditions and ensure the adequacy of a design. For example, three-dimensional (3D) Computational Fluid Dynamics (CFD) software or physical modeling can be used to estimate the head-discharge relationship of a specific labyrinth spillway design. In some cases, two-dimensional (2D) hydraulic modeling software can also be useful in analyzing the effects of spillway approach hydraulics or tailwater conditions.

In using these tools for spillway design, it is important to understand the limitations of the different types of hydraulic models. Generally speaking, physical models are more accurate than numerical models if the scale of the model is sufficiently large. Numerical models (2D/3D) can be accurate, but require means of validation or calibration. Even without calibration, numerical models can also be used as comparative tools to optimize spillway geometry and configuration.

III. RECOMMENDED DESIGN PROCESS

Ideally, the design process for a labyrinth spillway would consist of multiple phases of hydraulic modeling in an effort to decrease uncertainty in the design as follows:

1. Use published laboratory data to develop a preliminary design [1]. Unusual conditions can be conservatively accounted for if practicable.
2. Use CFD modeling to fine tune the design and understand the impacts of irregular hydraulic conditions.
3. Use a physical model to confirm performance and provide calibration of the numerical CFD model.

One example of a spillway design that followed this approach was the U.S. Army Corps of Engineers' (USACE) Lake Isabella Dam spillway renovation project which consisted of constructing a new 3,149 foot long arced labyrinth. Initially, USACE engineers designed the spillway using research published by Dr. Blake Tullis and his students. They then developed a CFD model of the proposed labyrinth and refined the design. This numerical model was then calibrated using a 1:45 scale physical model that was constructed at the Utah Water Research Laboratory as part of the final design effort (See Figure 1).

While this is the ideal, an appropriate approach to labyrinth spillway design and verification must be tailored to each individual project taking into account project goals, uncertainties, and risk tolerance. In some cases, it may make sense to accept the uncertainty associated with an uncalibrated CFD model as long as a greater degree of conservatism is incorporated in the final design. The following section summarizes a case study where this was the case. By applying a combination of published laboratory design data, engineering judgment, and detailed hydraulic modeling, economical and reliable labyrinth spillway designs can be achieved.



Figure 1. 1:45 scale physical model of the Lake Isabella arced labyrinth spillway at the Utah Water Research Lab (Photo by John Prettyman, U.S. Army Corps of Engineers)

IV. CASE STUDY: LAKE SCRANTON DAM REHABILITATION

The recent design of the labyrinth spillway at Lake Scranton Dam is an example of this design process and how it can be adapted to an individual project. Lake Scranton Dam is a composite masonry gravity/earthfill embankment dam built in 1898 in Lackawanna County, Pennsylvania (See Figure 2). In 2014, Pennsylvania American Water authorized the design of rehabilitation measures to bring the dam into compliance with current design standards and regulations. A primary objective of this rehabilitation effort was to increase the spillway capacity to accommodate the Probable Maximum Flood (PMF).

In order to achieve this, a portion of the existing reinforced concrete ogee crest spillway (See Figure 3) will be replaced with a labyrinth spillway. The discharge capacity of the proposed composite spillway was estimated using the latest published labyrinth and ogee weir design data. However, multiple features of the spillway deviate significantly from the idealized laboratory geometry upon which the design methods are based. Some of these features include:

- Varying and imbalanced approach flow conditions,
- Localized obstruction of flow caused by bridge low chord,
- Obstruction of flow caused by bridge piers,
- Labyrinth orientation projecting into the reservoir (rather than channelized as tested in the lab), and
- Varying exit channel configuration and potential for tailwater submergence.



Figure 2. Masonry section of Lake Scranton Dam.



Figure 3. Existing ogee crest spillway at Lake Scranton Dam.

In estimating the discharge capacity of the proposed spillway based upon empirical methods, conservative assumptions were made regarding the effective length of both the ogee and labyrinth weirs to account for flow separation around the piers and abutments. Ultimately, CFD modeling using Flow-3D software was used to refine the labyrinth design and confirm spillway performance since the spillway design deviates significantly from the laboratory method's geometry (See Figures 4 and 5).

The design was further complicated by the need to integrate the labyrinth within the footprint of an existing bridge, maintain the structural integrity of the existing bridge, avoid areas with poor foundation conditions, and match the existing condition 100-year peak outflow. Multiple labyrinth weir design and configurations were analyzed to identify the most efficient and cost-effective alternatives. The optimal design consists of replacing the majority of the existing ogee spillway with a five-cycle labyrinth weir (See Figures 6 and 7). Two of the cycles will work in conjunction with the remaining portion of the existing ogee and act as a "principal spillway" to maintain normal pool and pass lower frequency floods. The three additional cycles act as an "auxiliary spillway" and will be activated at the 100-year flood frequency.

The CFD model was used to confirm the discharge capacity of the spillway, and results were within five percent of the discharge capacity estimated using the empirical laboratory method. The numerical model was also used to investigate the impacts of several features in the surrounding terrain. In some cases, the model was used as a comparative tool to design improvements to the proposed grading in the vicinity of the spillway. The areas of concern that were analyzed or identified using CFD include:

- Spillway Approach – CFD of the proposed spillway showed an area of ineffective weir length during the design flood on the far left labyrinth cycle. This ineffective area was caused by a small projection of land into the reservoir upstream of the spillway. Proposed grading was modified to eliminate this projection, and CFD was used to verify improved hydraulic efficiency with the proposed grading.
- Downstream Channel – Initial CFD model runs indicated that during the PMF, significant local tailwater would partially submerge several of the labyrinth cycles, thereby reducing their discharge capacity. A downstream channel was designed to eliminate tailwater submergence effects on the hydraulic efficiency of the labyrinth weir, and CFD was used to verify improved hydraulic efficiency with the proposed grading.
- Bridge Low Chord – At the right spillway abutment, the low chord of the existing bridge is slightly lower than the maximum pool elevation. CFD was used to verify the assumption that the impact of the bridge low chord on discharge characteristics of the spillway is negligible.

Following refinement and confirmation of the spillway design using CFD, Pennsylvania American Water elected to accept the spillway design without completing a physical model. This decision was made based on a number of considerations including:

- The relative agreement in discharge capacity estimates between the numerical and analytic approaches (less than five percent difference),
- Acknowledgement that the hydrologic methods used to develop the design flood are conservative, and further refinement of the spillway rating curve would result in negligible reductions in risk, and
- Limited opportunities to further refine or modify the spillway design to reduce construction costs given the site constraints.

The proposed modifications to the existing dam and spillway are currently under construction and are anticipated to be complete in 2018.

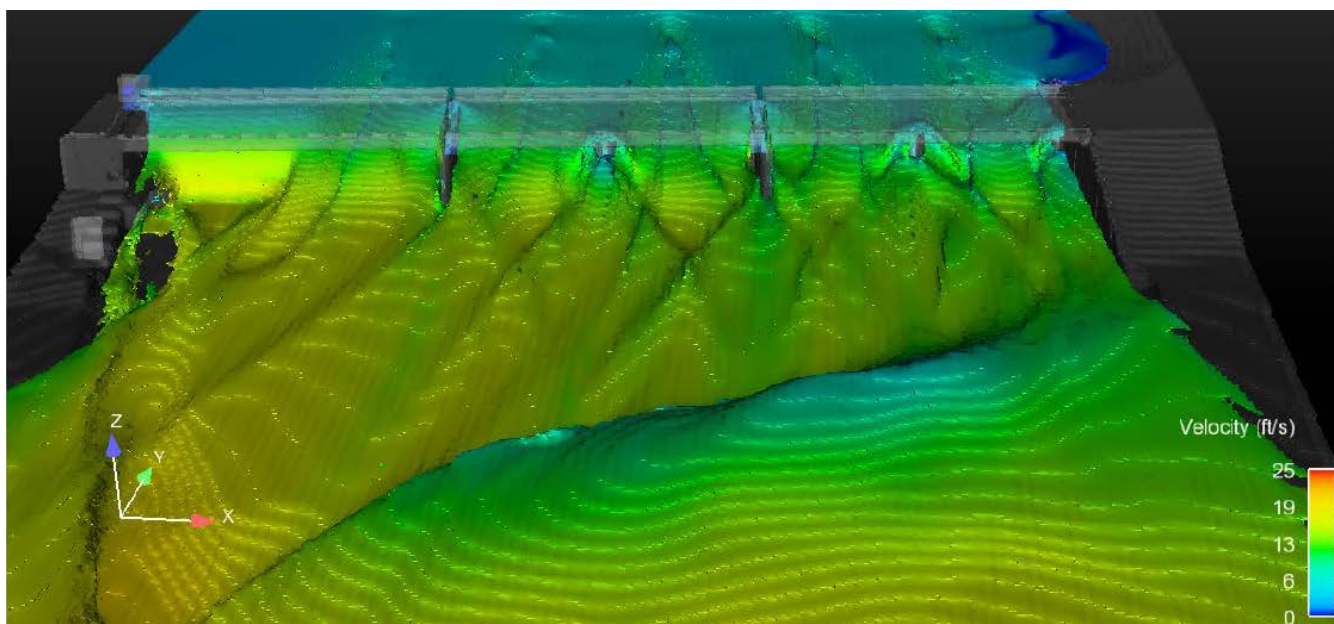


Figure 4. View looking upstream of CFD model results for proposed Lake Scranton spillway during the design flood (PMF).

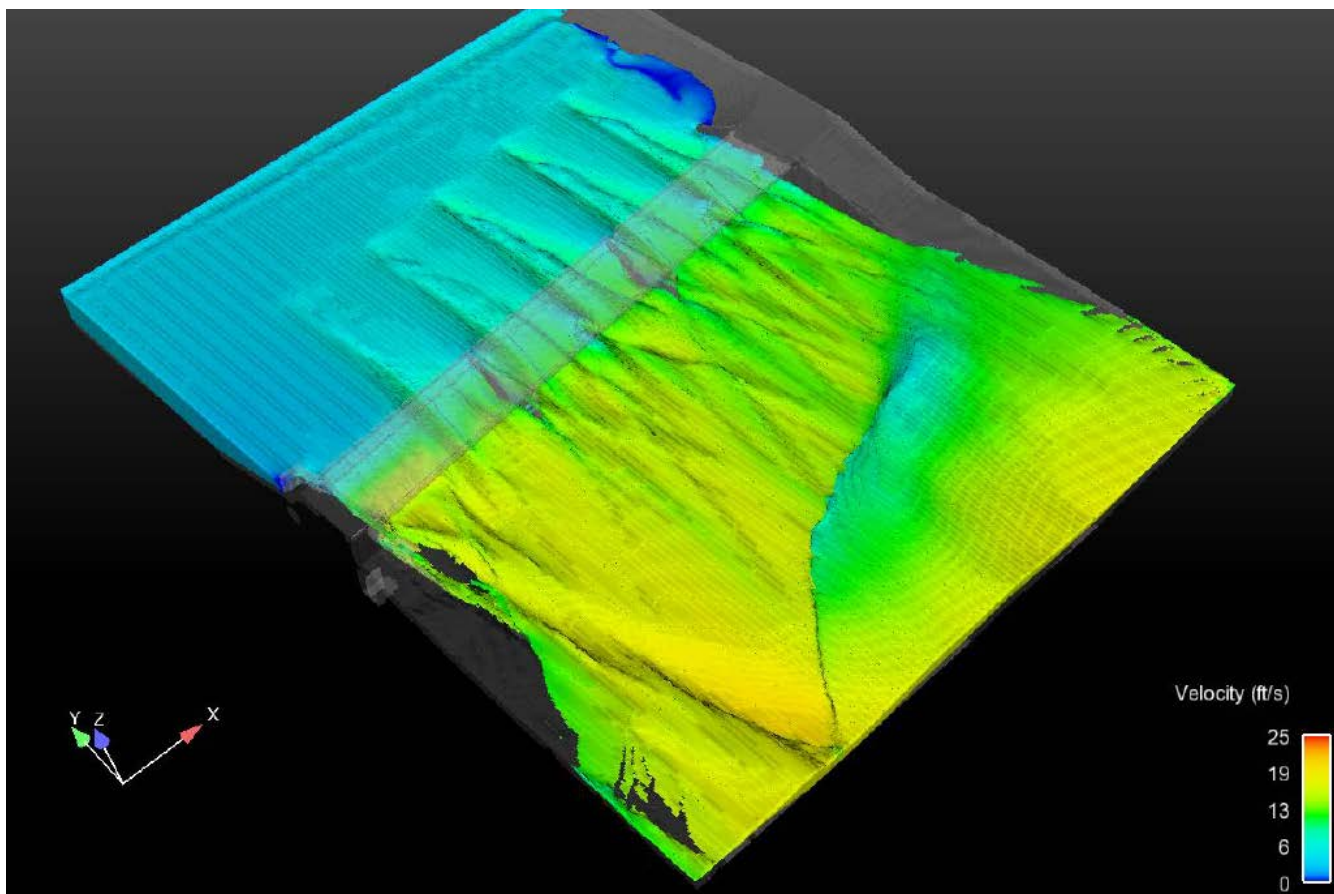


Figure 5. Overview of CFD model results for proposed Lake Scranton spillway during the design flood (PMF).

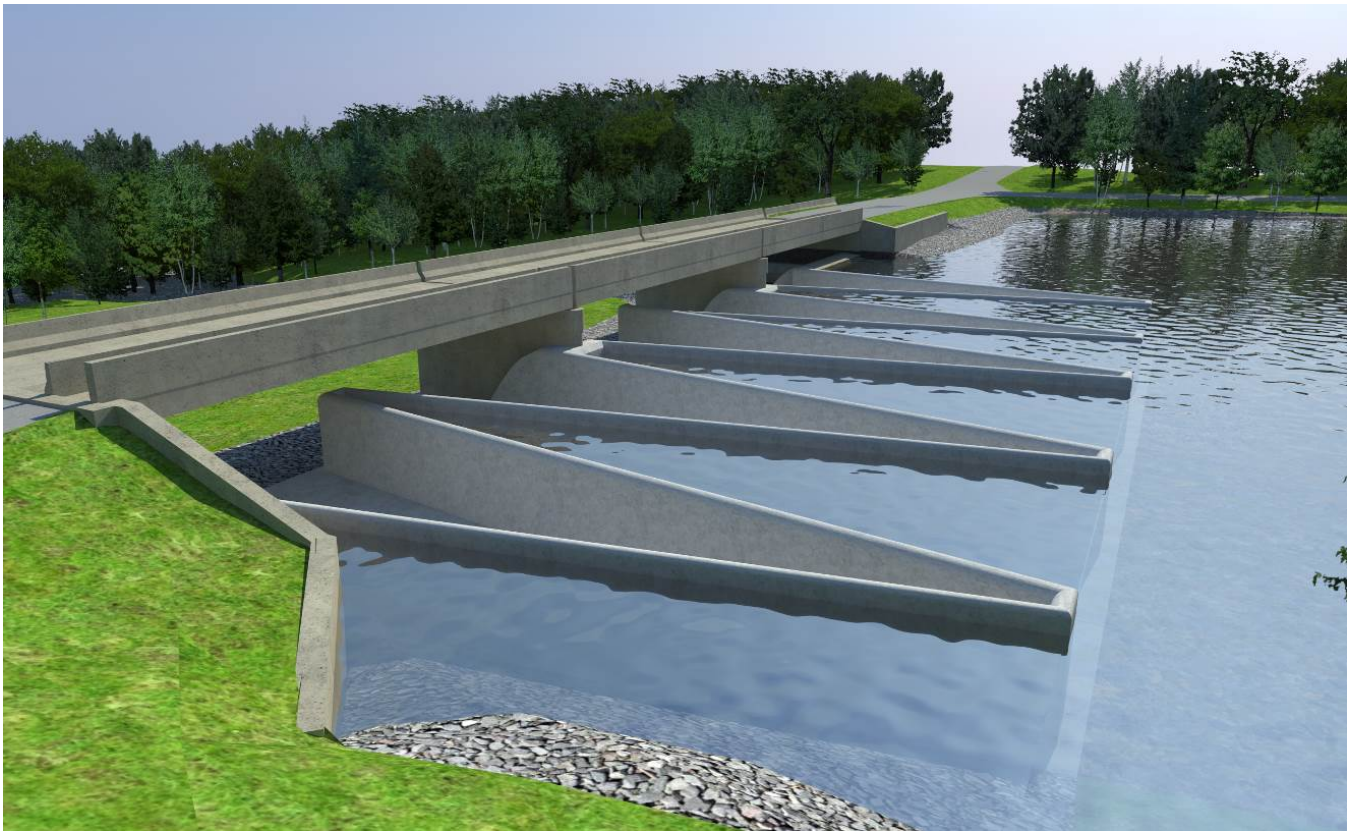


Figure 6. Rendering of proposed labyrinth/ogee spillway at Lake Scranton Dam.



Figure 7. Rendering of proposed labyrinth/ogee spillway at Lake Scranton Dam.

V. CONCLUSION

Real-world application of labyrinth spillway design methods often do not replicate the ideal flow conditions created in laboratory models and must account for irregular geometries and hydraulic conditions. These irregular conditions can have significant adverse impacts on the performance of the spillway. Fortunately, engineers have a variety of tools that can be used in conjunction with empirical laboratory methods to account for these irregular conditions and ensure the adequacy of a design.

An appropriate approach to labyrinth spillway design and verification must be tailored to each individual project taking into account project goals, uncertainties, and risk tolerance. By applying a combination of published laboratory design data, engineering judgment, detailed hydraulic computer modeling, and in some cases physical modeling, economical and reliable labyrinth spillway designs can be achieved.

VI. REFERENCES

1. Crookston, B.M. and B.P. Tullis, 2013. Hydraulic Design and Analysis of Labyrinth Weirs. I: Discharge Relationships. *Journal of Irrigation and Drainage Engineering* (2013.139:363-370). American Society of Civil Engineers.

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