How to Ensure Spillway Efficacy and Safety at Hydropower Dams

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Introduction

Because of increasing awareness over aging infrastructure and efforts to increase renewable energy generation cost effectively, hydropower has been receiving a lot of attention. In the U.S., the average age of dams is 40 years[i] . Currently there are 24 states plus the District of Columbia that have Renewable Portfolio Standards (RPS) policies in place, ranging from 4% to 23% in renewable energy generation requirements. Four other states have nonbinding goals for adoption of renewable energy instead of an RPS[ii]. The recent U.S. American Recovery and Reinvestment Act of February, 2009 provides additional incentives to develop hydropower.

In North America, the focus is not on building new dams, but rather on improving efficiency and power output from existing structures. Nonetheless, spillway performance is increasingly an area of concern for all dam owners and operators. There are two major drivers for this attention on spillways: more stringent flood design requirements and environmental pressures for fish passage.

Flood Design Requirements

When most of the modern hydroelectric dams around the world were built during the last century, flood records were relatively short and little was understood about the hydrology of flood prediction at that time. Additionally, the lack of experience with dam failures limited best practice design knowledge. Science and policy began to change in the U.S. during the 1970's, beginning with the National Dam Inspection Act in 1972, which mandated inspections of dams under their jurisdiction. Later, in 1977, President Carter appointed an interagency committee on dam safety (ICODS) resulting in a 1979 report with the first guidelines for federal agency dam owners. Work on the guidelines continued for another twenty years, and ICODS began an update to these guidelines in 1994 to meet new dam safety challenges and to ensure consistency across all agencies and users. The National Dam Safety Program Act of 1996, Public Law 104-33 incorporated modern hydrology and flood prediction methods. The final step in the review and update process was completed in 1998 with the "Federal Guidelines for Dam Safety."

Under the U.S. National Dam Safety Program, the states have certain authorities for all jurisdictional dams (34,750 dams with an impoundment exceeding 50 acre-ft or with an embankment height greater than 25 ft and excluding all dams with embankments less than 6 ft.). These authorities include: (1) reviewing and requiring modifications and approving plans to construct dams; (2) performing periodic inspections of construction; (3) issuing licenses to operate; (4) investigating each dam at least every 5 years; (5) issuing orders as needed to correct deficiencies; (6) adopting rules; and (7) requiring emergency action plans. Federally owned and operated dams fall outside of this jurisdiction

Given the raised awareness of flood danger to dams, and concerns about recent severe events, most states in the U.S. now require that dams be designed to withstand a percentage of the Probable Maximum Flood (PMF), which represents an estimate of the upper limit of run-off to be considered when determining the inflow design for a dam. The PMF is the flood flow calculated as run-off from the Probable Maximum Precipitation (PMP). The percentage of the PMF for which the spillway must be designed will depend upon the value of threatened property and upon the number of lives in danger if the dam were to fail. Sometimes, updated risk-based analyses taking newly calculated PMF's and updated property and population data into account represent a more severe flood than the 100 year or 500 year flood that many older dams were designed to withstand.

As an example of the possible dangers posed by record floods and insufficiently designed spillways, flooding in Great Britain during 2007 caused a greater-than-design flow over the spillway of the Ulley dam near Rotherham, structurally compromising the base of the dam. Emergency repairs were performed after a midnight evacuation of 1,000 people[iii].

In the U.S., a coal slurry dam in West Virginia with an inadequate spillway collapsed during a period of moderately heavy rain in 1972, killing 125 people[iv]. The historic and notable Johnstown flood of 1889 in western Pennsylvania, caused by the blockage of the emergency spillway at the dam, killed more than 2200 people[v] .

As more reliable long-term hydrological data is being gathered and processed, the PMF needs to be reviewed and revised accordingly. Revision often increases the PMF level. Changes in development and population will also have an impact on the financial and human costs estimated in a risk analysis. If a spillway cannot pass the higher design flow, overtopping may lead to dam erosion and failure. Higher flows can also cause problems with the spillway itself, such as the generation of a lifting force and possible cavitation at the spillway crest. Yet another cause for anxiety among dam owners is the fact that approximately 8300 state-regulated dams are classified as "high hazard" dams[vi], which means that failure can result in loss of life and significant property damage. These dams, in particular, are under the scrutiny of the states.

Fish Passage

Another major concern for dam owners, particularly those who are in the process of Federal Energy Regulatory Commission (FERC) dam re-licensing, is fish passage. The health of many of the rivers dammed during the last century has been in decline because spawning fish have been unable to travel upstream. There has been significant technology development over the last twenty years in the area of fish ladders and fish lifts that enable fish to pass through dams, thereby improving the ecological health of these rivers. Flow from spillways can hamper the performance of fish ladders and fish lifts by considerably increasing velocities and/or turbulence near the entrance to these upstream passage devices, discouraging fish from using them. Additionally, such undesirable flow characteristics may cause high levels of air entrainment, producing over-saturated total dissolved gas (TDG) concentrations, which threatens the life of fish.

Downstream passage for jouvenile fish has been drawing more attention in past decade. One alternative is using the spillway as a non-turbine route to pass fish. Fish-friendly spillway technology has been researched and developed for this purpose. One such technology is the Removable Spillway Weir (RSW), designed to be placed at the spillway entrance. It serves as a fish passage device during normal dam operation, placed at the crest of the existing spillway. It is stowed to rest on the river bed during flood discharge.

A number of spillways have been redesigned in recent years in order to enhance fish passage. These efforts not only benefit the local ecology and community, but also the dam owner who can improve public relations by showcasing investment in the regional recreational and environmental capital.

Tools for Safety Assurance and Design

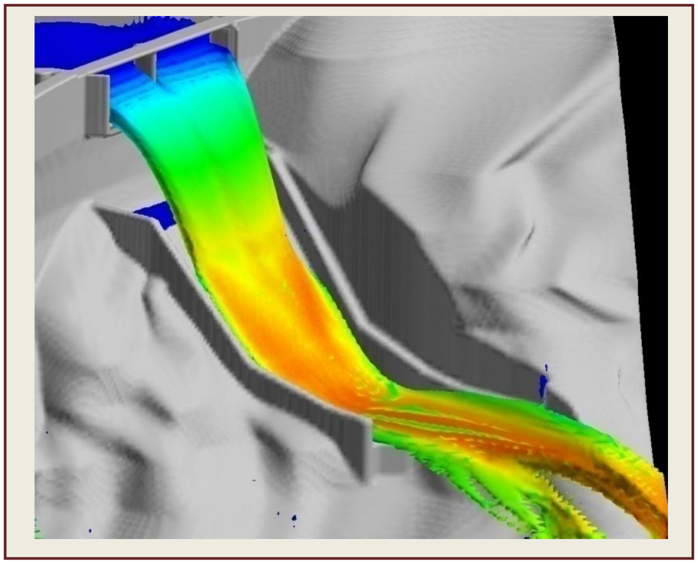
When faced with the challenge of showing state regulators that a spillway can properly withstand the PMF or in evaluating a possible new design for fish passage, numerical models or scaled physical models must be used. Scaled physical models can give extremely valuable hydraulic information, but can also be costly and time-consuming. With the advance in computer technology and the availability of more reliable and efficient computational fluid dynamics (CFD) codes, virtual prototyping of spillways has become an extremely useful tool for evaluating performance under varying flood conditions, and examining the effect of new design variations before any concrete is poured. Computational models do, however, have limitations. The use of turbulence modeling (parameterizing the turbulence to derive the effect of the unsteady eddies, enabling a steady state computer solution) is often one of the biggest concerns. Other parameterizations or ignored physics include air entrainment, spray, and cavitation. In a practice, therefore, CFD is not yet capable of completely replacing physical modeling. Integrating scaled physical models with computational models, however, creates a powerful combination, enabling the validation of the computer models on the scaled physical models, the use of computer models during design selection, and even the use of computer models to provide boundary input for smaller, more detailed physical models to confirm a final design.

The key to success when using computational flow modeling is an experienced user with a sophisticated understanding of hydraulics and fluid mechanics. Like any computational tool, the output is only as good as the input provided, and there are many settings and inputs associated with the empirical physics sub-models that are required for simulating something as complex as a reservoir or a spillway.

Application Examples

Shown below are four examples of how computer flow modeling has been used to improve spillway safety and/or fish passage at a number of dams. Three are related to dam safety, and one to fish passage.

Increased Flood Design Requirements

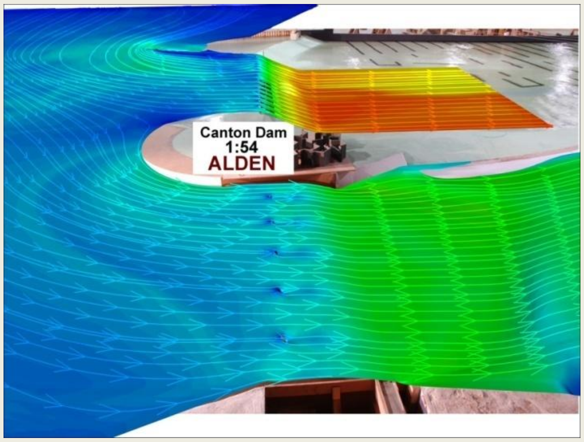


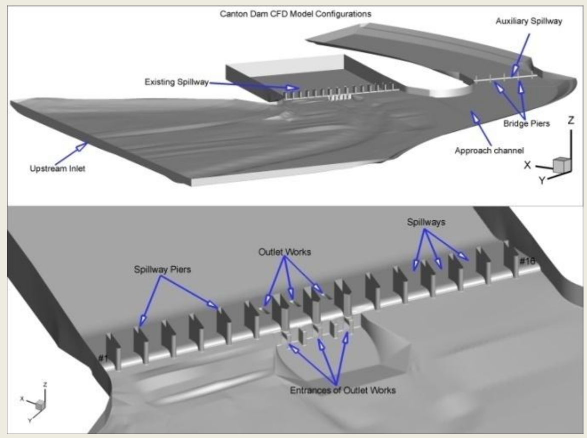
Smith Mountain dam is an existing structure for which the PMF was recently re-computed and was found to be greater than the design flow. The dam has two discontinuous flip bucket spillways that were physical scale-model tested at Alden in 1959, prior to construction. Alden recently used the FLOW-3D computational fluid dynamics (CFD) tool to predict the spillway performance under the new greater-than-design flow. Of particular interest was the trajectory of the water across the discontinuity in the spillway. In addition, the model was used to investigate the cavitation potential of the spillway, which could cause spillway erosion.

First, the CFD model was validated using the physical model results from 1959 by qualitatively comparing the water surface shape throughout the spillway and by quantitatively comparing the spillway rating curve (water crest height vs. flow rate). Once the physical model results were adjusted for scale effects, the CFD model results agreed to within 5%. After validation, the CFD model was used to predict the change in flow trajectory was onto the apron, showing that neither cavitation nor erosion were a concern.

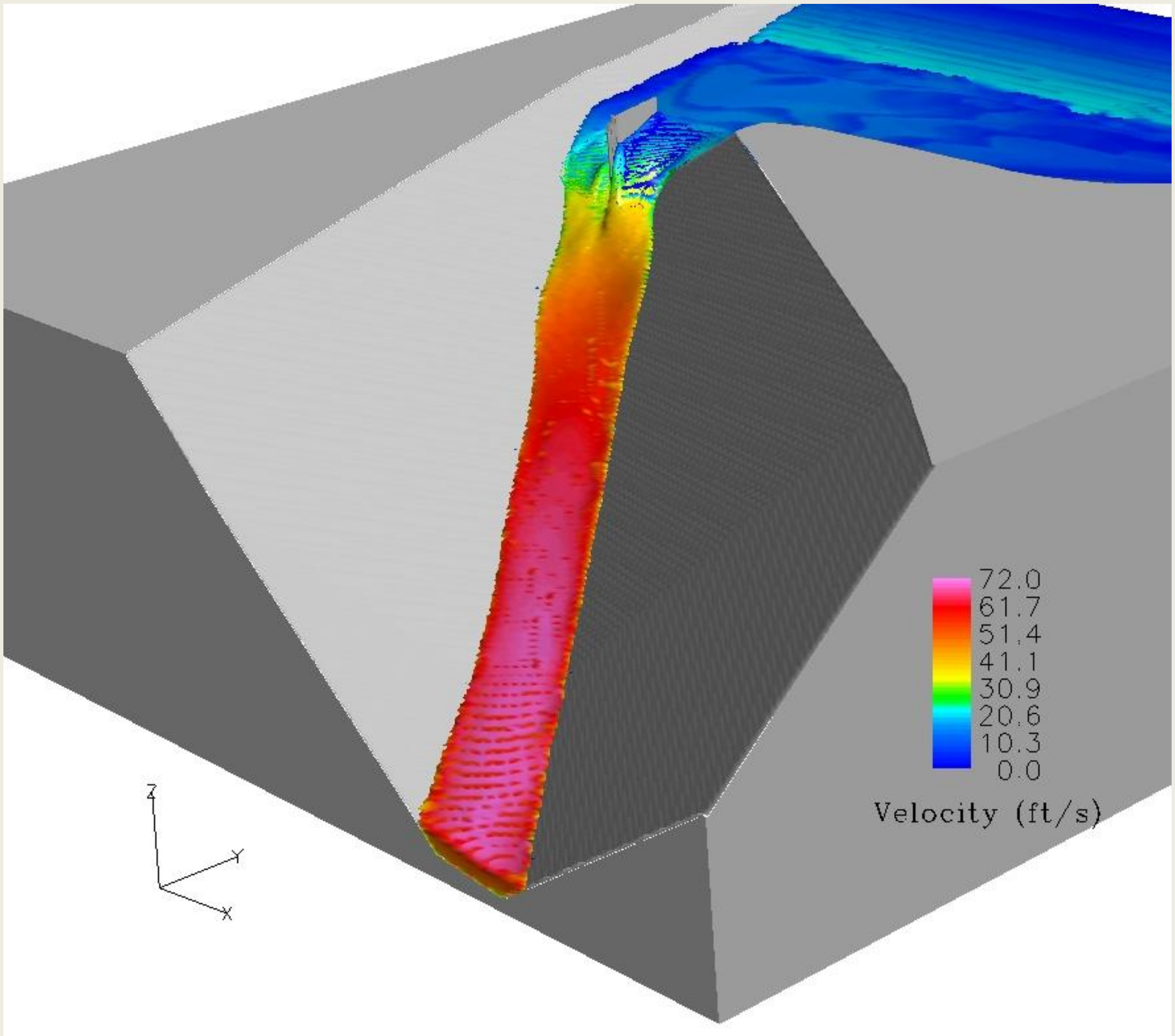
Another case study involving recomputed flood design is Canton Dam,located on the North Canadian River in Oklahoma, USA. The dam consists of one spillway with sixteen tainter gates with a total discharge capacity of 339,400 cfs at the maximum pool elevation. This capacity is insufficient to safely pass the revised PMF of 626,200 cfs. Therefore, the US Army Corps of Engineers (USACE) decided to add a 480 ft wide auxiliary spillway with nine 32 ft tall by 40 ft wide fusegates designed by Hydroplus Inc. In order to help USACE and Hydroplus optimize the design of the auxiliary spillway, an integrated approach combining a CFD model and a 1:54 scale physical model was proposed. A three-dimensional CFD model was first developed with the original design geometry, and simulations were conducted to predict flow patterns, water surface elevations throughout the reservoir, and flow rate through the existing and auxiliary spillways. Based on the CFD results of the original design, a series of design modifications were made in the CFD model and simulations were carried out for these modifications. By comparing the results for these modifications, one favorable design was chosen to be constr ucted in a scaled physical model. Physical m odel test results were then used to validate the CFD model. A good agreement of flow patterns, water surface elevations, and velocities between the CFD model predictions and physical model measurements was achieved, indicating the accuracy and reliability of the CFD model.

Spillway Rehabilitation





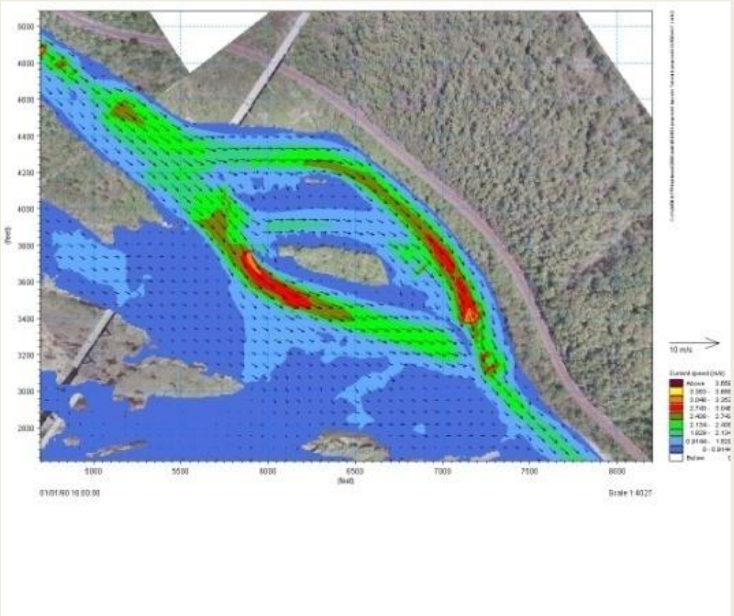
During a recent rain event in Hawaii, the ungated overflow spillway for a reservoir failed due to erosion of the substrate material. The dam owner needed to refurbish the spillway and chose computer modeling to investigate the spillway performance before the event and evaluate spillway performance during the spill. The CFD model was then modified to develop a spillway design which could contain the design flow within the discharge channel, preventing future erosion of the land around the structure. The spillway had a unique, asymmetrical and site-specific design which resulted in the sloshing of the flow and a hydraulic jump in the spillway chute. Multiple design options were considered, including the addition of a flow control vane to reduce sloshing in the chute. The water surface elevation and the pressure distribution on the spillway chute were used to show that the final design had adequate free board and low potential for cavitation. Construction of the new spillway was completed in 2008.



Spillway rehabilitation simulation, showing the effect of a suggested flow control vane in the chute

Fish Passage Concerns

Modifications to the Holtwood hydroelectric plant in Pennsylvania have been proposed to improve upstream and downstream fish passage at the facility. CFD was used to compute the flow over the spillway in the vicinity of the fish lift. Of particular interest in the study were the predicted flow patterns, velocity magnitude, and turbulence levels at the toe of the spillway. High velocities, high shear flow patterns, and high turbulence levels near the fish lift can repel fish and limit its effectiveness. Several modifications to the dam were considered to improve flow patterns for fish passage. In addition, several possible modifications at the toe of the dam were modeled to evaluate the ability of deflector walls to minimize these problems. The end result of this modeling was that a design was developed that was suitable for approval by the regulatory agencies.



Velocity contours and vectors from a CFD simulation at Holtwood Dam, indicating areas of concern for upstream fish passage

Summary

Spillway effectiveness and performance is a key to meeting the combined challenges of aging hydropower infrastructure and ensuring a minimal environmental impact of renewable energy. This white paper has introduced the technology of computational flow modeling and has shown how, when properly validated or used in conjunction with physical modeling, this can be an effective tool in ensuring spillway safety and designing new or refurbished spillways.

[i] http://internationalrivers.org/en/node/479
[ii] http://apps1.eere.energy.gov/states/maps/renewable_portfolio_states.cfm
[iii] The Independent, June 26, 2008
[iv] http://wvgazette.com/static/series/buffalocreek/BUF302B.html
[v] **McCullough, David, 1987. "The Johnstown Flood", Simon & Schuster.**
[vi] Emergency Action Planning for State Regulated High-Hazard Potential Dams, Findings, Recommendations, and Strategies, *FEMA 608, August 2007*