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PHYSICAL MODELING AS A DESIGN TOOL—NOT JUST FOR VALIDATION

RAS 2D: THE FUTURE OF RAINFALL-RUNOFF MODELING?

Physical Modeling as a Design Tool—Not Just for Validation

Brad Kirksey, P.E. | Tina McMartin, P.E. | Blake Tullis, Ph.D.

ABSTRACT

Scaled physical models are often used for design validation before construction or rehabilitation of a critical hydraulic structure. Why not incorporate a model earlier as an integral part of the design process? This can improve the design by optimizing hydraulic performance, exposing unforeseen potential challenges, and possibly reducing construction costs. Sometimes, the savings are even sufficient to pay for the modeling.

Using physical hydraulic modeling as a design tool also provides deeper understanding of how a structure will perform, improving confidence in the design approach and numerical modeling.

With our experience gained from incorporating physical models into the process for more than 10 projects—for new dam and spillway design, dam rehabilitations, spillway modifications, and spillway dewatering system design—we can suggest several good practices, including:

- Using sectional models or phased models to refine geometry before constructing the full model, developing the full model with the components to test in mind
- Building the model such that components can be enlarged, reduced, or reconfigured conveniently
- Reducing the footprint of the full model by using computational fluid dynamics (CFD) modeling to extrapolate results

- Using pressure taps to evaluate stagnation pressures for spillway stability
- Documenting the entire model with photo and video
- Using the physical model to calibrate CFD models for posterity after the physical model is demolished

Background

Using a scaled physical model to predict how water will move through dam appurtenances such as spillways and outlet works is invaluable for the design of hydraulic structures because it can simulate the hydraulic conditions of the prototype, provided that geometric, kinematic, and dynamic similitude requirements are sufficiently met. (See more under "What scale should your model be?")

Scaled physical modeling for dams in the United States dates to 1930, when the **Waterways Experiment Station** was built in Vicksburg, Mississippi, as a U.S. Army Corps of Engineers research facility to develop and implement a flood control plan for the lower Mississippi River. This station rapidly evolved to model not only fluvial hydraulics but also tidal hydraulics, dam appurtenances, and wave action.

The hydraulic modeling for the projects discussed in this article were all conducted at the **Utah Water Research Laboratory at Utah State University** in Logan, Utah. This laboratory has been building and testing physical scale models since its commissioning in 1965, in response to the need for research and the demand for laboratory support.

Other facilities operated by government, academia, and private industry have also contributed extensively to this field. Some examples are the **USDA-Agricultural Research Service Hydraulic Engineering Research Unit** near Stillwater, Oklahoma; the **Bureau of Reclamation Technical Service Center** in Denver, Colorado; **Colorado State University's Hydraulics Laboratory** in Fort Collins, Colorado; the **Iowa Institute of Hydraulic Research**; and **Alden Research Laboratory, LLC.**

Deciding If a Scale Model Is Right for Your Project

Physical model–based experiments performed primarily at government laboratories like the Waterways Experiment Station provide the basis for many of the engineering design manuals and empirical design tools used in the dam safety industry today.

These empirical studies have been invaluable in developing parity of design methods within the dam safety industry and have significantly reduced the total risk these types of structures might pose to the public. But standardization understandably leads to conservatism, and that conservatism has an associated cost.

Dam owners across the United States must balance the costs of dam safety improvements with other considerations, such as other capital projects, operation, and maintenance. Reducing unnecessary conservatism associated with empirical design through proper evaluation and documentation gives dam owners an added level of flexibility when making decisions about which projects to pursue. This can be achieved by using physical hydraulic modeling as a design tool.

The benefits of physical hydraulic modeling as a design tool include:

- Providing owners and engineers with a level of project detail that is more realistic than anything besides the prototype itself.
- Allowing owners and engineers to improve performance and/or lower construction costs while reducing design/performance uncertainty.
- Identifying problems in the preliminary design that require correction. While redesign might add design cost at this stage, it reduces the chance of higher construction costs or increased risk down the road from uncorrected design shortfalls.
- Providing designers owners, regulators, and other stakeholders with improved confidence in the anticipated hydraulic performance of the structure through visual observation of the model.

Getting Started

Physical modeling is often compared to playing in a sandbox: There is an element of youthful joy seeing the power and behavior of water. And what respectable engineer can stand to watch a model operate without wanting to tinker with it?

But the laboratory floor is not a blank canvas. You need a baseline model configuration to work from. Constructing a model is costly and time-consuming. Some models use enough lumber and other building materials to complete a small home. While the time and money spent on a model often are recouped through dam construction cost savings, efficiency is still important during a model study. The best approach is to design the model as you would the prototype.

Physical models should not be used for conceptual or preliminary design because modifying the model configuration is costly. Instead, use industry standard tools, calculations, and processes to establish a baseline for the physical model and to eliminate as many variables as possible.

Focus the physical model study on examining phenomena that either cannot be calculated another way or that would benefit from clearer understanding. Some typical phenomena that can be better understood through a physical model include:

- Weir discharge capacity
- Energy dissipation
- Water surface profiles
- Flow velocities
- Hydrodynamic pressures
- Flow patterns in abrupt constriction, expansions, or backwater areas
- Flow instabilities
- Aeration and turbulence
- Wave action and standing waves
- Water superelevation
- Debris flows
- Sensitivity of phenomena due to input variability

Designing Your Model

These questions and answers can help guide your preparation.

Should you use empirical and theoretical engineering calculations?
Keep in mind that you are designing a physical model rather than a prototype at this phase of the project, so use empirical and theoretical engineering calculations even if they have documented limitations that may be exceeded by your design.

Here's an example:
In designing the Leon Hurse Dam for the new Lake Ralph Hall, which is owned by Upper Trinity Regional Water District in North Texas, the design team planned to use a Reclamation Type III Stilling Basin at the base of a stepped chute. According to the initial calculations, the entrance velocity into the basin was 76.1 feet per second (f/s), and the unit discharge was 231 cubic feet per second per foot (ft^3/s/ft).

Engineering Monograph 25, *Hydraulic Design of Stilling Basins and Energy Dissipators* (Reclamation, 1984) suggests that entrance velocity should be less than 60 ft/s, and unit discharge should be less than 200 ft^3/s/ft. Using this guidance, the stilling basin would not be appropriate for design without first validating the design using a physical model. The design of the stilling basin was optimized with a physical model.

Should you use numerical (computer) modeling?
As long as the limitation of the modeling is understood, it is appropriate to use one-, two-, and three-dimensional (1D, 2D, and 3D) computational modeling under the following circumstances:

- **1D** is useful for uniform flow confined by linear geometry such as spillway approach channels, chutes, and discharge channels. It is often very useful in developing tailwater rating curves. But it is not advisable to use 1D modeling for sudden changes in geometry or turbulent/aerated flow.
- **2D** builds on 1D and is useful in areas with sudden geometry changes such as bends, expansions, contractions, or backwaters, but it still does not fully accurately predict the behavior of turbulent flow.
- **3D** allows for the greatest level of complexity in numerical modeling, particularly when the flow is highly complex and three-dimensional.

Practically anything that can be built as part of the physical model can be simulated in a CFD model. While CFD modeling can reasonably predict the behavior of aerated and turbulent flow, some surprises can still arise as part of the physical modeling.

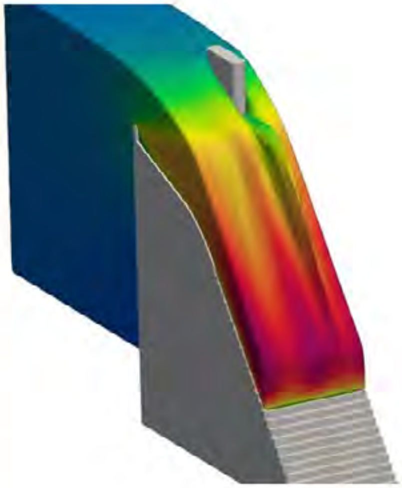
CFD modeling also can require significant modeling time and computation power. That is why it is preferable to start with spreadsheets, MathCAD, hand calculations, or 1D/2D modeling before developing the 3D CFD models. And because CFD modeling has become so accessible and prevalent in design, it is recommended that physical modeling be performed only on structures that have already been analyzed with a CFD model. This approach refines the design so that fewer changes are necessary as part of the physical model.

Here's an example:
For one project (that has to remain anonymous), the design team sought to increase the capacity of a side channel spillway

PLANNING

What Calculations and Numerical Models Should You Use?

1D	• Uniform flow confined by linear geometry • Not recommended for sudden changes in geometry or turbulent/aerated flow • Least labor and computational time required
2D	• Useful in areas of sudden geometry changes • Not recommended for turbulent flow • Moderate model building and computational time required
3D	• Allows for greatest level of complexity • Useful where abrupt three dimensional changes in geometry occur • Can require significant time and computation power



to reduce the maximum water surface elevation of the reservoir. There was physical space for a 350-ft-wide weir to spill into a narrower chute. At that point, the flows turned 90 degrees and passed through a 100-ft-wide constriction point where the chute crossed under a bridge.

The scoped conceptual design included a labyrinth weir to maximize the head-to-discharge relationship within the 350 ft of available space. Once design began, the team quickly discovered that the labyrinth weir would discharge more flow than could pass through the chute. The flows swamped the downstream bridge crossing and backed up water, submerging the labyrinth and reducing its discharge capacity. This was discovered by creating a simple 2D HEC-RAS (Hydrologic Engineering Center's River Analysis System) model of the spillway chute that was then plugged in as a tailwater rating curve for the labyrinth weir spreadsheet calculations.

Neither the 2D HEC-RAS model nor the labyrinth weir calculations were precise enough to use for final design, but they were straightforward tools that produced reasonable estimated performance of the spillway to eliminate the labyrinth option prior to the physical model.

What type of model should you choose?

The type of model depends on your goal. A comprehensive physical model (i.e., modeling all components of the prototype, approach and exit configurations, etc.) will provide the best visualization and clear understanding of the 3D flow patterns, but a larger-scale, component model may yield better data.

For example, it might be better to construct a larger-scale weir for developing a rating curve. For wide spillways or spillways with uniform flow, a sectional model might be preferable because the scale can be larger, with modifications easier to make.

For a complex project, you might want a model that matches the sequence of construction so that temporary conditions can be modeled as well as the final conditions of the project. As with the calculations and numerical modeling, physical component modeling and sectional modeling should be used to refine the design before modeling the entire structure outright. To achieve a reasonable balance, consult with the hydraulic laboratory as part of the scoping process for the study.

Photo 1

Photo 2

Leon Hurse Dam for the new Lake Ralph Hall (owned by Upper Trinity Regional Water District) in North Texas was tested both with a sectional scale model (Photo 1) and a full-width scale model (Photo 2).

Here's an example:
Upper Trinity Regional Water District's Leon Hurse Dam was studied with a sectional model for preliminary design of some spillway features. The physical model consisted of two cycles of the labyrinth weir situated on top of a roller-compacted concrete (RCC) gravity dam. The stepped chute was sloped at 0.8 horizontal to 1 vertical (0.8H:1V) and terminated in a Type III hydraulic jump stilling basin. This sectional model was used to approximate the head versus discharge relationship of the labyrinth weir, establish the crest-to-chute transition shape, and establish stilling basin depth, length, and baffle configuration.

Subsequently, a full-width model was constructed to finalize the design. At that point, more focus could be put on the nontypical features, such as the upstream intake tower effect on the rating curve, stilling basin wing wall configurations, bridge impingement, and others.

What scale should your model be?
Geometric similitude is achieved by building the model to a selected size scale ratio. To attain kinematic and dynamic similitude, the model must be operated with the predominant forces controlling the flow phenomena properly reproduced and scaled. For the type of models discussed here, gravity and inertial forces are predominant, and we used the Froude number for the similarity parameter to operate the models. We achieved similarity using a model Froude number equal to the prototype's Froude number.

It is important to scale the model so it is large enough to avoid or minimize the effects associated with the properties of water, which do not scale (i.e., surface tension and viscosity). Using a large enough model can minimize the Reynolds number (viscous) and Weber number (surface tension) effects. By minimizing these effects, the proper discharge, velocity, energy-dissipating characteristics, and pressures can be scaled to the prototype using the similarity parameters for Froude modeling.

The designer also must consider the hydraulic laboratory's capabilities. For instance, the Utah Water Research Laboratory can achieve model flow rates in excess of 100 ft^3/s and physical model footprints that exceed 6,000 ft^2. This allows the lab to accommodate large model scales to study complex flow behaviors, better manage experimental uncertainties, and reduce the potential for size scaling effects. However, this larger scale results in larger structures, higher pressures, and greater cost. Again, consulting with the lab as part of the scoping process can help find a reasonable balance.

What loading conditions should be modeled?

Key loading conditions include peak design flow rate, critical design case (if different from the peak), and a range of smaller events. The peak design flow rate may be developed through hydraulic routing of design storms or by operational constraints. The range of smaller events could correspond either to frequency events or be done at equal increments of the peak flow rate (i.e., 10%).

The most critical design case typically occurs at the maximum flow rate, but this is not always the case, so it is necessary to consider smaller flows. Furthermore, modeling very large flow rates might give a false sense of risk associated with the prototype's operation. For example, if a spillway is designed for the probable maximum flood (PMF), high exit channel velocities or water splashing over the training walls during modeling could cause concern despite the small probability of this event occurring. Documenting a more likely scenario, such as a 100-year storm (which might be orders of magnitude smaller than the PMF), can provide a greater level of comfort with the spillway's performance after seeing it perform in conditions that are easier to understand and more likely to occur.

Based on the scaled flow rate, most physical models use a calibrated flow meter to deliver known flow rates (independent variable) to the headworks of the model. The corresponding headwater elevations (dependent variable) are measured and control structure (e.g., weir, gate, orifice, etc.) head-discharge relationship developed. Tailwater elevations (often an independent variable based on a 2D or 3D numerical model of the downstream channel) are set at the downstream model boundary using gates, stoplogs, or similar structures.

Most commonly, physical models are operated at a series of steady-state flow conditions (i.e., one constant inflow rate at a time). A hydrograph can be routed through the physical model, but that can be complicated by limits on the model's ability to match discharge and tailwater changes in real time.

How much of the prototype should be modeled?

An experienced team familiar with the project can best answer this question. It is not as simple as extending the model a set distance in every direction from the structure. These extensions might be the most expensive components of the model. Deep water (high pressure) and natural topography are particularly costly and time-consuming to build.

Consider these factors:

- Which prototype elements are unique (need study) or have the potential for optimization (i.e., cost reduction)?
- Is there sufficient model extent to allow relevant flow phenomena to fully develop?
- What are the upstream (headwater) and downstream (tailwater) boundary conditions?
- Can any of these issues be reasonably evaluated using numerical modeling?

Additional considerations:

- Many laboratories pipe water into the models, so inlet velocities may have to be stilled with baffles and/or permeable media or else they will disrupt the results.
- Discharge channels usually drain by gravity into sumps in the laboratory floor, so flash boards may be required to control tailwater.

Brainstorming sessions and design charettes with relevant hydraulic modeling experts can help answer the questions. Include design team members from the hydraulic laboratory, along with specialists from other disciplines, such as geotechnical and structural engineers, to make sure the prototype that is being modeled can eventually be feasibly constructed.

Here's an example:

For the modernization of the Upper Brushy Creek Water Control and Improvement District's Dam 7 in Texas' Brazos River basin, the physical model focused on a new labyrinth auxiliary spillway cut into the right abutment. The CFD model found that the angled approach channel reduced the discharge of the spillway by 35%, relative to a more traditional approach channel alignment. The relative shallowness of the approach channel also resulted in the maximum headwater elevation occurring quite a distance upstream of the weir.

Physically modeling the entire approach channel and a portion of the reservoir would have added significant cost but little value to the study. Using the CFD model, the design engineers developed a correlation between the water surface elevation in the reservoir and the water surface elevation in the approach channel, thus allowing the model extents to be smaller, but maintaining a reasonable upstream boundary condition.

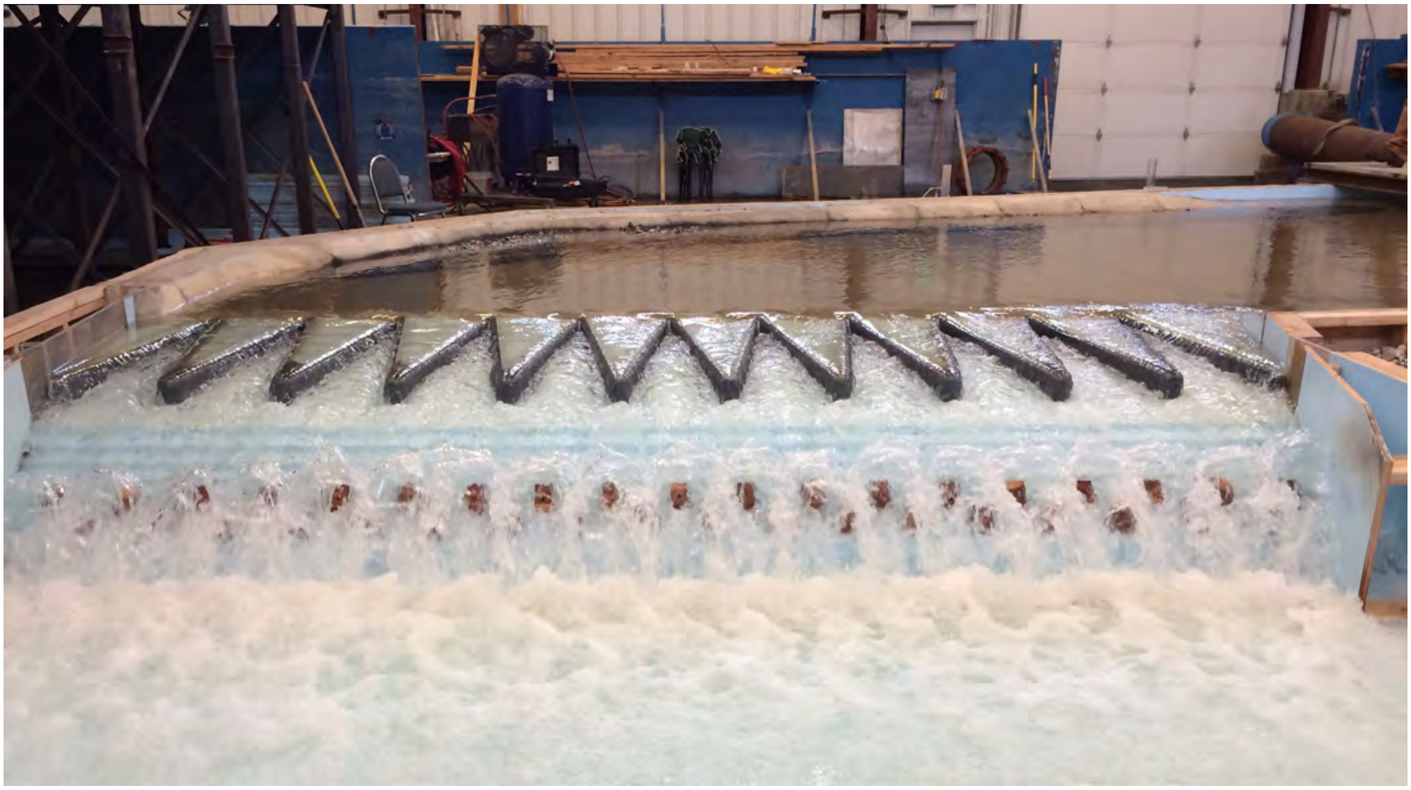


Photo 3

Photo 4

Physical modeling (Photo 3) of Upper Brushy Creek WCID's Dam 7 in Texas' Brazos River basin focused on a new labyrinth auxiliary spillway. Photo 4 shows the completed dam.

What adjustments could reduce cost or improve performance?

Address these questions before model construction, then build your model in a way that allows for changes. It is almost always easier to remove a component from the model than add to it.

Here are some variations used for models of dam spillways:

- Interchangeable weir with different crest shape to evaluate head versus discharge relationships
- Interchangeable weir abutments with different shapes and configurations to evaluate discharge efficiency
- Interchangeable bridge piers with different shapes and configurations to evaluate head loss
- Interchangeable chute blocks and baffle piers with different shapes, sizes, and locations to evaluate energy dissipation improvements
- Artificially tall training walls trimmed to proper height after initial model runs
- Artificially wide/deep approach channel, made narrower/shallower with concrete, gravel, or sandbags after initial model runs
- Artificially deep and long stilling basin, made shallower and shorter after initial model runs
- Stepped chute built to be overlaid with smooth steel plates to quantify the additional energy dissipation created by adding steps
- Stepped chute built with intermediate step size inserts to evaluate energy dissipation depending on the size of each step

Here's an example:

For the Bois d'Arc Lake dam, owned by the North Texas Municipal Water District, a physical model was developed to evaluate a Type II hydraulic jump stilling basin at the end of a long chute structure. The stilling basin was 60 ft wide and sized for the PMF design storm of 26,400 ft^3/s (prototype).

The baseline stilling basin was 40 ft deep and 146 ft long. One row of chute blocks and one row of baffle blocks (7.5 ft tall) were included in the baseline model. The baseline model was built so that the stilling basin training walls could be removed, and the chute blocks and baffle blocks could be reconfigured.

Through multiple iterations, the final configuration of the stilling basin was the same depth but was shortened to 84 ft. This required using two rows of 10-ft-tall baffle blocks. This configuration resulted in comparable performance of the basin and saved about $500,000 in construction cost. The physical model study cost $112,500 in 2014.

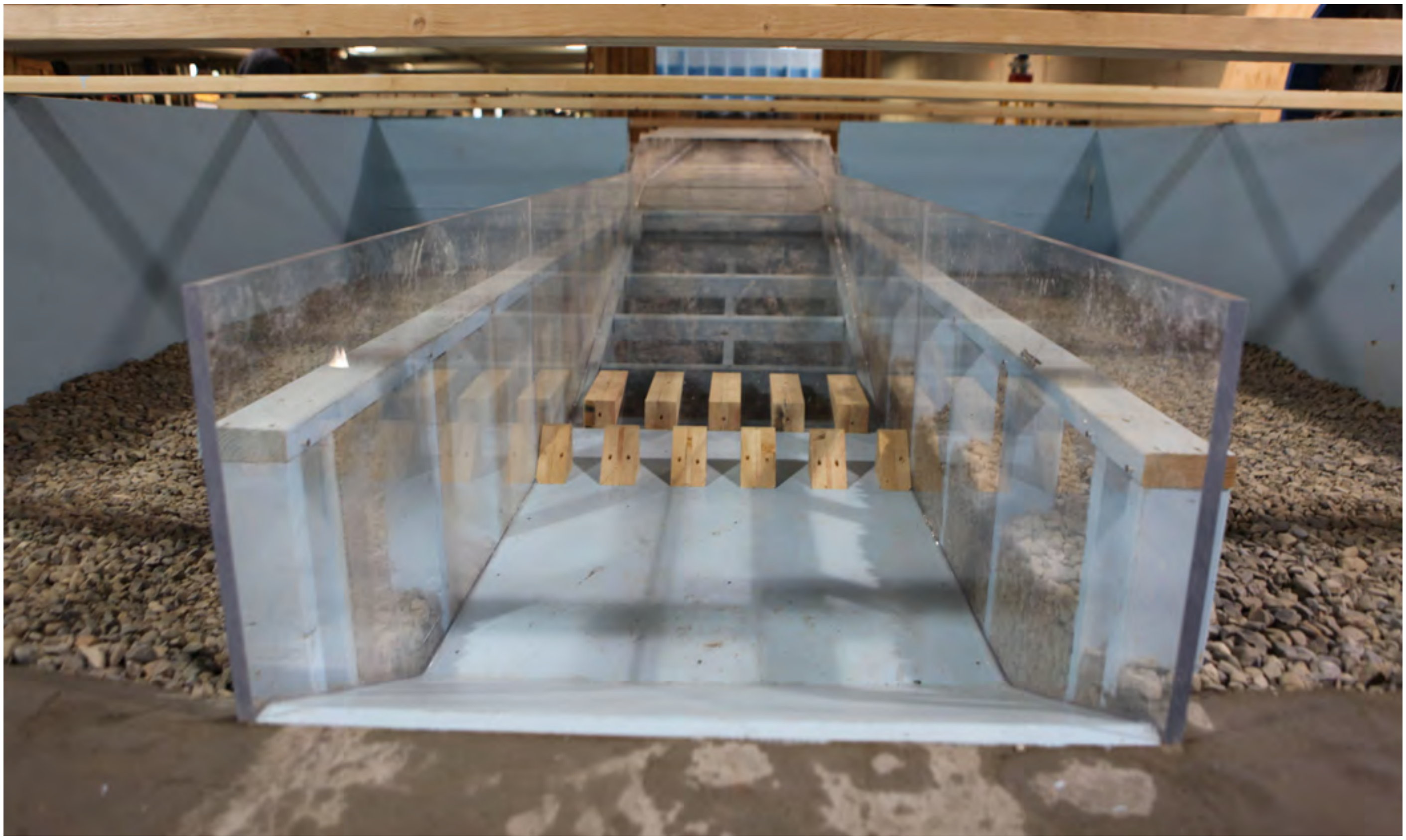


Photo 5

Photo 6

North Texas Municipal Water District's Bois d'Arc Lake Dam was modeled (Photo 5) to evaluate a hydraulic jump stilling basin at the end of a long chute structure. Clear acrylic was used for better views. Photo 6 shows the completed spillway.

Building Your Model

Model construction typically is the responsibility of the hydraulic laboratory. At the Utah Water Research Laboratory, for instance, staff design and construct the physical model to operate safely and efficiently given the lab's constraints and requirements and to meet the project's goals.

The following guidelines can help you get the most out of your model construction:

How should you convey the design concept to the lab? Drawings of the prototype structure are the best way to convey the design configuration. These drawings should be just like the construction drawings that will be provided to the prototype contractor. Also, provide a final PDF as well as the CAD (computer-aided design) files of the drawings to the laboratory.

At a minimum, the drawings provided to the laboratory should:

- Delineate the limits of the physical model in plan view and provide topographical data and aerial images of the model extents. The lab will build the terrain for this entire area and will want to adjust surface roughness of the model based on the conditions in the field (e.g., trees, grass, rock, etc.).
- Provide a dimensioned plan view of the model study area. Hydraulic dimensions such as orientation, length, width, and the like, are critical, but it is not necessary to detail structural dimensions (e.g., wall thickness, slab thickness).
- Provide a profile along the centerline that clearly shows the hydraulic dimensions of the model. Elevations, depths, and heights should be clearly called out and dimensioned.
- Provide topographical cross sections approximately every 50 ft (prototype), all the way downstream to the model extents.
- Include details of the exact geometry for proposed structures. Some complex structures such as labyrinth weirs or ogee weirs will either be 3D-printed or machined, so detailed geometry is critical.
- Indicate on the drawings the location of known instrumentation or specific hydraulic measurement points.

Should you prepare 3D CAD models of the design concept? Yes. With the advancement of 3D CAD modeling capabilities, a 3D model of the proposed surface and structures is recommended.

The topographical surface to be constructed at the lab should be clear in the model file; the lab personnel may choose to cut their own sections from the surface data. Ideally, the file should include just one surface to avoid confusion (instead of an existing excavation and proposed surface). STL files used to develop CFD modeling also are an easy way to convey the model configuration to clients or regulators.

What materials should be used for model construction? As the design engineer, rely on the lab's modeling expertise, but also think critically about what you are trying to accomplish.

Often, concrete structures are built with dimensional lumber and sheets of plywood because dimensions are even, with simple shapes and lots of right angles. The wood is coated with an epoxy paint to prevent water damage, and the finished surface mimics the scaled roughness of concrete.

Natural topography elements such as rivers and floodplains are often approximated using the average end area method. (See Photo 3.) Sheets of plywood, sheet metal, or similar material are cut to match the cross-sectional terrain at predetermined intervals, and the intervening space is filled with gravel, grout, or other materials depending on the surface roughness of the specific area.

Sometimes, special materials such as clear acrylic in certain portions of the model can help the design team see the hydraulic behavior in greater detail. High-density foam can be sculpted to create irregular geometry freehand. Also, 3D printing is gaining popularity for fabricating complex shapes. Again, make sure that the model can be modified as needed.

Pay specific attention to the location of the model instrumentation, which likely will include piezometers, pressure gauges, and so forth. And build the model so it can be seen and documented from all angles. This might require foot ramps, bridges, camera mounts, and other features.

Here's an example:
The chute for the Bois d'Arc Lake model was constructed entirely of clear acrylic so water surface elevations could be measured along the chute training walls and flow patterns could be seen from the underside of the labyrinth spillway.

Testing Your Model

The model-testing process occurs over a period of weeks following model construction. Often, there are kinks in the start-up process and anomalies that must be resolved by the laboratory personnel. After that, some initial results will be obtained, and the design team can then begin refinements.

This could take several iterations, all the while data are being collected, compared, and contrasted. Once a final configuration is established, the laboratory personnel will deliberately work through each load condition, taking precise measurements with routine and calibrated techniques and equipment before compiling the information into a model study report.

Here is what the design team can expect during model testing:

What data will model testing yield?
These are typical capabilities of hydraulic testing laboratories and should also be included in model study planning:

- Flow rates should be measured using calibrated flow meters. The flow meters should be calibrated using a weigh tank, and accuracy should be approximately ±0.20% or less. Flow meters might require recalibration periodically to ensure accuracy.
- Water surface elevations such as headwater and tailwater should be measured using a precision point gauge with a stilling well, staff gauges, or ultrasonic water surface sensors installed in low Froude number locations within the model.
- Flow velocities for nonturbulent flow should be measured with electromagnetic velocity probes or pitot tubes.
- Static pressures (piezometric head) should be measured with piezometers, continuous sampling pressure transducers, or calculated by subtracting reference elevations from a water surface elevation measurement.
- Points of measurement should be determined prior to model construction, but instrumentation should also be added where deemed necessary during model testing.
- Document each design alternative and the final configuration for each headwater and tailwater combination using digital still and video photography. Maximize the number of standard photo locations to allow for comparisons between different flow conditions and geometries. The camera should be mounted solidly for view frame consistency. Each photo or video should be clearly identified by alternative name/number, headwater elevation, tailwater elevation, and flow rate.

Who should see the model in operation?
Do not limit your modeling audience to hydrologic and hydraulic (H&H) experts; include dam design generalists from the project team who can provide input on constructability and dam safety aspects during testing configurations.

Testing also provides an invaluable opportunity for the owner to participate. This can help an owner better understand the power and volatility of turbulent water during the PMF and design storm events, even at smaller scale. Also, show the owner smaller events that are more likely to occur during the life of the project. While virtual witness tests are less ideal than in-person visits, you typically can accommodate for team members who cannot travel to the lab.

Can you make model changes that were unanticipated?
Absolutely, the project team should expect surprises. We have encountered numerous instances when the physical model's behavior differed significantly from what any of the other tools would predict. Typically, but not always, this results from aeration, turbulence, or vortices in the model. Adjustments, and sometimes significant rebuilds, are needed to resolve these issues. But this is why you build a physical model. Without it, you cannot predict these phenomena. When solving these problems, do not be afraid to innovate. There is usually quite a bit of room for optimization, as long as you consider your performance criteria and are confident in the results. You also can change conditions to explore what does not work as much as what does.

Here's an example:
At Upper Trinity Regional Water District's Leon Hurse Dam, a sectional model was built of the labyrinth spillway atop the RCC gravity dam, which has a steep downstream face forming the chute for the spillway. The labyrinth apron was horizontal in the baseline physical model to match the configuration that was modeled with CFD. Based on the CFD, the physical model's training wall height was set. As it turned out, aeration in the flow and the horizontal momentum of the flow coming off the labyrinth apron caused a jet of water to greatly exceed the training wall height.

This additional wall height was not feasible to achieve in the prototype, and thus the condition had to be eliminated. Through multiple iterations of the sectional physical model, the design team and laboratory personnel produced a curved transition between the labyrinth apron and the downstream slope that approximated the shape of an ogee and could be constructed without significantly complicating the means and methods of construction.

In this case, the model study did not reduce construction cost but eliminated the need for an excessively tall training wall and provided additional context about flow behaviors that would have gone undetected without the model study.

Photo 7

Photo 8

Modeling can help show an owner the power of turbulent water at a smaller scale than a real storm event. Models in Photos 7 and 8 show the difference between UTRWD's Leon Hurse Dam spillway operating at 3,600 cfs and 26,900 cfs.

Photo 9

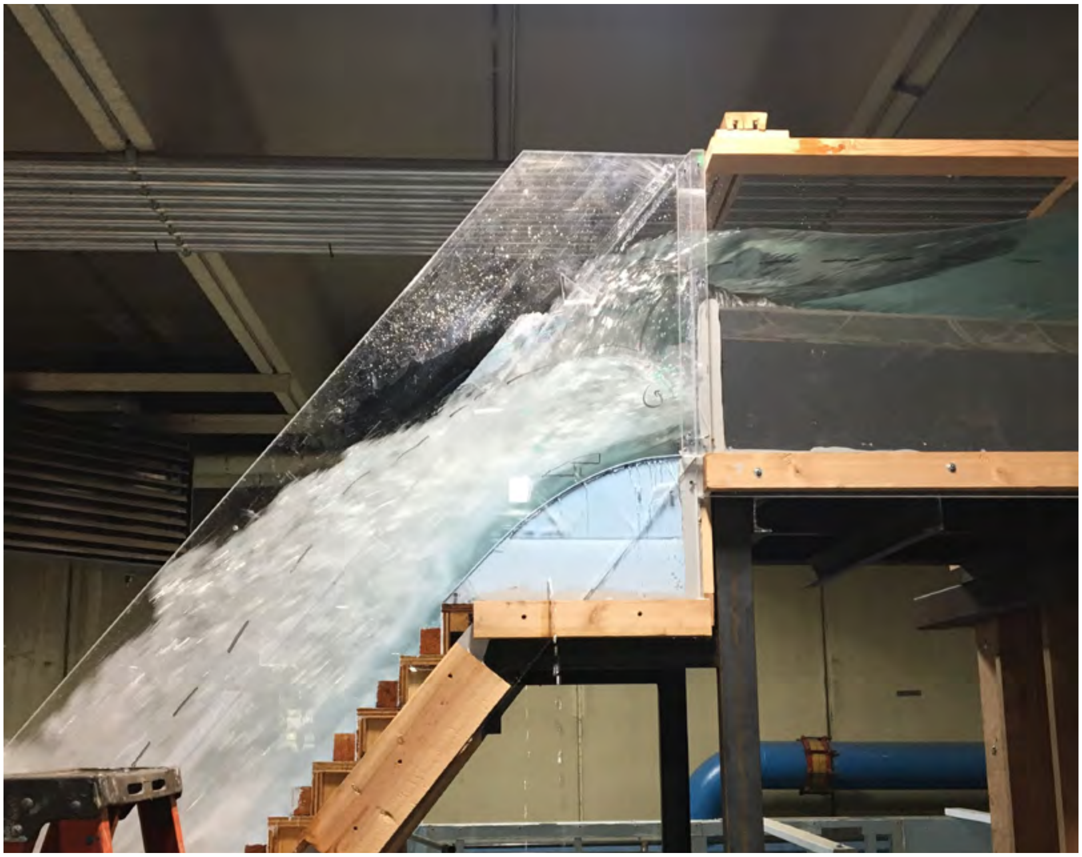


Photo 10

A model can provide additional context about flow behaviors that would have gone undetected without the model study. Photos 9 and 10 show the model of UTRWD's Leon Hurse Dam spillway operating at PMF discharge without and with an arced transition from the labyrinth apron to the chute.

What constitutes acceptable performance of the model?

To use physical modeling as a design tool, the project team must predetermine the performance criteria for the model. Otherwise, subjectivity and opinion can override good engineering judgment. While a visual assessment of the model is useful in broad strokes, it is not possible to refine the model visually without years of modeling experience.

Here's an example:
For the Dam 7 modernization, as described earlier, better understanding was needed of how the approach flow conditions would affect the head-discharge relationship of the auxiliary spillway. The laboratory modeled the angled approach the same as it was constructed in the CFD, but the project team hoped that the excavation quantity could be reduced because relatively hard limestone was being excavated.

To increase the head-discharge relationship, the design team could have changed the labyrinth configuration, deepened the approach, changed the approach angle, widened the spillway, and so forth. To increase total discharge, the top of the dam could have been raised.

Because a physical model is such a good visual tool, it was tempting to vary any of the independent variables in the physical model (approach angle, labyrinth configuration, etc.). Instead, the design team optimized most variables through empirical and computational methods and reduced the physical model optimization to two variables: approach channel width and depth.

To do the numerical and modeling optimization, the design team had to understand what constituted successful optimization: a certain discharge (100% PMF of 50,000 ft^3/s) at a certain peak water surface elevation (below maximum top-of-dam design elevation). Based on these parameters, the design team and laboratory staff added gravel to the model to incrementally narrow the width of the approach channel, simulating reduced excavation.

Four reduced excavation configurations were evaluated with the model that did not adversely impact the optimum hydraulic capacity. This change in configuration saved the dam owner approximately $150,000 in limestone excavation cost. (The physical model cost $104,000 in 2013).

Conclusion

The practices and examples provided in this article illustrate the value of physical hydraulic modeling beyond simple design validation. We have seen time and again that when performed as an integral part of the design process, physical modeling can improve design, optimize hydraulic performance, and reduce construction costs. In some cases, the savings pay for the cost of physical modeling.

Our goal in sharing these lessons learned and best practices is to serve as an industry resource and improve the effectiveness of modeling as a tool to give design teams and owners deeper understanding and greater confidence in the hydraulic performance of their structures.

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Over the past 20 years, Freese and Nichols, Inc., and the Utah Water Research Laboratory at Utah State University have collaborated on more than 10 different scaled physical models.

Brad Kirksey, P.E.

Associate, Freese and Nichols, Inc.
181 Village Ct., Suite 7, El Paso, TX 79922
817-735-7535 • brad.kirksey@freese.com

Brad Kirksey is a water resources design project manager and engineer with experience in the study, inspection, design, and rehabilitation of water resources facilities, including earthen embankment dams, concrete gravity dams, dam outlet works, flow control valves, and large outlet works gates. He has overseen the design of dam rehabilitations and new dam construction projects worth more than $200 million. Brad also leads the Water Resource Design Technical Excellence Program at Freese and Nichols.

Tina McMartin, P.E.

Associate, Freese and Nichols, Inc.
10431 Morado Circle, Suite 300, Austin, TX 78759
512-617-3120 • tina.mcmartin@freese.com

Tina McMartin is a water resources project manager and engineer specializing in design, rehabilitation, and inspection of dams. She has served as project manager and lead designer on large high hazard dam rehabilitation projects, historic dam improvement projects, and numerous dam-safety related studies. She has significant experience in the development of construction contract documents and technical oversight of dam-related construction projects. She also performs dam safety reviews and facilitates emergency action plan tabletop exercises.

Blake Tullis, Ph.D.

Associate Vice President, Office of Research, Utah State University
1450 Old Main Hill, Logan UT 84322
435-797-3194 • blake.tullis@usu.edu

Blake Tullis is an associate vice president for research and a professor of civil and environmental engineering at Utah State University (USU). He joined the USU faculty in 1997 with a joint appointment at the Utah Water Research Laboratory for hydraulic engineering research, where he was associate director from 2015 to 2019. He currently supports USU's Sponsored Programs, Environmental Health and Safety, Laboratory Animal Research, Research Development, and Technology Transfer programs and oversees the Seed Grant and Capital Equipment Grant programs. Blake is a fellow of the American Society of Civil Engineer's Environment and Water Resources Institute and has received the American Society of Civil Engineers (ASCE) Hydraulic Structures Medal and the Association of State Dam Safety Officials Terry L. Hampton Hydraulic Structures Medal. He was named the 2016 College of Engineering Teacher of the Year.

ASDSO Peer Reviewers

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