Combining Computational and Physical Modeling to Design the Keeyask Station

To develop a design for the proposed 675-MW Keeyask station, Manitoba Hydro integrated computational fluid dynamics modeling and physical modeling. Using CFD modeling to determine the conceptual configuration of the facility and spillway, then verifying with physical modeling, revealed good agreement between the two methods.

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To validate the proposed design of the 675-MW Keeyask Generating Station on the Nelson River in Manitoba, Canada, Manitoba Hydro performed computational fluid dynamics (CFD) modeling and then physical modeling. Combining results from these two modeling techniques allowed Manitoba Hydro to validate the proposed design of the Keeyask station, while providing further confidence in the use of CFD modeling for optimizing hydro plant design.

To validate the proposed design for the Keeyask station, Manitoba Hydro first used three-dimensional (3D) CFD modeling to visualize flow fields and evaluate alternative designs for the station.

Second, personnel carried out two physical model studies:

— A comprehensive study of the river closure, diversion works, and spillway. The goals were to confirm the plans for managing river flow during construction and to confirm the overall performance and discharge carrying capacity of the proposed spillway; and

— A sectional study of the spillway. The goals were to determine uplift and downpull forces on the spillway gates and detect any tendency for gate vibration; determine the pressure along adjacent spillway piers and on the rollway surface to ensure that excessive negative pressures do not occur for a variety of gate openings; determine water surface profiles to aid in the selection of pier height geometry; and verify the estimated discharge capacity of the diversion sluiceway and final rollway.

Background on Keeyask

The site of the Keeyask station is 730 kilometers north of Winnipeg, Manitoba, Canada, at the head of Stephens Lake (see Figure 1 on page 2). Stephens Lake is the reservoir for Manitoba Hydro's 1,220-MW Kettle station. The proposed axis for the spillway, powerhouse, and main dam crosses the Nelson River at the foot of Gull Rapids. The proposed facility will develop 18 meters of the available 27 meters of head between the tailwater of Manitoba Hydro's 224-MW Kelsey station and Stephens Lake. Seven generating units are to be installed, with a total capacity of 675 MW at a plant discharge of 4,000 cubic meters per second (cms).

The arrangement selected during the planning stage of the design for the Keeyask station consists of:

— A 3-kilometer-long dike on the north river bank;

— A powerhouse on the north side of the river, connected to the dyke via the north dam and the powerhouse north transition (a concrete gravity section);

— A spillway on an existing island, about 1.5 kilometers south of the powerhouse, equipped with seven fixed roller vertical lift gates;

— A powerhouse south transition, central dam, and spillway north transition to connect the spillway and powerhouse; and

— A 2-kilometer-long dike on the south river bank, connected to the spillway by a south dam and the spillway south transition.

River diversion will take place in two stages. Stage I involves construction of a series of cofferdams to allow construction of the principal structures in the dry. Stage II involves closing off the south channel of the river and building two parallel cofferdams to divert flow through the open sluices of the partially completed spillway. During this stage, the south dam will be constructed in the dry.

CFD modeling

The model selected to perform these assessments is FLOW-3D from Flow Science in Santa Fe, New Mexico.[1] This CFD model is capable of simulating the

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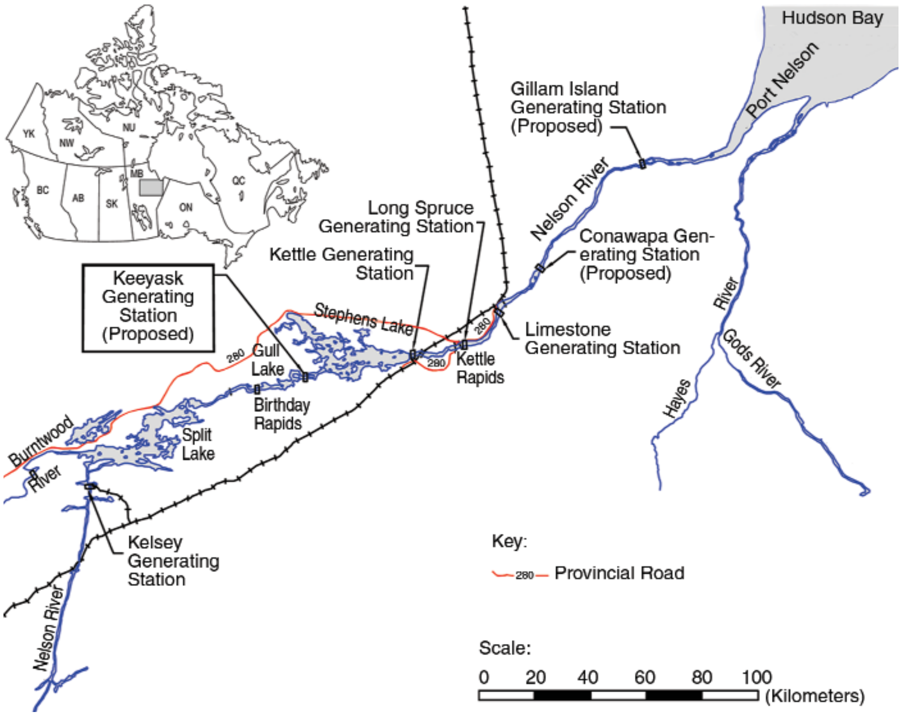

Figure 1: The 675-MW Keeyask Generating Station will be located on the Nelson River, between the existing 1,220-MW Kettle and 224-MW Kelsey stations.

dynamic and steady-state behavior of liquids and gases in one, two, or three dimensions. The model can simulate free surface flows and can handle transitions between subcritical and supercritical flow within a single model setup. These capabilities make it well-suited for simulating the varied and complex flow conditions associated with most water resource projects.

Setting up and calibrating the model

The CFD model covered an area about 3.3 kilometers long by 2.7 kilometers wide. Simulations were conducted to represent flow conditions near the cofferdams during passage of the construction design flood. The initial maximum tailwater level used for the CFD model was 141.1 meters at Stephens Lake, which represents the normal maximum lake level.

The model was later revised using updated bathymetric data used during the physical modeling. The model extent was adjusted to cover the same approximate area as the comprehensive model — 3 kilometers long by 2 kilometers wide — centered on the spillway structure. The boundary conditions were: a velocity boundary to control flow into the upstream end and a continuative outflow boundary at the downstream end (which was controlled by the natural river bed contours).

The model was set up to use the renormalized group turbulent model and the generalized minimum residual method implicit pressure-velocity solver. The renormalized group method was chosen for its robustness. The generalized minimum residual method, although requiring more memory than other methods available in the CFD model, was selected for computational speed. The mesh was set up in terms of Cartesian coordinates (x, y, z) and used nested mesh blocks to refine the grid in areas that required finer meshing. The area around the spillway structure had a grid spacing of 1 meter by 1 meter by 1 meter. This spacing was necessary to resolve the shapes of the spillway piers, abutments, and spillway crest.

Once the CFD model was developed, it was calibrated against stage-discharge curves at gage locations where measurements were available. Some modifications to the downstream portion in the rapids section were required to calibrate the model. Because limited cross-sectional data was available in the rapids section of the river, some changes to the model were made based on photographs taken during lower flows.

Modeling the proposed design

The next step was to construct the cofferdams, spillway structure, abutments, and piers using AutoCAD software. These solid geometric objects then were saved as stereolithographical (STL) files that were brought into the CFD model.

The CFD model was intended to address the principal hydraulic concerns. After gaining confidence in the model's capabilities, it was used to assist in the pre-commitment design studies for the Keeyask station. The model was used to provide guidance on several technical design issues, including:

— Spillway design, including confirmation of spillway discharge estimates;

— Simulation of 3D flow patterns in the forebay and tailrace;

— Refinement of cofferdam layouts;

— Refinement of powerhouse intake design;

— Channel design; and

— Refinement of river management strategies, including river closure.

For the spillway, 3D numerical simulations were undertaken to confirm the anticipated hydraulic performance of the proposed arrangement. Results indicated that pier and abutment losses would be very low. As a result, an approximate 5 percent increase in spillway capacity at the design head could be realized. This allowed designers to raise the spillway invert, thereby reducing overall construction costs.

The river diversion for this project will take place in two stages. The first stage involves blocking the north and central channels to build the central dam and powerhouse cofferdam. The second stage involves removing the spillway cofferdam, to allow construction of the south dam cofferdam across the southern portion of the river. Flow-3D and a one-dimensional backwater model supplied by Flow Science were used to estimate water levels and velocities under open water conditions at various locations during construction of these cofferdams.

The resulting velocity magnitudes were used to determine the size of the stone needed for the rockfill used for construction of the cofferdam, for selected river discharges. It is important to have a good estimate of the velocities and hydraulic forces acting on the rockfill over time. Appropriate rock sizes must be selected to resist drag forces, which will move individual boulders downstream. These design rock sizes vary depending on the degree of advancement of the cofferdam and the local bathymetry along the closure line.

Researchers performed both CFD simulation and physical modeling for a case in which the cofferdam is nearly complete near the right bank closure site. Although velocities calculated

This partial model of the spillway for the proposed 675-MW Keeyask station was developed to confirm rating curves for full and partial gate openings for both diversion and final rollway conditions, as well as to verify pressures and gate behavior.

using the CFD model and those measured using the physical model were similar, the rock size required for closure in the physical model was less than that recommended using theoretical calculations based on the measured velocities. In this case, the theoretical calculations provide a conservative estimate of the required stone size. On the other hand, the physical model allows actual testing of the stone size necessary for closure.

A small project with a limited budget may benefit from the more economical and conservative option of using only CFD modeling. However, for large or potentially sensitive projects, using physical modeling in addition to CFD modeling can provide advantages.

Physical modeling

The LaSalle Consulting Group constructed two physical hydraulic models — a comprehensive model and a partial model — in its laboratory. These models were used to confirm and refine the spillway structure design and to address potential problems during construction of the river diversion cofferdams.

Setting up the models

The comprehensive model, built to scale of 1:120, encompassed a 3-kilometer stretch of the Nelson River, centered on the projected spillway zone. Model boundaries were defined by concrete block perimeter walls, waterproofed on the inside and laid on the laboratory floor. Riverbed contours were drawn on the floor inside the walls using projection slides taken off the bathymetric and topographic charts. Once the contours were traced, aluminum rods were bent to take the individual contour line shape and were then carefully adjusted to the correct level on top of vertical steel rods by means of a laser level.

After the contours were leveled into position and checked, the model was filled with pea gravel (carefully vibrated into place) and leveled flush with the rods. The final step was to consolidate the surface of the gravel with successive applications of liquid cement slurry. Special care was taken to respect as closely as possible a Manning number of 0.035 for a rock surface by lightly applying fine gravel on the final cement coat.

The spillway and sluiceway components were made of Plexiglas, which approximates the roughness of concrete at model scale. The rollways were constructed such that they could be quickly installed in the sluiceways when carrying out tests with the completed bays. Each bay was equipped with two gate slots and gates to allow simulation of the full range of possible flows.

Water was supplied to the model from a permanent pumping station and measured with a calibrated 90-degree V-notch weir (precision of ±1 percent). Entry to the model was via a perforated T-header at the upstream limit. At the downstream end of the model, the tailwater was controlled by the natural river bed contours.

Water levels in the model were determined by means of manually read point gages located above manometer pots. This arrangement allowed measurement of the water surface level to the nearest 0.1 millimeter on the model. Six gages were installed: three along the main river channel (gages NL-17, NL-15, and NL-14), and three in the spillway channels (gages A, B, and C). An additional gage, gage NL-16, was installed downstream from the main dam after completion of the spillway stage I cofferdam construction tests.

Point velocity values were measured at 0.2 and 0.8 of the depth of the model using a mini-current meter from Nixon equipped with a 12-millimeter propeller.

To obtain an overall evaluation of the flow conditions at any given location, researchers used time lapse photography to obtain surface velocities and trajectories. A digital camera was installed on a tripod above the zone to be covered, and surface floats were introduced into the flow upstream. Successive photographs were taken at known time intervals as the floats moved downstream. Velocity was calculated using the distance traveled by each float and the time interval between photos.

Modeling the proposed design

The first model test consisted of verifying stage-discharge curves at the gage locations where measurements were available. Initial calibrations showed water levels were too high in the downstream area of the model and too low in the upstream area. As a result, researchers lowered bed contours by 1 to 2 meters at the downstream end of the model and placed small clusters of rocks to increase the upstream riverbed roughness. These modifications resulted in obtaining model rating curves that were very close to the prototype.

Figure 2 on page 4 shows the comparison of CFD model and physical model rating curves and the prototype measurements for four different discharges between 1,600 cms and 6,100 cms at gage NL-17. The curve at this gage and the other two gages (NL-15 and NL-14) show good agreement.

Three batches of model material were prepared by blending sand, screenings, and gravel to obtain the average diameter and gradation range specified in the study requirements.

Modeling the spillway

Physical model tests also were carried out to reproduce construction of the cofferdam needed to build the spillway during a constant flow of 3,930 cms (1:2 year mean daily discharge). The most

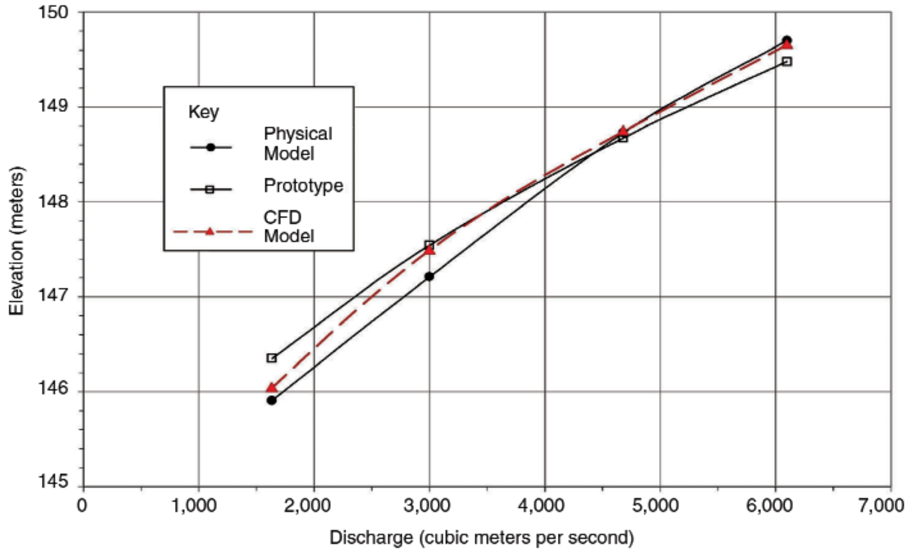

Figure 2: Comparison of the rating curves at one gage in the physical model for the 675-MW Keeyask station shows good agreement between the physical model, CFD model, and prototype.

critical zone during construction of this cofferdam was found to be at the upstream corner. This is where maximum velocities (about 5 meters per second) were measured. Once past this corner, the main flow followed the south channel of the river. This flow concentration, combined with the local bed form, resulted in the formation of back eddies along the river leg of the cofferdam. Velocities in that zone were low.

A similar flow pattern was observed at the downstream corner, and the final downstream leg of the cofferdam was also in a zone of very low velocities.

Water levels at gages NL-17 and NL-15 start to increase when about one-third of the cofferdam is built. Water levels at gage NL-14 remain unchanged.

With this cofferdam completed, the maximum rise in water level is about 0.55 meter at gages NL-17 and NL-15 and 0.2 meter at gage NL-14. The rise in water level will submerge one of the downstream islands.

After completion of this cofferdam, flow in the model was increased to 6,240 cms, the construction design flood. The cofferdam crest elevation was found to give the prescribed 1-meter freeboard predicted by the CFD model.

The spillway capacity tests with the initial configuration of the diversion structure showed that flow control was taking place at the entrance to the approach channel and not at the structure, due to high bed levels.

As a result, upstream water levels were higher than those anticipated from the original CFD studies. The original CFD model had assumed a bed elevation of 144 meters upstream of the spillway approach channel, as a result of limited bathymetric data in this area at the time of model construction. Newer bathymetric data used in the physical model upstream of the spillway approach channel resulted in the increased water levels. Excavation of the river bed to reduce the entrance of the approach channel to elevation 144 meters was carried out to lower upstream water levels to target values. With the entry of the channel excavated to elevation 144 meters, excavation along the left bank was limited to a small zone near the entrance to the approach channel. The spillway structure invert was raised by 0.6 meter, to an elevation of 138.9 meters, without affecting the upstream water levels. Subsequently, incorporating these changes into the CFD model confirmed that raising the spillway invert would not affect the upstream water levels during diversion.

Before construction of the cofferdam needed for construction of the south dam, the upstream and downstream legs of the spillway cofferdam were removed. Tests on the model showed that leaving the river leg cofferdam remnants in place had no effect on the spillway capacity and that the upstream leg of the cofferdam should be left in the upstream corner. This creates a zone of back eddies and low velocities in the first 250 meters of the south dam cofferdam upstream axis, thus maximizing the length along which it is possible to advance the south dam cofferdam with quarry run material.

Closure of the Nelson River with the south dam cofferdam was identified in the planning stage as one of the most difficult construction activities. To guard against all eventualities, three construction schemes were devised: single-, double-, and three-leg advancement approach. The cofferdam tests using the physical model showed that the single-leg method was feasible. Therefore, the other approaches were not tested.

The physical model test results also showed that the critical zone for advancement (i.e., where an increase in material from quarry run to average stone size of 0.6 meter is required) was located between 120 and 100 meters from the south bank. This zone applied to all flow rates tested. For all flow cases tested, the use of an average stone size of 1.2 meters was not required.

The natural profile of the south shoreline opposite the south dam cofferdam axis contributes in diverting the river flow away from the shore. As a result, velocities along the south shore both upstream and downstream of the south dam cofferdam are low and bank protection was not required.

Tests were done on the model to optimize the discharge channel configuration. Ideally, flow should be spread out as evenly as possible across the spillway discharge channel to maximize energy dissipation. However, it was observed that the flow in the discharge channel was skewed toward the right bank, due to the high bed levels at the discharge channel outlet along the left bank.

To reduce this skewness, the width of the discharge channel was modified. The right and left wall alignments were gradually adjusted until flow in the discharge channel was uniformly distributed. The final configuration resulted in a downstream width of 133 meters, instead of the original width of 215 meters. With the final rollways installed, the spillway capacity was tested for a wide range of flow conditions, from 3,000 cms to the spillway capacity design flow of 11,300 cms. Comparison of the model water levels registered at gage NL-15 and the theoretical levels showed good agreement.

Developing a partial model

A partial model consisting of two full bays and two half bays of the spillway, together with 200 meters of approach and 175 meters of tailrace channel, was constructed at an undistorted scale of 1/50.

Tests were carried out to confirm theoretically derived rating curves for full and partial gate openings for both diversion and final rollway conditions. Tests were also made to verify pressures and gate behavior. These latter tests were dynamic and carried out with an aluminum gate equipped with a hydro-elastic hoist system.

The physical model test results for diversion and final rollway conditions with the gates fully open were compared to Flow 3-D simulations carried out by McGill University.[2] The result of the CFD and physical modeling for this aspect agreed very closely. With the diversion sluiceway fully open, the difference in results was 0.85 percent or less. With the final rollways fully open, the difference in results was 5.25 percent or less.

Lessons learned

There appears to be promising agreement between the results of the two modeling techniques. From using CFD analysis over the past ten years, our level of trust has increased to the point that we are now confident in using CFD modeling for general study purposes and some final design applications. Physical modeling is still recommended for final confirmation on major hydraulic applications where a significant element of risk is involved either for construction and/or operation.

CFD modeling has been found to be suitable in determining the final conceptual configuration for the hydraulic design of the facility in a relatively short time frame. It provides flexibility in being able to quickly change the conceptual details and configuration and allows the design to advance in stages, first using a coarse grid/mesh to scope the design and then refinining the grid/mesh as the design advances. It must be noted that care is required in setting up the CFD model (which comes from experience), which has a direct bearing on the modeling results. Another consideration is that the cost to buy or rent the CFD model is high, and this cost needs to be weighed against the cost of a physical model study.

On major design projects, it is recommended that both modeling techniques be integrated during design to provide the optimum hydraulic engineering solution. During the early stages of design, CFD modeling is quite adequate for purposes of feasibility and pre-engineering design. Before advancing to final design, the element of risk should be evaluated to determine whether confirmatory physical modeling would add value engineering to the final design. ■

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Notes

[1]"FLOW-3D User's Manual," Flow Science, Pasadena, Calif., 2002.

[2]Gacek, J., and S. Gaskin, "Thesis for Master of Engineering: Numerical Simulation of Flow through a Spillway/Diversion Structure," Department of Civil Engineering and Applied Mechanics, McGill University, Montreal, Canada.

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