COMPUTATIONAL FLUID DYNAMICS: DIVERSE APPLICATIONS IN HYDROPOWER PROJECT's DESIGN AND ANALYSIS

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ABSTRACT

Hydropower Dam designers and developers are discovering the capabilities of computational fluid dynamics for a range of applications, from hydraulic design to the analysis of dam break flooding.

The design and engineering assessment of hydroelectric facilities involves developing an understanding of the very complex behaviour of moving water. To accomplish this, the engineer must develop a thorough understanding of the complexities of fluid flow phenomena - complexities that are often highly two and three dimensional in nature. In early years, physical model studies would have been the only practical medium available to gain insight into the three-dimensional and time-dependent nature of fluid flow. However, physical modelling is typically only undertaken during the final stages of design, and can be costly to execute. With the advancements in computing power made since the 1980's, CFD analysis has emerged as a powerful alternative design tool, and can be used to provide insight into hydraulic design at all levels of study.

Manitoba Hydro and Acres International Ltd., both of Winnipeg, Manitoba, Canada, have undertaken an extensive 3-dimensional modelling program as a part of pre-commitment level studies for three proposed hydropower projects in Northern Manitoba. These three projects are the Gull Generating Station (680 MW) on the Nelson River, near Gillam, Manitoba, and the Notigi (100 MW) and Wuskwatim (200 MW) Generating Stations, both on the Burntwood River, near

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Thompson, Manitoba. A sophisticated computer model, FLOW-3D®, was carefully reviewed and tested prior to ensure its use as a design tool would be appropriate. Following this confirmation, the 3-dimensional model was used to evaluate a number of complex hydraulic design issues associated with these three plants.

1) INTRODUCTION

The design and engineering assessment of hydroelectric facilities involves developing an understanding of the very complex behavior of moving water. In designing each component of a proposed facility, the engineer must be able to efficiently and reliably verify the adequacy of the hydraulic design under all plant operating conditions.

To accomplish this, the engineer must develop a thorough understanding of the complexities of fluid flow phenomena - complexities that are often highly two and three dimensional in nature. In early years, physical model studies would have been the only practical medium available to gain insight into the three-dimensional and time-dependent nature of fluid flow. However, physical modeling is typically only undertaken during the final stages of design, and can be costly to execute. Recently, computational fluid dynamics (CFD), has gained wide acceptance in the design and evaluation of the performance of hydraulic structures and machinery, providing a valuable complement to traditional engineering methods.

CFD analysis involves the solution of the governing equations for fluid flow, the Navier Stokes equations, at thousands of discrete points on a computational grid, giving the analyst a full three dimensional representation of the fluid flow domain. These numerical simulation capability gives engineers the power to quickly and inexpensively explore different design options and often demonstrates how a water resource project can be constructed and or operated more efficiently. It can be used early in the design phase to provide initial insight into critical design issues, and can also be used to compliment or reduce the need for any planned physical model studies.

Recently, Acres Manitoba Limited (Acres) and Manitoba Hydro used CFD analysis to advance hydraulic design in pre-commitment studies for a number of major hydroelectric projects in northern Manitoba. These projects include the Gull Generating Station (675 MW) on the Nelson River, near Gillam, Manitoba, and the Notigi (117 MW) and Wuskwatim (210 MW) Generating Stations, both on the Burntwood River, near Thompson, Manitoba. A sophisticated computer model, *FLOW-3D*®, was carefully reviewed and tested prior to its use as a design tool. Following this test phase, Acres and Manitoba Hydro utilized the three-dimensional model to evaluate a number of complex hydraulic design issues associated with these projects. The proposed Wuskwatim project forms the focus of this paper.

2) PROJECT BACKGROUND

The Wuskwatim Generating Station will be located on the Burntwood River just downstream of Wuskwatim Lake. Situated at the site of Taskinigup Falls, the plant will develop approximately 22 m of head, will have a total powerhouse discharge capacity of 1100 m^3/s, and will boast a total generating capacity of 210 MW. During times of flood on the Burntwood River, excess flow will be discharged through a 3 bay spillway structure, located to the north of the main powerhouse. The plant will be capable of passing the Probable Maximum Flood discharge, estimated to be approximately 2650 m^3/s.

The three dimensional rendering drawing shown in Figure 2.1 illustrates the overall project layout. In this figure, the foreground shows the main dam and powerhouse, with the forebay at its full supply level. The spillway is located to the left of the powerhouse.

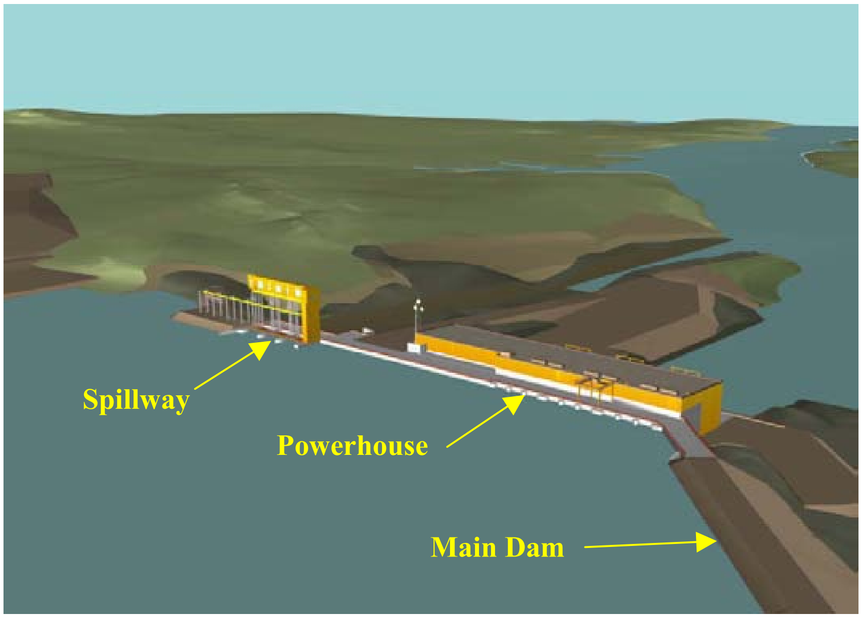


Figure 2.1*: Three-dimensional rendering of Wuskwatim project layout.*

Acres were responsible for the engineering design of each of the project's components. Given that the results of these studies (and the corresponding cost estimates for the plant) would be used by Manitoba Hydro in making important investment decisions, it was important that the designs be to the highest level possible for a pre-investment study. In order to ensure the utmost quality in the hydraulic design of the structures, a state-of-the-art numerical model was selected and used to test and refine design concepts. Normally,

physical model studies would have been the only means available to provide additional insight into the complex flow conditions resulting from the interaction of hydraulic structures with flowing water, but such costly studies would not typically be undertaken until the final design phase of the project. By using advanced numerical modelling techniques, the design engineers were able to identify and address critical design issues early in the design phase and optimise the overall hydraulic design.

Accordingly, the *FLOW-3D*® model (Flow Science, 1997), developed by Flow Science Incorporated of Los Alamos, New Mexico, USA was selected for use in this important task. It is a CFD model capable of simulating the dynamic and steady state behavior of liquids and gases in one, two or three dimensions and does so through solution of the complete Navier Stokes equations of fluid dynamics. Further detail on the model is given in section 3.

3) FLOW-3D

FLOW-3D® is a well-tested, high fidelity CFD software product developed and supported by Flow Science, Inc. It is designed to assist the investigation of the dynamic behavior of liquids and gases in a very broad assortment of applications. *FLOW-3D*® has been designed for the treatment of time-dependent (transient) problems in one, two and three dimensions. Steady state results are computed as the limit of a time transient. Because the program is based on the fundamental laws of mass, momentum, and energy conservation, it is applicable to almost any type of flow process. For this reason, *FLOW-3D*® is often referred to as a "general purpose" CFD solver.

One of the major strengths of the *FLOW-3D*® program for hydraulic analysis is its ability to accurately model problems involving free surface flows. An interface between a gas and liquid is referred to as a free surface. In *FLOW-3D*®, free surfaces are modeled with the Volume of Fluid (VOF) technique, which was reported in Hirt and Nichols (1981). The VOF method consists of three ingredients: a scheme to locate the surface, an algorithm to track the surface as a sharp interface moving through a computational grid, and a means of applying boundary conditions at the surface.

FLOW-3D® uses a simple grid of rectangular elements, so it has the advantages of ease of generation, regularity for improved numerical accuracy; and it requires minimal memory storage. Geometry is then defined within the grid by computing the fractional face areas and fractional volumes of each element that are blocked by obstacles. The equations of motion are solved based on a finite difference technique.

FLOW-3D® includes great many physical models, including shallow water, viscosity, cavitation, turbulence, sediment scour, homogenous and adiabatic bubbles, surface tension, porous media, particles and more. Among the industries in which *FLOW-3D®* is put to use are: metal casting, ink jet design, process engineering, consumer products, civil hydraulics, environmental engineering, aerospace, coating, maritime, oil & gas and MEMS.

4) VERIFICATION OF MODEL

The use of CFD analysis is relatively new to the engineering community, and prior to relying on CFD analysis to assist in the hydraulic design of the proposed hydropower projects, considerable effort was made to verify the performance of the model under a number of real life applications. The model had been used with good success by engineers at Acres over a period of approximately three years to study a variety of complex hydraulic design issues. These past projects included the successful modeling of:

- Two and three dimensional dambreak studies
- Hydroelectric Intake and Spillway design
- Channel Improvement studies on a large northern river

- Replication of past physical model studies to verify model performance
- Fishway design
- Trash boom design
- Dilution studies of a contaminated lake
- Confirmation of existing Spillway capacity
- Prediction of Intake head loss.

But perhaps what most impressed the design team over this period of time was the ability of the model to replicate the results of past physical model studies and observed field measurements, with very good success. Three such example applications are described below.

4.1) Simulation of Conawapa Diversion Port

Physical model study tests were previously carried out to refine estimates of discharge through the 8-m high diversion ports of the proposed 1390 MW Conawapa Generating Station on the Nelson River. Flow conditions through the ports are highly three dimensional in nature, and in the past physical model studies were the only practical medium available to develop discharge estimates for these large structures. To establish confidence in the *FLOW-3D®* model's ability to predict discharge capacity through a diversion port structure, the model was configured to replicate the Conawapa physical model study (Lasalle Consulting Group Inc., 1992). Figure 4.1 illustrates a section view through the diversion port, as setup within the *FLOW-3D®* model.

The physical dimensions of the diversion port simulated with the *FLOW-3D®* model were based on the prototype dimensions used to configure the actual physical model. Fluid properties in the numerical model (viscosity, density, etc) were set to standard properties for water at a temperature of 20 degrees Celsius. Two test cases were then simulated representing operation of the fully open port at headpond elevations covering the anticipated operating range during diversion.

A comparison of the *FLOW-3D*® results, shown in Figure 4.1, confirmed the *FLOW-3D*® model's accuracy in matching the physical model test results.

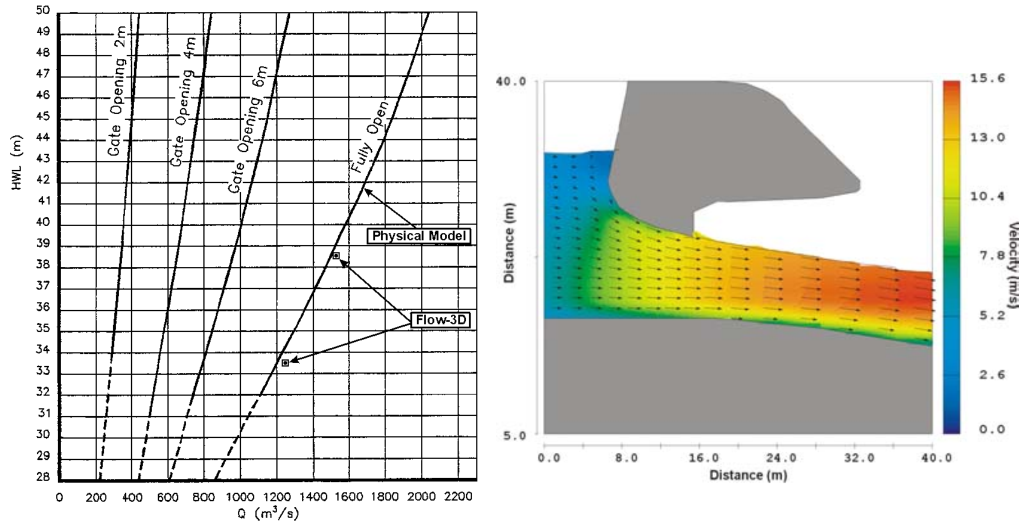


***Figure 4.1**: This figure presents a comparison of the CFD results with results from a physical model study for a fully open diversion port (see left) and a velocity magnitude profile of the FLOW-3D® results (see right).*

4.2) Simulation of Conawapa Stage II Diversion

A second simulation was undertaken which tested the model's ability to replicate complicated flow patterns. For this case Acres developed a simulation of a diversion scheme proposed to be used during the construction of the Conawapa hydropower project. In earlier design studies employing physical model studies, engineers found that one particular diversion scheme resulted in the formation of some very intriguing flow patterns in the model. As illustrated in Figure 4.2, taken from the actual model study report (Northwest Hydraulic Consultants LTD., 1992), flow was being diverted through the partially completed powerhouse and the completed spillway structure. The partially removed Stage I cofferdam created a significant barrier to flow, particularly as it approached the north bank powerhouse location. As shown in Figure 4.2, the *FLOW-3D*® model closely reproduced both the flow patterns and the magnitudes of flow velocity observed in the physical model.

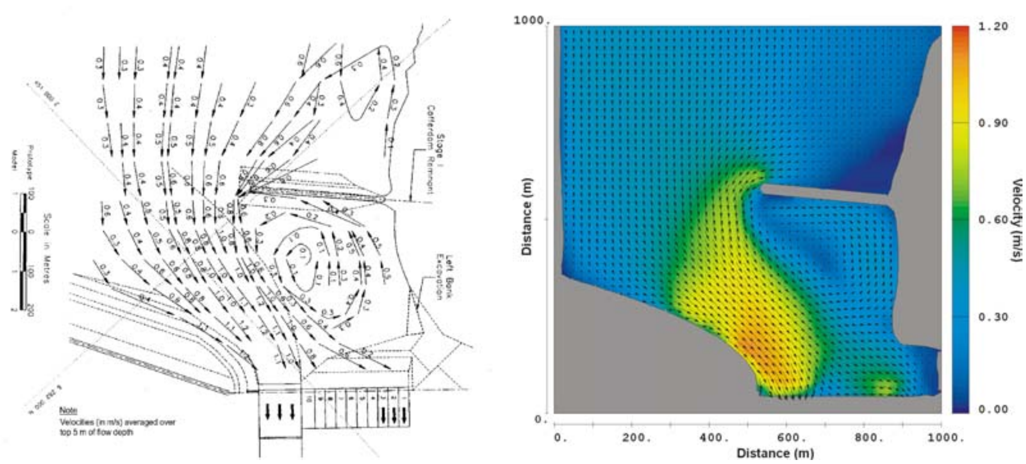


***Figure 4.2**: Manitoba Hydro initially used a physical model to analyze flow behavior at a diversion structure for the proposed Conawapa hydro project (see left). Then a computational fluid dynamics model was applied to the same diversion design, in a simulation that closely reproduced both the patterns and magnitudes of flow velocity observed in the physical model study (see right).*

4.3) Simulation of Kelsey Generating Station

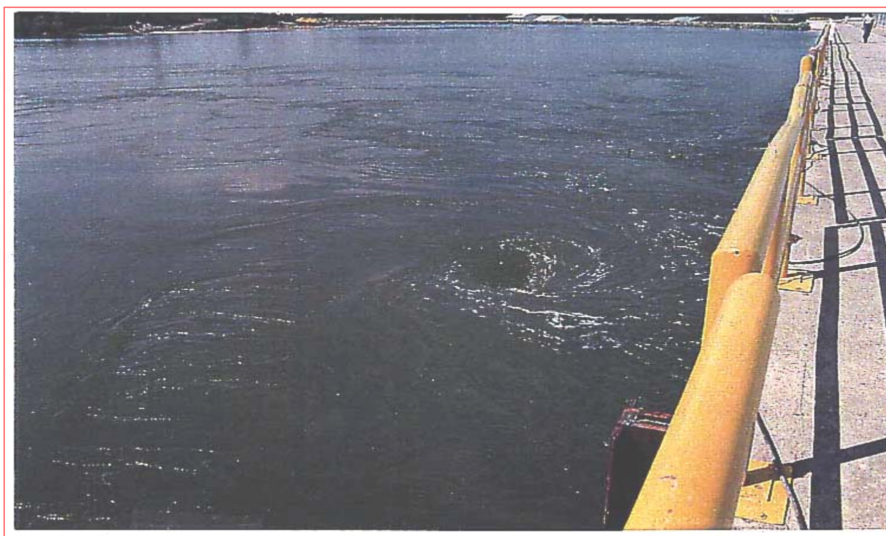
The quality of the flow approaching a powerhouse and the resulting intake velocity distribution will have an impact on the turbine performance characteristics of a hydroelectric plant. Asymmetrical flow conditions resulting from an upstream flow obstruction, or a curved approach channel can reduce a plant's generating capacity significantly. This was the case at Manitoba Hydro's 223 MW Kelsey hydroelectric plant located in northern Manitoba. Site personal had observed an increased head loss across units 6 and 7 of station's seven units Powerhouse, located on the Nelson River.

Based on gathered observations, it was known that this hydraulic problem is highly three-dimensional in nature, and would not be adequately addressed using 1-D or even 2-D numerical models. To compound the complexity of the problem, flow conditions are affected not only by the approach channel geometry, but also by the accumulation of debris and trash at these two units.

These conditions result in the formation of a large eddy and vortex upstream of units 6 and 7.
This vortex formation results in the loss of hydraulic efficiency since it:

- Produces nonuniform flow conditions
- Introduce air into the flow, potentially creating rough operating conditions for hydraulic machinery, increasing head loss and decreasing unit efficiency
- Draws debris into the intake.

The *FLOW-3D*® model was setup to simulate the Kelsey Generating Station approach channel and intakes. *FLOW-3D*® was able to simulate the eddy, and its approximate location under typical operating conditions as seen in Figures 4.3 and 4.4. Differential head losses were calculated using unit 4 as a benchmark. Head losses resulting from the asymmetric approach channel configuration were found to be 0.61 ft for unit 7 and 0.52 ft for unit 6. Although slightly low, these simulated losses agreed well with observed losses.



Infront of unit 7

Figure 4.3*: Formation of Eddy in front of unit 7 at Kelsey Generating Station.*

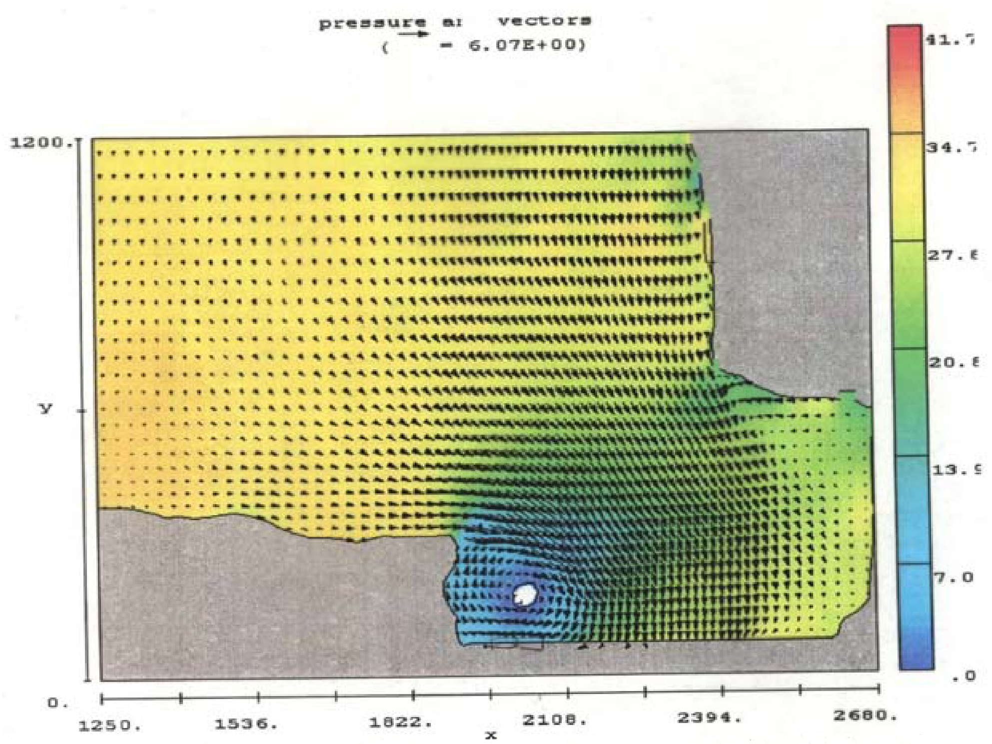


Figure 4.4: *FLOW 3D model of Formation of Eddy in front of unit 7 at Kelsey Generating Station.*

5) Sample Design Applications

After gaining confidence in the numerical model's capabilities, the model was used to assist in the pre-commitment level design studies for the proposed Wuskwatim Generating Station. The model was setup and used to provide guidance on a number of technical design issues, including but not limited to:

- Spillway design, including confirmation of spillway discharge estimates
- Simulation of three dimensional flow patterns in the project's forebay and tailrace area
- Refinement of cofferdam layouts
- Refinement of powerhouse intake design
- Channel design
- Refinement of river management strategies, including river closure.

Although it would not be possible to describe in detail each of the applications described above within the limitation of this paper, a number of representative examples have been presented below as they relate to the design of the Wuskwatim project.

5.1) Intake Design Comparison

The proposed Wuskwatim powerhouse is equipped with three units, and has a maximum plant capacity of 1100 m^3/s. As a part of the powerhouse design, the *FLOW-3D®* model was used to evaluate the overall hydraulic performance of a number of powerhouse intake configurations. Two of these alternatives are shown in Figure 5.1. The use of a three-dimensional numerical model allowed design engineers to quickly visualize resultant flow fields, and evaluate alternative designs early in the design process.

Based on the simulation results, it was concluded that each of the tested alternatives produced a relatively streamlined flow field, minimizing the potential for formation of air entraining vortices. Each alternative was also tested to ensure that cross flow velocities within the intake were minimized, and that there was an equal distribution of flow between all three units. The primary difference between alternatives was in the vertical distribution of flow at the Intake entrance, as shown in Figure 5.1. Of the designs tested, the alternative shown in the right side of Figure 5.1 exhibited the most even distribution of velocity, resulting in the lowest estimated trashrack losses at the entrance to the Intake.

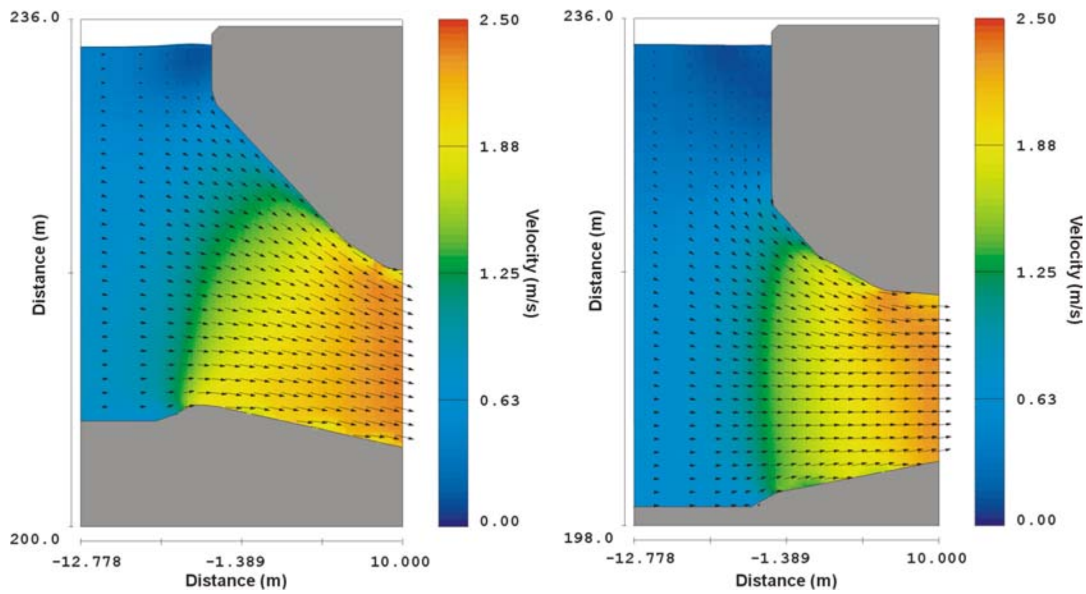


Figure 5.1*: 3-D Model of velocity profiles for two alternative intake designs for the Wuskwatim project.*

5.2) 3-D Spillway Model

Three-dimensional numerical simulations were also undertaken to assist in the hydraulic design of the Wuskwatim spillway structure. The proposed spillway for this project is comprised of three gated sluiceways, each nine meters wide, separated by intermediate piers. The spillway is designed to handle the Probable Maximum Flood (PMF) of 2650 m^3/s at a design head of 15.8 m. The approach channel to the spillway consists of a relatively deep channel excavated into rock. In order to maximize spillway efficiency, designers aligned the approach channel sidewalls to coincide closely with the spillway entrance wall – a feature that was expected to reduce abutment contraction losses for the structure.

A three-dimensional numerical model was setup and utilized to confirm the anticipated hydraulic performance of the proposed arrangement. The results indicated lateral contraction effects, and therefore abutment losses, would be substantially decreased for the proposed design, and as a result an approximate 5% increase in spillway capacity at the design head was realized. This in turn allowed designers to raise the spillway invert, thereby reducing overall construction costs.

The model was also utilized to assess the need for downstream stoplogs and guides for the spillway structure. The spillway discharges into a relatively steep channel, and as a result it was anticipated that little would be required to protect against tailwater effects in the event that one of the bays were to be closed for maintenance, while other bays continued to operate. To test this assumption, a three-dimensional D model was setup of the spillway in which a single bay was assumed to be closed, while the other two bays operated with the gates fully raised. Figure 5.2 shows the results of the simulation. As shown, the momentum of the water being discharged from the operating bays prevents water from entering the "dry" bay from downstream. Accordingly, downstream stoplog requirements for the structure were reduced, again lowering overall anticipated construction costs.

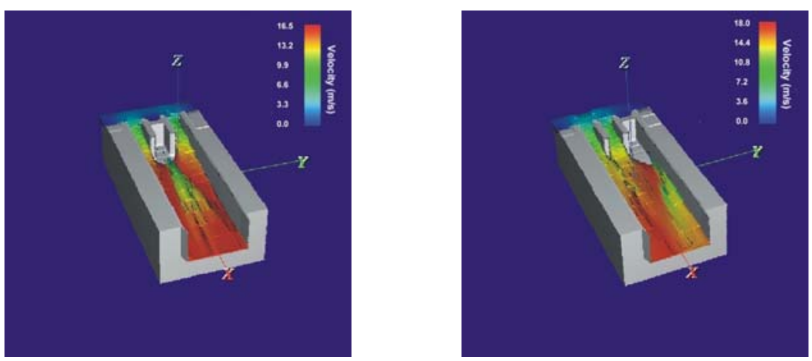


Figure 5.2: *Three-dimensional velocity magnitude plots of Wuskwatim spillway during the construction design flood, with north bay closed (see left) and with center bay closed for maintenance (see right).*

5.3) Ice Formation and Approach Channel Performance

For power plants located in northern environments, it is essential that upstream flow conditions allow for the development of a strong and stable ice cover during the winter period. Should a cover fail to form, frazil ice generated in the open water reaches will pass through the plant, potentially accumulating on trashracks and within water passages. The steady growth of this frazil ice accumulation will eventually constrict flow, leading to excessive headloss and consequently a loss in generation capacity.

In order to prevent this from happening at Wuskwatim, the intake and approach channels were carefully designed to allow for the early formation of an ice cover by juxtaposition of frazil pans. Based on experience gained at other locations in northern Manitoba and elsewhere, to induce the formation of a stable, juxtaposed ice cover, the velocity and Froude Number along the channel have been limited to 0.7 m/s and 0.07 respectively under full plant operating conditions. The resulting flow conditions were modeled with the aid of a three dimensional numerical model to evaluate the velocities and flow patterns associated with the final channel design. The purpose of the simulation was two fold: to ensure that surface velocities along both the natural and the excavated approach channel did not exceed the limiting value of 0.7 m/s, and to ensure that the excavated channel immediately upstream of the powerhouse structure smoothly conveys powerhouse flows down into the intake structure. The results of the simulation presented in Figures 5.3 and 5.4 confirmed the appropriateness of the design.

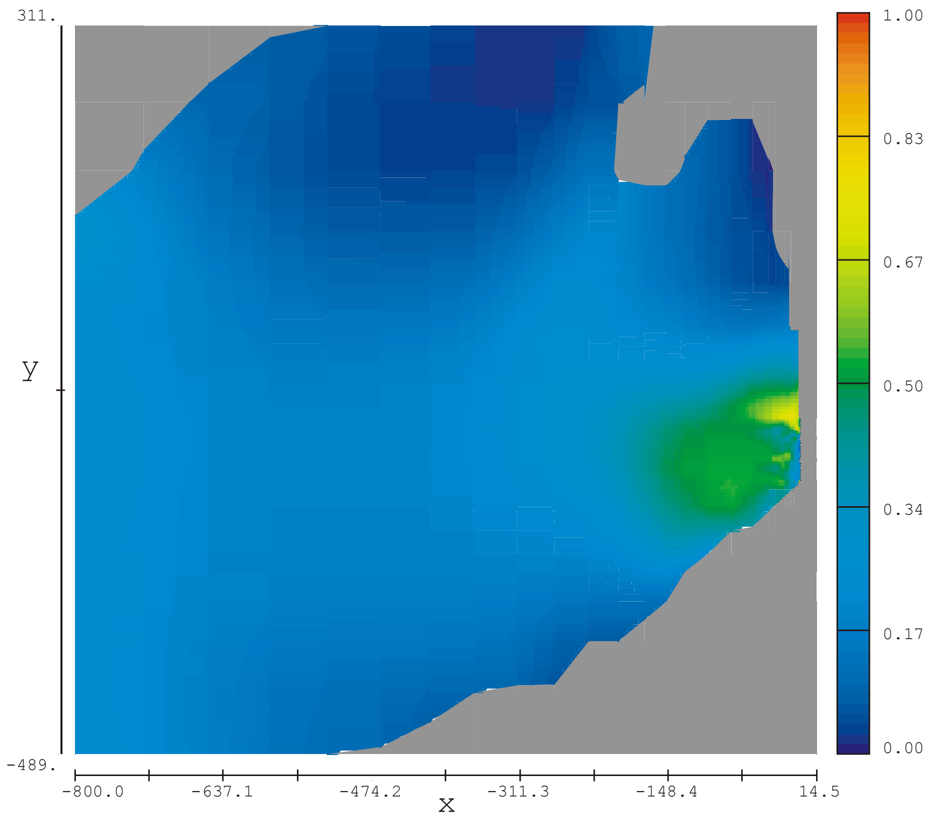


***Figure 5.3**: Plan view of surface velocity magnitude for Wuskwatim forebay at FSL of 234 m.*

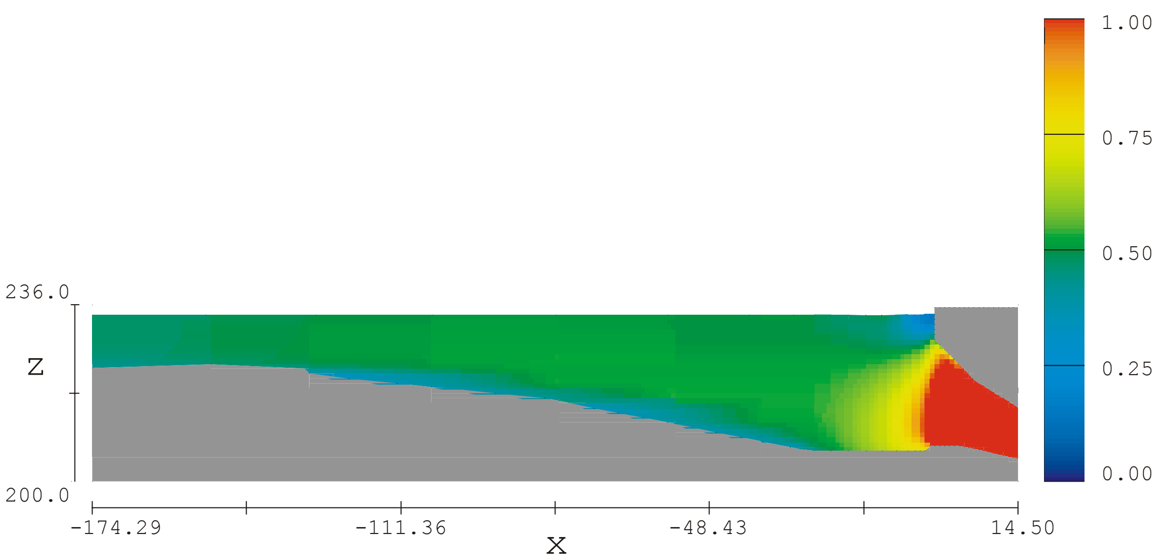


***Figure 5.4**: Profile of velocity magnitude along Wuskwatim intake channel.*

5.4) Simulation of River Closure

River closure is an important component of any river management scheme. At Wuskwatim, the Main Dam is to be constructed within the natural river channel at the head of Taskinigup Falls. Before construction of the dam can take place, flow in the natural river channel must be diverted through the fully completed spillway in order to allow closure of the river, and dewatering of the dam's foundation area. This will be accomplished at Wuskwatim through the advancement of a single rockfill cofferdam across the brink of Taskinigup Falls. As this cofferdam is advanced, it forms a barrier to flow over the falls and causes flow to be diverted through the completed spillway structure. Once the cofferdam been completely advanced across the river, all flow will be through the completed spillway, and the closure operation will be complete.

In planning for the river closure operation, it is important to have a good estimate of the velocities and tractive forces acting on the dumped rockfill as the cofferdam is advanced. Appropriate rock sizes must be selected to resist drag forces, which will act to move individual boulders downstream. These design rock sizes will vary depending on the degree of advancement of the cofferdam, and the local bathymetry along the closure line.

To provide the best estimate possible in these design studies, the FLOW3D model was setup to simulate the river closure operation in a full three-dimensional format. The model was initially setup and calibrated to represent the natural river channel based on existing topographic data and sounding lines. The model was able to closely match existing rating curves upstream of the falls, providing confidence in its representation of the area hydraulics. Following this, the setup was modified to include the proposed spillway and approach channel, previously setup and calibrated as a part of an earlier initiative. This combined model was run to assess hydraulic conditions for varying extents of cofferdam closure. In each case, predicted velocity profiles in the vicinity of the tip of the advancing cofferdam were used to determine the required rock sizes for that end location. The necessary stone size to prevent movement by flowing water was calculated using the predicted velocity, and the Izbash equation. Based on the study results, the highest velocity achieved during closure operations (5 m/s) occurred at a point some 20-m from the right bank closure site. The stone size required to resist movement at this critical location was estimated to be 0.81 m.

Figure 5.5 illustrates sample simulation results for a case in which the cofferdam has been advanced to within 20 m of the right bank closure site.

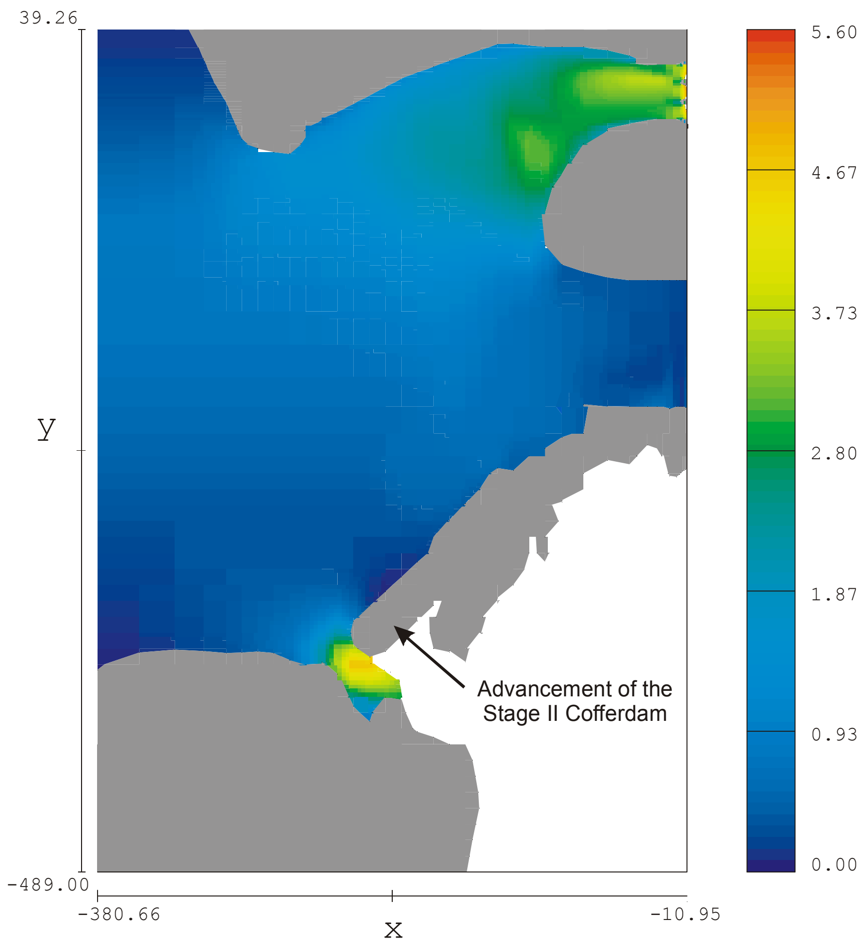


***Figure 5.5**: Plan view of velocity magnitude of Wuskwatim river closure.*

6) SUMMARY

CFD analysis has been successfully utilized to provide considerable design support for advanced hydropower design. The use of this tool has allowed engineers at Manitoba Hydro and Acres Manitoba Ltd. to provide early input to critical design issues, and to refine hydraulic design to a level normally achieved only through the undertaking of physical model studies. The CFD model can also be used to provide insight into any planned physical models, allowing designers to streamline the testing program by reducing the number of options to be evaluated. In the case of the Wuskwatim project, the confidence gained through the use of the three dimensional numerical model allowed engineers to eliminate the need for a costly comprehensive physical model at the final design level.

Insights gained through detailed modeling of the Spillway structure have allowed design engineers to raise the proposed invert level for the structure, and to reduce requirements for downstream stoplogs – both resulting in significant cost savings to the project. The high level of engineering afforded through CFD analysis lessens the risk that major modifications may be necessary at later design phases. These modifications would likely add to the cost of the project, and hence a more refined design will provide a better overall cost estimate at the early phase. Also, the three dimensional models developed for use in these pre-investment studies will be available for use in final design studies, allowing engineers to quickly check the impact of any proposed modifications to be considered during the final design phase.

Finally, the benefits achieved through this detailed numerical analysis reach beyond the initial project benefits. The successful application of CFD analysis in these studies is a major step towards increasing the industry's confidence in the use of CFD techniques to assist in all types of hydraulic design whether for waterpower, flood control, irrigation, navigation or water supply.

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David M. Fuchs, P. Eng., is an Intermediate Engineer at Acres Manitoba Ltd. He was involved in the detailed model setup, running the model, obtaining results, preparation of figures and also participated in the hydraulic design for the proposed hydroelectric projects presented in this paper.

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