TECHNICAL NOTE / NOTE TECHNIQUE

Assessment of spillway modeling using computational fluid dynamics

Paul G. Chanel and John C. Doering

Abstract: Throughout the design and planning period for future hydroelectric generating stations, hydraulic engineers are increasingly integrating computational fluid dynamics (CFD) into the process. As a result, hydraulic engineers are interested in the reliability of CFD software to provide accurate flow data for a wide range of structures, including a variety of different spillways. In the literature, CFD results have generally been in agreement with physical model experimental data. Despite past success, there has not been a comprehensive assessment that looks at the ability of CFD to model a range of different spillway configurations, including flows with various gate openings. In this article, Flow-3D is used to model the discharge over ogee-crested spillways. The numerical model results are compared with physical model studies for three case study evaluations. The comparison indicates that the accuracy of Flow-3D is related to the parameter P/H_d.

Key words: computational fluid dynamics, numerical, physical model, spillway, rating curve, Flow-3D.

Résumé : Les ingénieurs en hydraulique intègrent de plus en plus la dynamique des fluides numérique (« CFD ») dans le processus de conception et de planification des futures centrales. Ainsi, les ingénieurs en hydraulique s'intéressent à la fiabilité du logiciel de « CFD » afin de fournir des données précises sur le débit pour une large gamme de structures, incluant différents types d'évacuateurs. Les résultats de « CFD » dans la littérature ont été globalement sont généralement en accord avec les données expérimentales des essais physiques. Malgré les succès antérieurs, il n'y avait aucune évaluation complète de la capacité des « CFD » à modéliser une plage de configuration des évacuateurs, incluant les débits à diverses ouvertures de vannes. Dans le présent article, le logiciel Flow-3D est utilisé pour modéliser le débit par des évacuateurs en doucine. Les résultats du modèle de calcul sont comparés à ceux des essais physiques pour trois études de cas. La comparaison montre que la précision du logiciel Flow-3D est associée au paramètre P/H_d.

Mots-clés : dynamique des fluides numérique, numérique, essais physiques, évacuateur, courbe des débits jaugés, Flow-3D.

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Introduction

In recent years, numerical modeling techniques have been increasingly applied in an array of engineering applications. Computational fluid dynamics (CFD) is a type of numerical method aimed at solving problems involving fluid flow. A variety of diverse problems can be reproduced using CFD including the flow of water around solid objects and structures. This type of application is of considerable interest to hydraulic engineers in the design process of spillways for hydroelectric generating stations.

Information regarding the flow of water over spillways has historically been obtained through the use of physical model experiments. In these studies, scaling laws are used to perform experiments on miniature versions of hydraulic structures. Construction of scale models, as well as renting a facility, obtaining the required instrumentation, and hiring skilled researchers to perform the testing, can be quite costly. Physical model testing can also be very time consuming and as a result, physical model studies are normally only carried out in the later stages of the design process. Computational fluid dynamics presents a cost-effective solution that can be easily employed throughout the entire design process. Hydraulics engineers are therefore interested

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in CFD and are eager to verify the capability of the numerical modeling software.

The following paper will introduce results obtained using the CFD software Flow-3D (Flow Science, Inc. 2007) and compare the data to that obtained from physical model experiments. Attention will focus on the ability of CFD to model gated discharges.

Flow-3D background

Flow-3D has the ability to ignore the air surrounding the flowing water by using the volume of fluid (VOF) method developed by Hirt and Nichols (1981). This method also allows the numerical model to create a sharp interface between the water and air without using the fine meshes required by other CFD software. Another method, developed by Hirt and Sicilian (1985), known as the fractional area–volume obstacle representation (FAVOR) method, is also a trademark of Flow-3D. It allows the program to use fully structured grids that are very easy to generate throughout the entire flow domain. Other CFD programs may require the use of deformed grids to model flow over and around structures. Flow-3D utilizes a finite difference solution scheme and also has the ability to calculate solutions using various implicit and explicit solver options. The ability of using multiple and nested meshes as well as the re-run capability available in Flow-3D are other options that make the numerical model suitable for spillway modeling.

Over the past decade, many studies have been completed that compare experimental results obtained using numerical models with data obtained in physical model testing and (or) established design guides. Most of the evaluations available used the CFD software Flow-3D, including a study by Savage and Johnson (2001). This study compared CFD-generated discharge rating curves to both physical model data and the United States Bureau of Reclamation – United States Army Corps of Engineers (USBR–USACE) calculations. The study found that Flow-3D slightly overestimated the discharges for upstream water levels above $0.7H_d$ with respect to the physical model data, whereas the USBR and USACE discharges ranged from 1.5% to 5% below the physical model data. The relative error of all three comparisons increased significantly as headwater levels were reduced. Gessler (2005) was successful in producing CFD discharges that were reasonably close to physical model values. Gessler (2005) found CFD overestimated discharges from physical modeling, but noted that physical models are known to underpredict discharges and that a 5% difference between CFD and physical model data is well within the accuracy of physical modeling. Gessler (2005) further noted that the results should not be considered confirmation of the ability of CFD to model all spillway configurations. A review of several CFD applications to spillways in Australia was presented by Ho et al. (2006) who noted that numerical model discharges overestimate physical model flow rates by 3%. They also stated that when looking at different types of problems involving spillways, providing additional comparisons to established data would increase confidence in numerical models. Teklemariam et al. (2001, 2002) discuss the use of CFD analysis to obtain input on critical design issues in the early stages of development for potential hydroelectric generating stations and how CFD was used to gain insight into various design issues, including detailed modeling of spillways.

Three case study comparisons

Three case study comparisons were performed on spillways from different Manitoba Hydro generating stations that have physical model data available. Assessments were undertaken for the spillway at Limestone (1330 MW) along with a preliminary design of the Wuskwatim (206 MW) spillway and the potential Conawapa (1380 MW) generating station spillway. Physical model data for Limestone was obtained from a report completed by Western Hydraulic Laboratories Inc. (1980), whereas data for Wuskwatim was taken from Lemke (1989) and data for Conawapa was available in a report by LaSalle Consulting Group Inc. (1992). To verify the ability of CFD to model a variety of spillway configurations, each of the above-mentioned spillways has a different P/H_d ratio. The ratios are 0.9, 1.4, and 1.8 for the Wuskwatim, Limestone, and Conawapa spillways, respectively. The P/H_d ratio is an important parameter that affects the discharge coefficient of an ogee-crested spillway. It is, therefore, a good parameter to vary in an attempt to verify the general ability of CFD to model ogee-crested spillways.

Free overflow discharge and water surface modeling

The numerical model was similarly prepared for each of the three spillways when performing all free-overflow simulations. Single fluid flow was selected and typical fluid properties for water were implemented in each case, along with turbulence being accounted for with the renormalized group (RNG) model. A single uniform and symmetric mesh was used for each simulation and similar boundary conditions were applied to the edges. Fluid blocks were initialized upstream and downstream from the spillways and default numeric options were utilized. The upstream and downstream boundary conditions were both specified with a constant fluid height and were applied at locations where no further increases in distance from the spillway resulted in changes to the simulation results. The resulting location for the upstream boundary was 30 m upstream from the crest, whereas the downstream boundary was simply placed downstream from the base of the spillway, where it had no effect on simulation results.

For each of the three spillways considered, the discharge rating curves were modeled using an initial mesh size of 1 m until the flow reached a steady state. This was followed by a mesh refinement to 0.5 m to increase accuracy, whereas some select simulations were run using a 0.25 m mesh. It was found that the 0.5 m mesh provided acceptable results and that the approximate 1% increase in accuracy that resulted from using a 0.25 m mesh did not warrant the significant increase in computational time. It should be noted that this procedure of reducing the mesh size until only minimal (1% to 2%) changes in results occurred was completed for all free overflow and gated simulations. A comparison between 0.5 m mesh CFD and physical model discharges for various headwater levels is provided for each of the three spillways in Table 1. The CFD discharges for

Table 1. Computational fluid dynamics (CFD) versus physical model discharges.

HWL (m)	Physical model (m^3/s)	CFD (m^3/s)	Error (%)
Wuskwatim (P/H_d = 0.9)			
234	240	262	9.0
236	495	529	6.9
238	815	867	6.4
240	1200	1250	4.2
242	1625	1673	2.9
243.2	1900	1946	2.4
244.7	2240	2307	3.0
Limestone (P/H_d = 1.4)			
72.4	189	194	2.8
74.95	1176	1208	2.7
77.55	2765	2833	2.4
79.65	4398	4471	1.7
80.9	5460	5607	2.7
82.4	6860	7014	2.2
84.93	9520	9695	1.8
85.83	10 500	10 721	2.1
Conawapa (P/H_d = 1.8)			
45	735	555	–24.4
47	1680	1514	–9.9
49	2905	2798	–3.7
51	4480	4348	–2.9
53	6370	6137	–3.7
55	8260	8150	–1.3
57	10 500	10 369	–1.2
58	11 550	11 559	0.1
58.5	12 145	12 182	0.3

Note: HWL, headwater level.

each of the spillways are within experimental error of physical model values for higher headwater levels. Also note the trend presented in Chanel and Doering (2007) and displayed in Fig. 1 — that the CFD discharges tend to decrease relative to physical model flow rates as the spillway P/H_d ratio is increased.

Further confidence in the numerical model setup was obtained by comparing CFD and physical model water-surface profiles. The profiles were obtained using a different mesh resolution in each of the three cases as mesh refinement was stopped once a successful comparison was obtained. One successful water surface profile comparison was obtained for both the Wuskwatim and Conawapa spillways, whereas two CFD profiles for the Limestone spillway were found to be in agreement with physical model data (Chanel and Doering 2007).

Modeling gated discharge

After successful free overflow discharge rating curves and water surface profiles were obtained with Flow-3D, gated discharge modeling was attempted. Initial simulations were completed for the Wuskwatim spillway with a 4 m gate opening and the same uniform symmetric mesh that was used for the free overflow simulations. Use of a 1 m mesh resulted in CFD flow rates that were not in agreement with physical model values as the CFD flow rates overestimated physical model discharges by approximately 15%. It should also be noted that there were only minimal improvements in the comparison as the mesh size was reduced, even when the mesh was refined to 0.25 m. Additional resolution in the vicinity of the gate was explored using localized nested meshing in an attempt to improve the CFD modeling data. Use of this technique easily allowed for enhanced resolution around the gate without having to implement the fine mesh throughout the entire flow domain, which would significantly increase simulation time. A 0.5 m mesh with a 0.25 m nested mesh surrounding the gate was employed and resulted in a substantial improvement in the comparison with physical model values. These results, along with results from the resimulated discharge using another nested 0.125 m mesh inserted surrounding the gate are shown in Table 2. Use of this second nested mesh significantly improved the comparison with physical model data to the point where the error was within the accuracy of the physical model. Some additional simulations were also run with a smaller mesh size; however, further mesh refinement resulted in only a 1% change to the results. It should be noted that the generalized minimum residual (GMRES) pressure solver option in Flow-3D was required to obtain convergence for all simulations using nested meshing.

After obtaining a successful comparison with physical model data for the 4 m gate opening, additional simulations were run with both 2 and 6 m gate openings. The mesh size was kept the same for each gate opening and all the acquired results were normalized and are displayed in Fig. 2. This figure shows the 6 m gated simulation discharges to be nearly exactly the same as physical model data, whereas the 4 m gated results slightly overestimated the physical model. For the 2 m gate opening, the numerical model significantly overestimates the physical model. For this spillway, it is evident that as the gate opening is reduced, the CFD gated discharges are increasing relative to the physical model. This likely indicates that a smaller gate opening requires a finer mesh to capture the entire flow pattern.

Upon completion of the gated Wuskwatim comparisons, simulations with various gate openings were completed for the Limestone spillway. Again, the 4 m gated simulations were completed first and in this case, use of a 0.5 m mesh with a nested 0.33 m mesh resulted in a fairly successful comparison with physical model data. Similar simulations were then completed for the 2 and 6 m gate openings and provided reasonably good results. A normalized CFD to physical model comparison for all three gate openings is displayed in Fig. 2. One should note the fairly large difference in the 6 m gate opening comparison for the lowest headwater level considered and that the slopes of the CFD rating curves seem to be different from the slope of the physical model curves for both the 4 and 6 m gate openings.

Finally, discharges with various gate openings were obtained for the Conawapa spillway. In this case, the gate openings considered were 1, 3, and 5 m as data for these openings were available in the physical model report. The normalized CFD to physical model comparison is displayed in Fig. 2. In this case, the comparison with physical model data was the least successful of the three spillways considered. The error was exceptionally high for the small 1 m

Fig. 1. Averaged error trend.

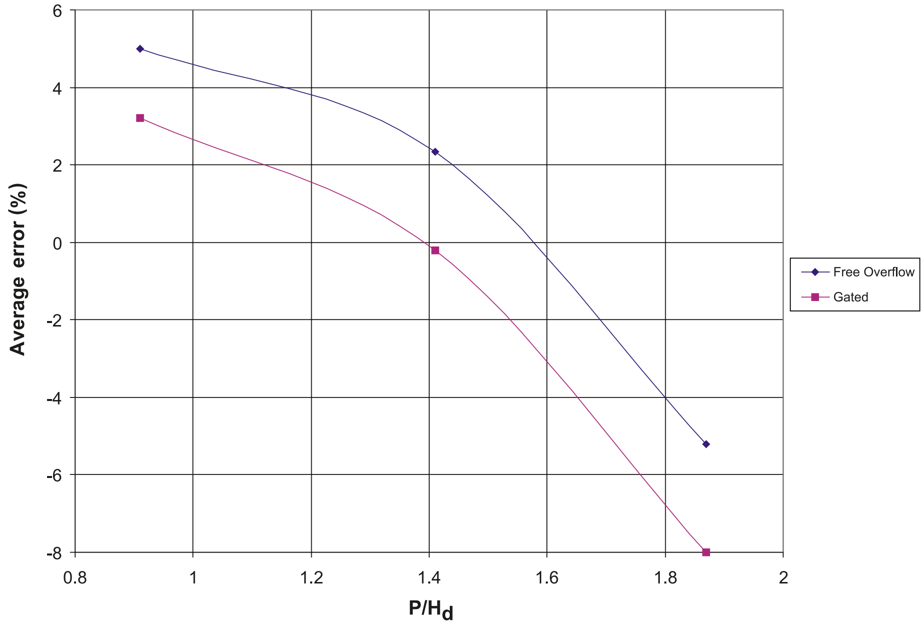
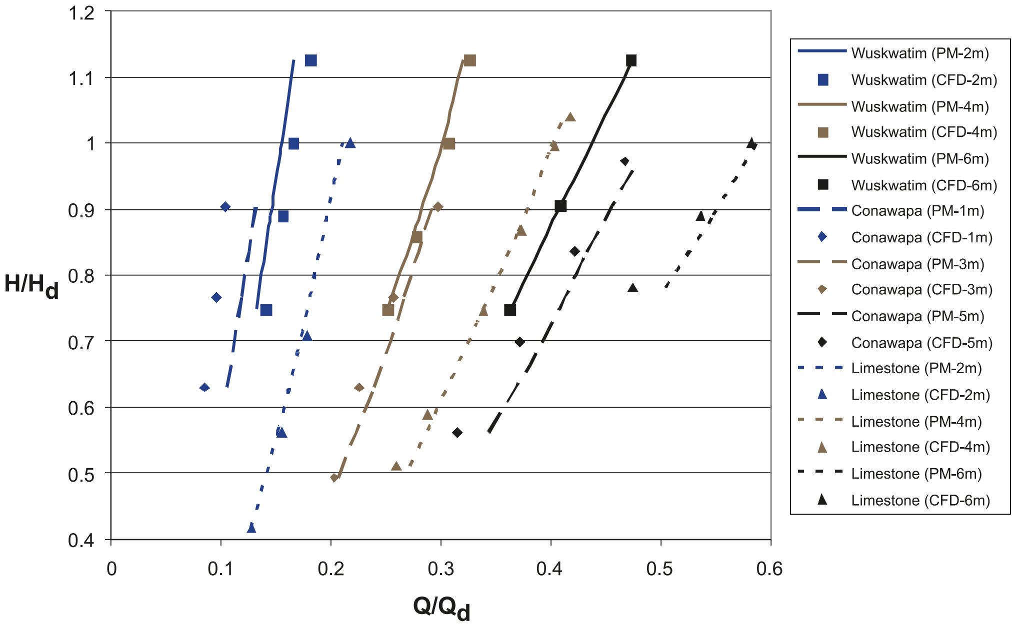


Table 2. Wuskwatim 4 m gate opening discharge comparison with nested meshing.

		0.5–0.25 m mesh		0.5–0.25–0.125 m mesh	
HWL (m)	Physical model (m^3/s)	Discharge (m^3/s)	Error (%)	Discharge (m^3/s)	Error (%)
240.0	681	736	8.0	683	0.2
241.4	745	806	8.1	755	1.3
243.2	817	885	8.3	833	1.9
244.8	869	954	9.8	884	1.7

Note: HWL, headwater level.

Fig. 2. Gated rating curve comparison. CFD, computational fluid dynamics; PM, physical model.



gate opening, with CFD underestimating physical model discharges by about 20%. The error is much lower for the 3 and 5 m gate openings and is in fact still within experimental error for some of the headwater levels compared.

Computational fluid dynamics – physical model results trend

In a conference paper by Chanel and Doering (2007), it was observed that there may be a potential trend between the relative percent errors, as compared with physical model data, in CFD free overflow discharge with the spillway's P/H_d ratio. Examination of the three free overflow discharge comparisons revealed that as the spillway height to design head ratio is reduced, the CFD-computed discharges increase relative to the physical model values. A similar trend was also noticed when comparing Flow-3D with physical model flow rates from simulations with various gate openings. Averaging the relative error for each gate opening and then comparing the errors with the spillway's P/H_d ratio resulted in nearly the same tendency as the free overflow discharges. Figure 1 presents the change in P/H_d along with the average percent error for each spillway for both gated and free overflow simulations. As shown in the figure, the CFD discharges begin by overestimating physical model values for the lowest P/H_d ratio, whereas CFD flow rates decrease as compared with physical model values as the ratio is increased. It should be noted that the gated simulations were completed with different mesh sizes and this would likely also have an affect on the results.

Summary and conclusions

Numerical model simulations were undertaken on three spillways with differing P/H_d ratios using the CFD software Flow-3D. Initially, a review of free overflow discharge rating curve and water surface profile comparisons completed by Chanel and Doering (2007) were presented. These successful comparisons acted as a calibration for the models before the gated discharge comparisons presented in this paper were completed. The gated rating curve comparisons were generally successful; however, there is some significant error for the smallest gate opening in the Wuskwatim and Conawapa cases. Inspection of the averaged percent error in CFD gated discharge as compared with physical model data revealed that the free overflow discharge error trend in Chanel and Doering (2007) is also present in the gated discharge error. Further investigation of simulations with different mesh resolutions, turbulence options, and numerical options are required for all three spillways considered, especially for the smaller gate openings.

Overall, the potential for Flow-3D to model various spillway geometries and configurations appears great. It should be noted that CFD should not be considered a complete replacement for physical modeling; however, it can definitely be used as a supplementary tool throughout the spillway design process.

Acknowledgements

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List of symbols

H	head
H_d	design head
HWL	headwater level
P	spillway height
Q	discharge
Q_d	design discharge