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16th Australasian Fluid Mechanics Conference: An Evaluation of Computational Fluid Dynamics for Spillway Modelling

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Abstract

Computational Fluid Dynamics (CFD) is used extensively by engineers to model and analyse complex issues related to hydraulic design, planning studies for future generating stations, civil maintenance, supply efficiency, and dam safety. The integrity of computed values from CFD models is of considerable economic importance in the design, upgrading and maintenance of hydroelectric generating stations.

CFD models have the ability to predict many characteristics of flow over a spillway and Manitoba Hydro has had good agreement with physical model results in the past. However, to date there has not been a review that brings all the available information together for a comprehensive assessment.

The objective of this research is to build upon previous investigations on the use of CFD modelling, by focusing specifically on the ability to accurately model spillways using CFD. This paper discusses three-dimensional numerical modelling of several different spillway configurations using the CFD software Flow-3D and compares the predicted rating curves, pressures, and water surface elevations to corresponding physical model experimental values. The numerical model results were generally in agreement with physical model data, however, the relative differences in discharges were found to have a P/H_d dependency. The accuracy for a given model resolution and associated computational time required was also considered.

Introduction

In the design of overflow spillways for hydroelectric generating stations, information regarding the hydraulics of the flow over and around the structure is of interest. The desired hydraulic data includes discharge rating curves, pressures over the rollways and on the piers, water surface profiles, and velocity profiles. Obtaining an accurate estimate of the discharge rating curve is important as knowledge of the structure's discharge capacity allows for evaluating the capability of the spillway to safely pass the design flood at the prescribed forebay level. One must be aware that as forebay levels exceed design water levels, pressures over the spillway crest can become negative. If these pressures get too low, cavitation may occur and cause significant damage to the surface of the concrete rollway. Water surface profiles are also often desired in order to determine appropriate pier heights such that overtopping does not occur.

A variety of flow data have historically been obtained through the use of empirical information and physical model studies. The use of physical models can be very costly and time consuming and so this type of analysis is often only performed near the end of the design phase as a confirmation to ensure the spillway will perform as planned. In recent years, however, the development of numerical models and vast augmentation in computational power has led to increased use of CFD for modelling spillway behaviour. Major advantages of using CFD include its ability to quickly explore various options throughout the entire design process. Although the cost to purchase or lease one of the superior CFD software packages can be quite high, the benefits that can result from using one of these packages readily justifies the expenditure.

This paper presents a comparison of discharge rating curves obtained through numerical modelling with the CFD software Flow-3D to data acquired from physical model studies. The three-dimensional modelling was undertaken on three Manitoba Hydro generating stations with significantly different spillway height (P) to design head (H_d) ratios. The three generating stations are Wuskwatim (206 MW), Limestone (1330 MW), and Conawapa (1380 MW) with P/H_d ratios equal to approximately 0.9, 1.4, and 1.8, respectively. A comparison of the water surface profile from selected upstream water elevations is also included for each of the spillways listed above. In addition, a further comparison of pressures along the spillway surface is included for select upstream water elevations for only the Wuskwatim and Limestone spillways as no pressure measurements were included in the Conawapa physical model report. Manitoba Hydro has used Flow-3D for over a decade and they have had considerable success with the program in certain applications as discussed in Teklemariam *et al*. [10,11]. As a result, this study was undertaken to further evaluate the ability of Flow-3D to model a variety of spillway configurations.

Flow-3D in Spillway Applications

The numerical model used by Manitoba Hydro and in this investigation is Flow-3D. This program employs a finite difference solution scheme and uses the Volume of Fluid (VOF) method, developed by Hirt and Nichols [3], which allows the model to include only the water portion of the flow and ignore the surrounding air. Use of this method results in significant reductions in simulation times as the motion in the surrounding air is neglected and this type of programming allows a sharp interface between the water and air to be created without the use of very fine meshes required by other CFD programs. Flow-3D also uses a Fractional Area/Volume Obstacle Representation (FAVOR) method by Hirt and Sicilian [4] to define obstacles. This method allows Flow-3D to use fully structured computational grids that are much easier to generate than the deformed grids used by most other CFD programs.

The majority of documents on the use of CFD to model spillways utilize Flow-3D and generally the program has been successful at reproducing either physical model results or U.S. Army Corp of Engineers (USACE) and U.S. Bureau of Reclamation (USBR) design curves. Savage and Johnson [9] compared results from Flow-3D simulations to physical model results and both USBR and USACE data for a standard ogee-crested spillway. They found that Flow-3D slightly over-predicted the physical model flow-rates for heads greater than $0.7*H_d$ while the USACE and USBR standards under-predicted physical model discharges by about 1.5% and 5%, respectively over that range. The relative difference of all three comparisons significantly increased as compared to the physical model for reduced headwater levels. In addition, the paper presented successful comparisons of CFD measured pressures to both physical model and USACE values. Ho *et al*. [5] present a review of the CFD software used to model various spillway applications throughout Australia. The paper states that CFD flow-rates for heads equal to and above design levels are generally 5% higher than physical model data. The document also provides a general conclusion that numerical models overestimate physical model discharges by 3%. Another conclusion is that CFD is capable of reproducing the trend of physical model pressures along a crest section. Ho *et al*. [5] also presented a summary of CFD to physical model comparisons of water surface profiles. Gessler [2] states that physical models are known to under-predict discharges by up to 3%. He also indicates that a difference between CFD and physical model results of 5% is well within physical model accuracy. Gessler [2] and Ho *et al*. [5] both stress that additional comparisons between CFD and either physical models or established design guidelines would provide further confidence in the ability of CFD to model spillways.

Wuskwatim Generating Station Comparison

Wuskwatim is one of several potential Manitoba Hydro generating stations. Construction for the project officially began in 2006. The site for this proposed station is along the Burntwood River in northern Manitoba and the station has a potential output of 206 MW.

The physical model data for this comparison was obtained from a University of Manitoba thesis by Lemke that compared the hydraulic performance of preliminary designs for orifice and overflow spillways in the proposed Wuskwatim generating station [7]. The report provides a variety of information including discharges, pressures, and water surface elevations over a range of operating conditions for both types of spillways. Information about the fully open single bay overflow spillway was subsequently used in the CFD comparison. The document also includes details of the spillway geometry, displayed in figure 1, as well as upstream model approach conditions that were used to help prepare an Auto-Cad drawing. Additional information regarding the spillway geometry was obtained directly from the 1:36 scale physical model that remains in storage in the University of Manitoba Hydraulics Research & Testing Facility. It should be noted that the actual Wuskwatim Spillway will not include a flip bucket for energy dissipation as in this preliminary design.

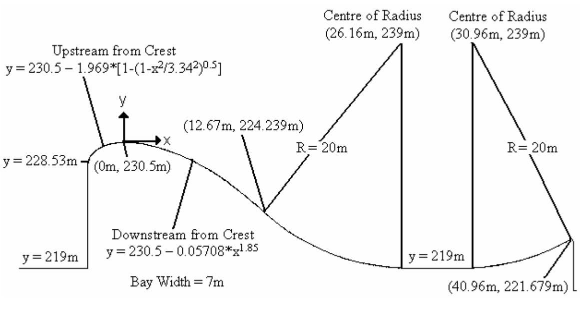

Figure 1. Preliminary design of a flip bucket overflow spillway for the Wuskwatim generating station [7].

Once the Auto-Cad drawing, including pier walls and upstream geometry, replicated the physical model experimental setup, it was exported as a stereolithographic image and imported into Flow-3D. The remainder of the numerical model was then prepared for simulations. Turbulence was accounted for by applying the Renormalized group (RNG) model, which was selected based on its robustness and accuracy. Typical fluid properties for water were implemented with fluid height specified as upstream and downstream boundary conditions and only the water portion of the fluid was included in the simulations as a result of Flow-3D's VOF method discussed above. Initial simulations for comparing discharges were performed using a 1 m mesh size in all directions. The simulations were allowed to approximate steady-state before the mesh size was refined to 0.5 m. A comparison between the discharge results from the physical model and the CFD simulations with a 0.5 m mesh size is shown in figure 2.

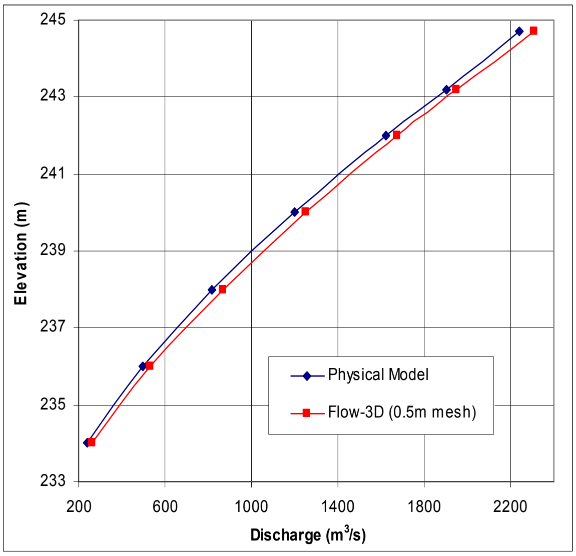

Figure 2. Wuskwatim discharge rating curves.

*H_d	Water Elev. (m)	Phys. Model (m^3/s)	1 m mesh		0.5 m mesh	
			CFD	Diff. (%)	CFD	Diff. (%)
0.28	234.0	240	264	10.0	262	9.0
0.43	236.0	495	530	7.0	529	6.9
0.59	238.0	815	870	6.7	867	6.4
0.75	240.0	1200	1260	5.0	1250	4.2
0.91	242.0	1625	1692	4.1	1673	2.9
1.00	243.2	1900	1979	4.1	1946	2.4
1.12	244.7	2240	2325	3.8	2307	3.0

Table 1. Wuskwatim discharge comparison.

As shown in table 1, the discharge obtained using a 1 m mesh size is relatively good and as the mesh size is refined, the difference between the CFD and physical model results decreases. For a 0.5 m mesh, the relative difference of the CFD results is within 5% for higher upstream water elevations. This difference increases steadily as water levels are reduced. Some select simulations were also run using a 0.25 m mesh size and although these simulations resulted in additional reductions in the relative difference, the reduction did not warrant the substantial increase in computation time that resulted. Overall, these results are in good agreement with typical CFD results found in the literature and are well within physical model accuracy of 5% as stated by Gessler [2] for higher flow-rates.

Once successful flow-rate comparisons were obtained, further simulations were completed with the goal of reproducing water surface profiles and rollway pressures. Initial comparisons of the centre-line water surface profile for a headwater level of 244.7 m obtained using a 0.5 m mesh resulted in a moderately good comparison to physical model data. Subsequent simulations were therefore run using a 0.25 m mesh and the resulting profile compared quite well with physical model data other than at the first and last points as shown in figure 3. Similarly, the rollway pressures under an upstream headwater level of 242 m were initially obtained using a 0.5 m mesh. The CFD results followed the general trend of the physical model, however, ensuing simulations using a 0.25 m mesh resulted in a significant improvement to the comparison. The resulting pressure contours are displayed in figure 4 while a comparison to physical model results is shown in figure 5. One should note that figures 4 and 5 show data from approximately the same location. It should also be noted that the CFD pressure data was not taken from directly on the spillway surface but was extruded from the nearest possible point to the spillway surface at each location. Despite this potential source of error, the Flow-3D data still seems to correlate quite well with the physical model values.

In an attempt to obtain more accurate pressure with the CFD software, the simulations were rerun using the new generalized minimum residual (GMRES) method as the selected pressure solver option in the numeric tab. This method is alleged to be highly accurate and good for convergence but requires more memory than the default successive over-relaxation (SOR) method. This change in pressure solver was found to have little impact on the pressure results while taking slightly longer to simulate.

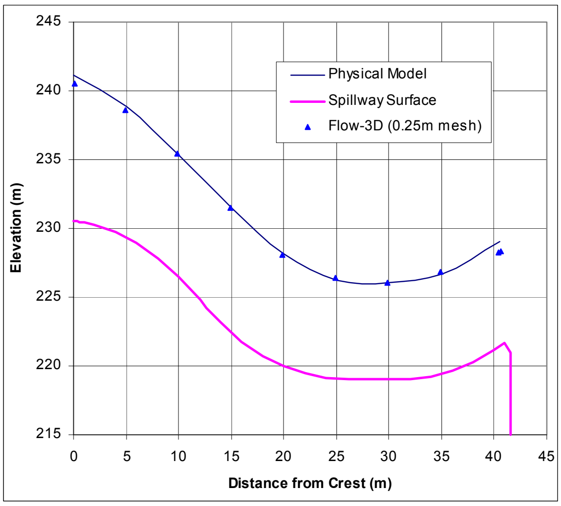

Figure 3. Wuskwatim centre-line water surface profile.

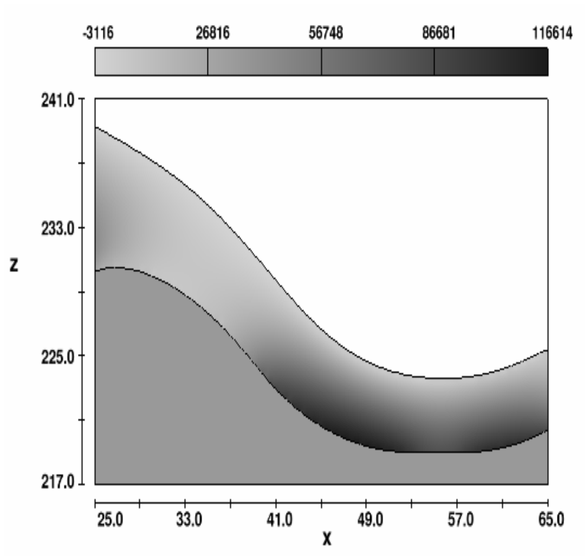

Figure 4. Flow-3d pressure contours (Pascals).

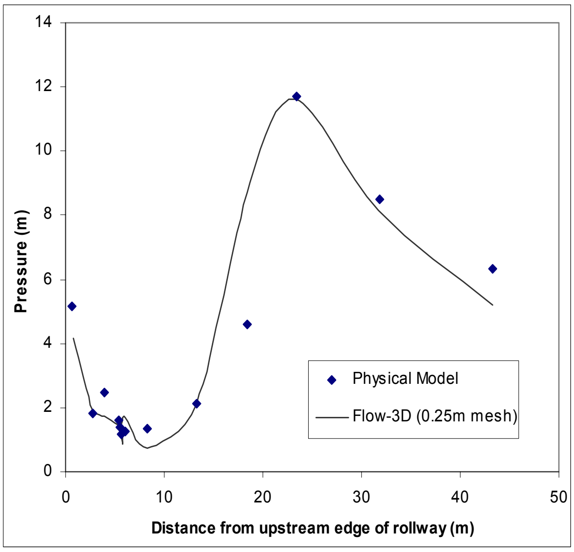

Figure 5. Wuskwatim rollway pressure.

Limestone Generating Station Comparison

The Limestone generating station is currently the largest in Manitoba with a production capacity of 1340 MW. It is located in northern Manitoba along the Nelson River and was completed in 1990.

The spillway at Limestone consists of 7 bays that are each 13 m wide. Information about the spillway was obtained from a physical model study report by Western Canada Hydraulics Laboratories that was completed in 1980 [12]. The report and study was undertaken on a version of the Limestone spillway that included a flip-bucket for dissipation of energy at the base of the spillway. This geometry differs from the CFD model that is based on the actual constructed spillway which utilizes a stilling basin for energy dissipation. This difference should not, however, affect the discharge comparison as the flow is supercritical well before reaching any variations in geometry. There are other slight differences between the physical model and CFD model geometry, however, the variations are located low enough on the upstream face that they should have a negligible affect on discharges.

The Limestone spillway geometry used for this comparison was provided by Manitoba Hydro in the form of a stereolithographic image. In order to perform CFD simulations, this geometry file was imported into Flow-3D and other preliminary information was specified. It should be noted that in order to reduce mesh size and decrease simulations times, only 1 bay and 2 half bays were used representing a slice out of the complete spillway geometry as shown in figure 6. In this configuration a symmetry boundary condition was specified on both sides of the two half bays. This simplification was deemed acceptable as several comparisons confirmed negligible differences in discharge as compared to simulations with the entire 7 bays. As was done in the Wuskwatim discharge simulations, a 1 m mesh was initially used followed by a mesh refinement to 0.5 m in all directions to provide more accurate results. A comparison of CFD and physical model discharge rating curves is displayed in figure 7 with relative differences provided in table 2.

The CFD discharges were found to be in excellent agreement with the data obtained from the physical model report. The CFD results are within 3% for the entire range of upstream water elevations simulated when using a 0.5 m mesh size. This directly follows the general trend presented by Ho *et al*. [5]. Considering the accuracy of the physical models, these results show that CFD has been successful at reproducing experimental results in this application.

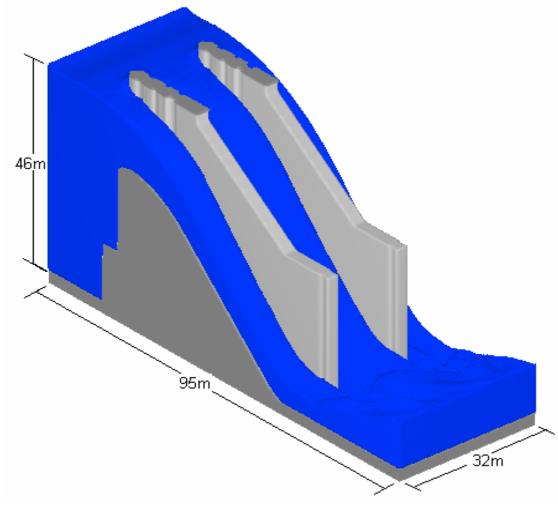

Figure 6. Limestone CFD configuration.

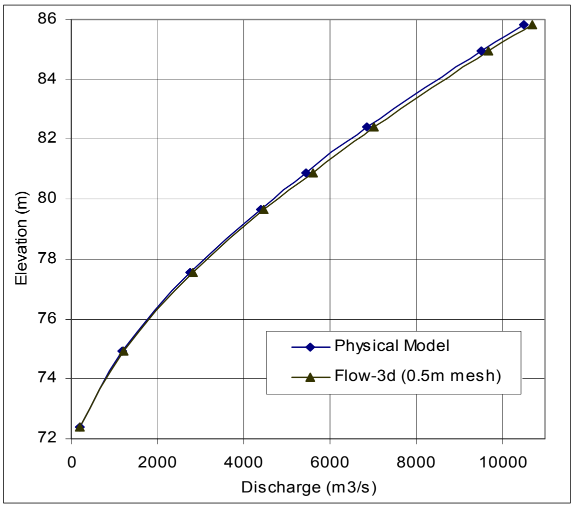

Figure 7. Limestone discharge rating curves.

*H_d	Water Elev. (m)	Phys. Model (m^3/s)	1 m mesh		0.5 m mesh	
			CFD	Diff. (%)	CFD	Diff. (%)
0.08	72.40	189	204	7.8	194	2.8
0.27	74.95	1176	1246	6.0	1208	2.7
0.46	77.55	2765	2890	4.5	2833	2.4
0.61	79.65	4398	4571	3.9	4471	1.7
0.70	80.90	5460	5683	4.1	5607	2.7
0.81	82.40	6860	7156	4.3	7014	2.2
0.99	84.93	9520	9814	3.1	9695	1.8
1.06	85.83	10500	10889	3.7	10721	2.1

Table 2. Limestone discharge comparison.

Upon completion of the discharge comparison, further comparisons of water surface profiles and pressure measurements from the CFD model to results from the physical model report were completed. A coarse cell simulation initially yielded a fairly good comparison. The mesh was then refined to a 0.33 m symmetrical grid and the resulting profiles for two different headwater levels are shown in figure 8. The results seem to agree over most of the spillway except for the last two points of the 84.9 m headwater level profile. The reason for this divergence is believed to be that the flip bucket located in the physical model but not the numerical model is affecting the results. Pressure measurements were then obtained from simulations with a headwater level of 77.5 m and compared to physical model results. For this simulation, a 0.33 m mesh was used to obtain the CFD pressure contours as shown in figure 9. Data was then extracted to be plotted against physical model results as shown in figure 10. Note that figures 9 and 10 cover approximately the same x-coordinates despite the difference in x-axes values.

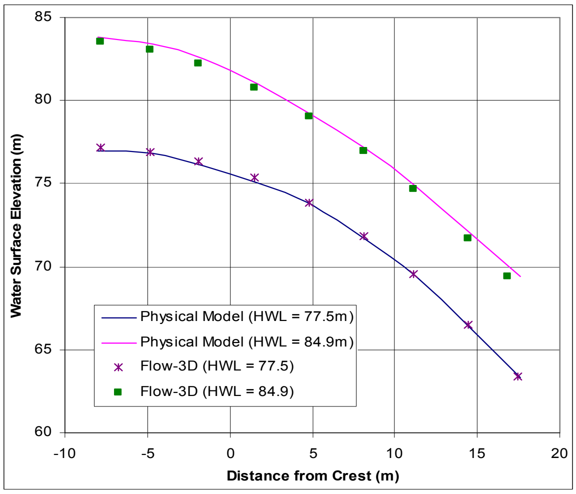

Figure 8. Limestone water surface profiles.

The CFD pressures appear to follow the general trend of the values obtained in the physical model report. In this comparison, the first 4 points were obtained 2.5 m to the left and right of the centreline while the remaining readings were taken along the centreline. In the physical model the pressures on the left side of the rollway differed from that on the right, while in the CFD model the values were identical. As a result, only one line is shown for the CFD model. It should be noted that the GMRES pressure solver option was also applied to this pressure comparison and once again the new technique resulted in minimal changes to the pressure data while also taking longer to simulate.

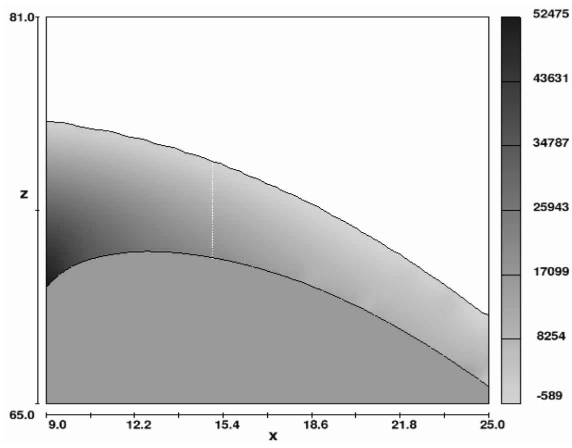

Figure 9. Flow-3D pressure contours (Pascals).

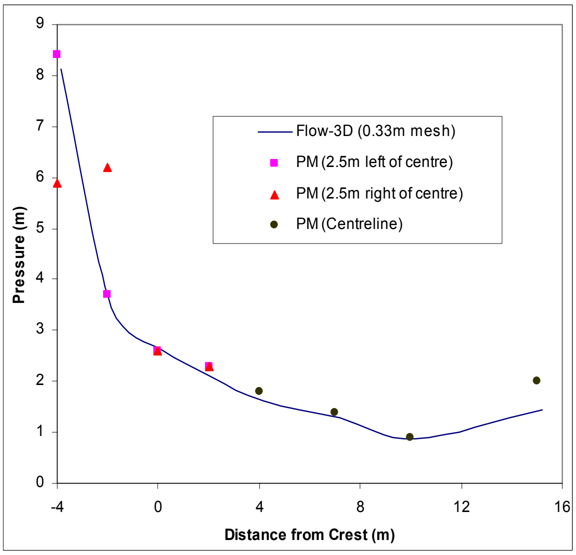

Figure 10. Limestone rollway pressure.

Conawapa Generating Station Comparison

Another one of Manitoba Hydro's potential generating stations is Conawapa. The proposed site for this generating station is 28 km downstream from Limestone along the Lower Nelson River. If constructed, Conawapa would be the largest hydroelectric station ever built in Manitoba with a generating capacity of 1380 MW.

The spillway for this proposed project would be similar to that of Limestone generating station but it has a significantly higher spillway height to design head ratio. A sectional hydraulic model study for the Conawapa spillway was completed in 1992 by LaSalle Consulting Group [6]. The model geometry that was used in LaSalle's study differs slightly from the current model configuration upon which a Flow-3D model obtained from Manitoba Hydro was prepared. In the physical model study, the upstream face of the spillway had a different shape in bays 1, 3, 5 and 7 than it did in bays 2, 4, and 6. The CFD model provided did not include this difference and also had to be adjusted vertically as the current crest location is 0.7 m lower that the crest location in LaSalle's study. Subsequent simulations resulted in an underestimation of discharge for all headwaters as shown in table 3. Only simulation results with a 1 m mesh size are provided as a reduction in mesh size would only lower discharges, resulting in greater difference.

$*H_d$	Water Elev. (m)	Phys. Model (m^3/s)	1 m mesh	
			CFD	Diff. (%)
0.15	45	770	543	-29.6
0.29	47	1680	1479	-12.0
0.42	49	2905	2746	-5.5
0.56	51	4480	4258	-5.0
0.70	53	6370	6024	-5.4
0.84	55	8260	7998	-3.2
0.97	57	10500	10150	-3.3
1.04	58	11550	11298	-2.2
1.05	58.2	11760	11564	-1.7

Table 3. Conawapa discharge comparison with small geometry differences.

Since the results obtained using the slightly different spillway geometry did not follow the general trend of CFD overestimating physical model results, a new Auto-Cad drawing was developed using geometry details from the physical model report. The model was prepared in a similar manner to that of the previous CFD to physical model comparisons. As was done in the Limestone simulations, only a slice out of the entire spillway geometry was included in the modelling in order to reduce simulation times. In this case 2 full bays and 2 half bays were included in order to have an equal amount of the different bay shapes. A comparison of the discharge rating curves is shown in figure 11, while the percentage difference between CFD and physical model is provided in table 4.

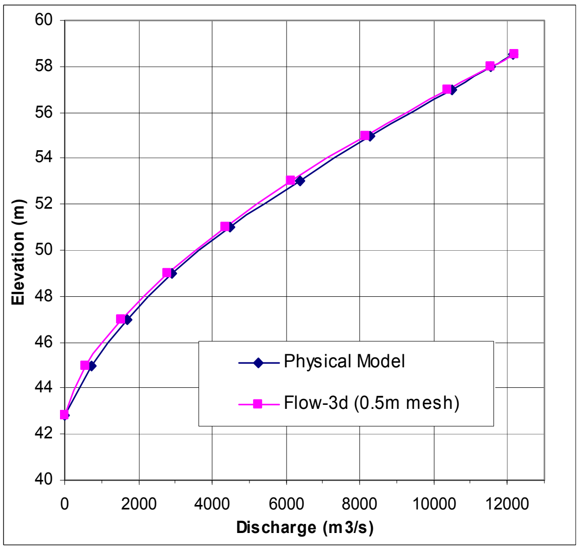

Figure 11. Conawapa discharge rating curves.

$*H_d$	Water Elev. (m)	Phys. Model (m^3/s)	1 m mesh		0.5 m mesh	
			CFD	Diff. (%)	CFD	Diff. (%)
0.15	45	735	574	-21.9	555	-24.4
0.29	47	1680	1548	-7.9	1514	-9.9
0.42	49	2905	2832	-2.5	2798	-3.7
0.56	51	4480	4425	-1.2	4348	-2.9
0.7	53	6370	6244	-2.0	6137	-3.6
0.84	55	8260	8283	0.3	8150	-1.3
0.97	57	10500	10553	0.5	10369	-1.2
1.04	58	11550	11748	1.7	11559	0.1
1.08	58.5	12145	12369	1.8	12182	0.3

Table 4. Conawapa discharge comparison.

The results for this comparison still do not follow the general trend found in the literature. In this case the CFD discharge only overestimates the physical model for headwater levels above the design head and underestimates flow-rates for all lower headwater levels. Despite this inconsistency, the CFD results for upstream water elevations greater than $0.4*H_d$ are still within the accuracy of physical model results.

Further simulations were conducted with the redrawn spillway geometry in order to obtain water surface profiles. In this case the water surface profile obtained from the Flow-3D simulation corresponded reasonably well with the profile from the physical model report as shown in figure 12. This CFD data was obtained using a 0.4 m mesh as a further reduction in mesh size led to difficulties with convergence. Pressure comparisons for the Conawapa spillway were not completed since pressure data was not recorded in the physical model testing.

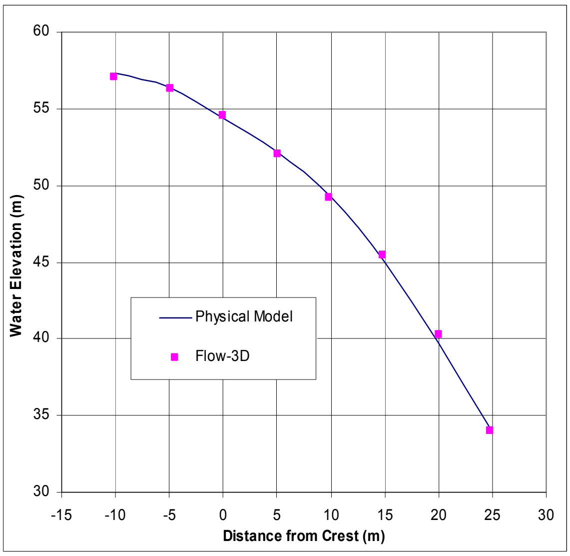

Figure 12. Conawapa water surface profile.

CFD-Physical Model Relative Difference

Further examination of the relative difference from all three discharge comparisons revealed a possible trend connecting the percent difference to the spillway P/H_d ratio. It can be seen that the CFD discharges tend to decrease relative to the physical model discharges as the spillway height to design head ratio is increased.

Spillway	P/H_d	Avg. % Difference
Conawapa	1.8	-5.2
Limestone	1.4	2.3
Wuskwatim	0.9	5.0

Table 5. Average CFD-physical model difference.

As shown in table 5, the average difference in the Conawapa spillway comparison is negative with the P/H_d ratio being the highest. In the Limestone comparison, the P/H_d ratio is reduced and the CFD results increased relative to the physical model. Finally, the Wuskwatim spillway presents a further reduction in the P/H_d ratio and the CFD results once again increase relative to the physical model data. Although there does seem to be a trend in the results, further simulations on spillways with additional spillway P/H_d ratios are required to validate the relationship.

Conclusion

The ability of the CFD software Flow-3D to reproduce spillway discharges to well within the accuracy of physical model studies has been presented. The model was generally successful at providing discharge rating curves for spillways from three Manitoba Hydro generating stations with different spillway height to design head ratios.

The results from 2 of the 3 comparisons were found to follow the general trend found in literature that CFD tends to overestimate physical model results by 3-5% for higher flow-rates. The Conawapa CFD discharges however, did not follow this trend and in fact underestimated physical model results for all headwater levels below the design head. Further investigation of the results led to the possibility of a trend linking a spillway's P/H_d ratio and the relative difference in discharge between CFD and physical model results. Additional simulations are required to establish the validity of this trend.

Flow-3D was also successful in reproducing water surface profiles for all three spillways modelled. The data from the simulations lies very close to data obtained in the physical model study reports. The capability of the software to produce pressure measurements along the rollways that follow the general trend of physical model experimental results has also been displayed for both the Wuskwatim and Limestone spillways.

These results provide further evidence in the capability of CFD to model various spillway geometries. Additional comparisons of rating curves, pressures, and water surface profiles with various gates openings as well as velocities would be helpful in confirming the ability of CFD. Although CFD may never fully replace physical modelling in more complex situations, the confidence of using only numerical models in more general applications is certainly being enhanced by these types of comparisons.

Acknowledgments

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