E-proceedings of the 38th IAHR World Congress
September 1-6, 2019, Panama City, Panama
doi:10.3850/38WC092019-0998

APPLICABILITY OF A 3D NUMERICAL MODEL FOR FLOW SIMULATION OF SPILLWAYS

ESTEBAN AGUILERA(1), OSCAR F. JIMÉNEZ(2)

(1,3) School of Civil Engineering, University of Costa Rica, Rodrigo Facio Campus, San Pedro, San José, Costa Rica
eaguilera@carboncr.com; ojimenez@carboncr.com

ABSTRACT

This work constitutes a first phase of the evaluation of a three-dimensional flow simulation program capable of simulating the flow on spillways. The chosen program is OpenFOAM, which is free, open source and developed under a finite volume discretization.

A standard Creager crest type geometry was evaluated, for which data of physical models are available in the literature in order to compare the results obtained with the CFD program. The effects of mesh sizes, turbulence models and proportional geometries were studied. Subsequently, for a single crest geometry, the slope of the upstream face and the height of the approach (P/H_0) were varied, evaluating each case under different flow rates. There were evaluated around 840 simulation cases distributed between calibration and numerical evaluation cases.

The program showed good results for the flow profiles, pressures and discharge capacity for weirs with low arrival speed, up to $P/H_0 = 1.0$. With the correct size and mesh geometry, most results are within few percent of the empirical measurements. Given the evaluated conditions and the type of dam studied, as well as good results for certain ranges, the program showed that is functional for design purposes.

This project had the limitation related to the number of cases, with substantial different geometries, simulated due to the time stipulated in the development of the project and the computational cost involved in the calculation times, which is closely linked to the computational capacities of the computers used for the simulation of the analyzed cases.

Keywords: Spillway Design; Flow over Weir; numerical simulation; OPENFOAM; Computational Fluid Dynamics

1 INTRODUCTION

In the design process of hydraulic structures is essential to analyze the behavior of water by calculating its movement, at different moments of time, to know its pressure, depth and flow velocity. For some cases, the equations have been derived to approximate these values in a sufficient way for design purposes. However, there are complex structures, such as spillways, in which there are no simplified expressions to reliably calculate the flow conditions, which have strong variations in the three orthogonal directions. In these cases, the usual practice is to develop physical models that can be time consuming and expensive. The application of three-dimensional numerical flow models for those calculation purposes, can replace in some cases the creation of the physical models, making the design process cheaper. Depending of the computational capabilities, a greater range of geometric variations of the spillway can be evaluated in a short time during the design process, achieving a more optimized design.

3D CFD simulations have multiple applications into the spillways design process because numerical simulations allow to obtain the velocity profile in all the three directions, the location of the free surface even in the zone with rapidly varied flow, the pressure distribution in the crest profile of the spillway and on the side walls or pillars, and the influence of the geometry of the crest (upstream and downstream) in the discharge capacity.

The objectives of the present study (E. Aguilera & O. Jiménez, 2018) were: a) General evaluation of available free access 3D CFD program by comparing the capacities and limitations of different programs and their capacity to simulate the flow over spillways, as well as looking in the literature its application to spillway design; b)apply the chosen model in the simulation of several cases to validate the results of the flow behavior over the spillways with the available laboratory data in the literature, in this case the USBR discharge coefficients curves; c) description of a methodology for numerical flow simulation over spillways, using the selected software (the OpenFOAM suite in the present case).

2 CHOICE OF CFD SIMULATION PROGRAM

A bibliographic search of use of 3D programs in applications related to flow through spillways, the revision of their user manuals to determine their simulation capabilities and their discretization schemes , the evaluation of its meshing capacities and how its meshes adapt to irregular geometries, in addition to its availability of use both for academic purposes and for professional practice, were considered.

Within the present work 10 programs were studied of which 4 are open access while the remaining 6 are commercial. The free access programs evaluated are OpenFOAM, Telemac, SSIIM and Delft 3D, of which the first one is open source. OpenFOAM and SSIIM work with a discretization of the equations in finite volumes, the Delft3D in turn handles a discretization in finite differences while the Telemac works with finite elements. The commercial programs considered are Flow-3D, Fluent, Star CD, Phoenics, NUMECA and ADINA, of which, Flow-3D uses finite differences, ADINA contains a discretization in finite elements, and the rest work with finite elements.

One of the most important points in the choice of a program was the existence of adequate support from a community of users so that doubts could be resolved effectively and expeditiously. Another very important point was the ease of creation of the meshes and the adaptability of these to irregular geometries. Finally, that the program was ideally open access in order not to have a temporary license that limited the time of development or the possibility of expanding the scope of the research in future work. From the analysis of the different types of discretization schemes it was concluded that the finite volume schemes were more stable compared to the finite differences, and their expressions easier to understand from a physical point of view. Comparing their advantages and disadvantages, the OpenFOAM program was chosen as the right one for the development of the present study. Although it lacks an official graphical interface that makes the creation of the cases a little slower, it has a good user support on the internet, good mesh creation capabilities, allowing the import of meshes created in third-party programs.

3 METHODOLOGY

The OpenFOAM program was applied to calculate a series of water flow simulations on spillways with a crest geometry defined according to WES criteria (1987).

The simulated problems can be grouped into two types: quasi-three-dimensional models and three-dimensional models. The classification is given according to whether the movements of the flow in all directions are taken into account (entirely three-dimensional problems) or if on the contrary the flow in the direction parallel to the axis of the spillway is neglected, taking into account only the directions vertical and longitudinal. The latter is achieved by taking advantage of the fact that the OpenFOAM allows specifying a special contour condition for that purpose in planes whose normal is parallel to the direction assumed to be zero flow.

First, a series of calibration cases were carried out where some parameters were varied in order to determine their influence within the calculation, such as the size of the cells of the grid, the choice of the turbulence model, as well as the verification of the assumption of proportionality of the variables as a function of the design load of the crest. Subsequently, water flow simulations were carried out on particular cases of geometry of the Creager profile of the dam, using the recommendations of configuration of the parameters found during the realization of the calibration cases, and in which the numerical values of the profile of the upper layer, the pressures on the crest and the discharge capacity were compared with respect to the values reported in the literature by the US Bureau of Reclamation (USBR, 1987) and the Waterways Experiment Station (WES 1987). Geometries were considered without intermediate piers and with type 2 piers (according to USBR classification).

The type of simulated cases corresponds to spillways with a free condition downstream, in such a way that there is no control of the downstream level, so there is no degree of drowning that could affect the discharge capacity of the spillway. The analysis of the profiles of the water level and the pressures on the crest was limited to the area of the dam given by $-1.0 < x/H_0 < 1.8$, where H_0 is the design load of the dam, given that it corresponds to the range of stations for which there is information in WES Design Charts reports. However, the calculation domain was larger than these limits to ensure that boundary conditions will not affect the results.

The comparison of the discharge capacity of the spillway between the computational program and what is reported in the literature was made from the value of the discharge coefficient and its variation in the presence of changes in the geometry. The discharge coefficient was obtained numerically from the velocity and depth of flow values.

3.1 Mesh Generation

The meshes of all the cases considered in the present work were generated by the utilities blockMesh and snappyHexMesh, developed for this purpose as part of the OpenFOAM package. The blockMesh tool was used to create the mesh for quasi-three-dimensional cases, by defining multiblock meshes, which contained the definition of the coordinates of each vertex, the vertices that defined each block (hexahedron), as well as the number of subdivisions of each block in each direction and the vertices that defined each type of contour condition. This definition was used in the case of simple geometries.

On the other hand, the snappyHexMesh utility was used to generate more complex geometries, where there was variation of the geometry along the axis of the spillway, for example, with the presence of lateral walls and pillars. For this definition, solids were created in STL form and subtracted from a base mesh defined with the blockMesh utility.

3.2 Contour Conditions

The simulated cases contemplate a constant inflow at the inlet at the upstream boundary, in the downstream boundary (outlet) a free condition of the water level is specified (it is allowed to be defined by the flow conditions), an atmospheric pressure fields is specified as the condition of the upper contour (atmosphere), and a wall contour is specified in the bottom (bottomWall) and along the body of the spillway.

The location of the faces (patches) where specific boundary conditions are set, such as the input and output, is done within the definition of the mesh, while the specific definition of the boundary types are defined separately in the OpenFOAM for each variable file.

The only difference in the definition of the boundary conditions between quasi-three-dimensional and entirely three-dimensional cases is how the faces perpendicular to the axis of the dam (front / back) are defined; those boundaries are defined as a plane of symmetry in the entirely three-dimensional cases while in the quasi-three-dimensional cases the condition is defined as "empty" with the purpose to ignore the flow through it.

The specific types of boundary conditions used in the simulated cases of this work are shown in Table 1, where the conditions for the quasi-dimensional models are indicated in italics whereas the three-dimensional models are indicated in bold.

Table 1. Specific Boundary Contours for Each Variable

Boundary (Patch)	**Alpha (alpha.water) (*)**	**Velocity (U)**
Inlet	variableHeightFlowRate	variableHeightFlowRateInletVelocity flowRate: Q variable for the specific case
Outlet	zeroGradient	zeroGradient
Atmosphere	inletOutlet	pressureInletOutletVelocity
bottomWall	zeroGradient	fixedValue
spillway	zeroGradient	fixedValue
front	*empty*/**symmetryPlane**	*empty*/**symmetryPlane**
back	*empty*/**symmetryPlane**	*empty*/**symmetryPlane**

Boundary (Patch)	**Pressure (p_rgh)**	**k**	**Omega/Epsilon**
Inlet	zeroGradient	fixedValue	fixedValue
Outlet	zeroGradient	inletOutlet	inletOutlet
Atmosphere	totalPressure	inletOutlet	inletOutlet
bottomWall	zeroGradient	kqRWallFunction	omegaWallFunction
spillway	zeroGradient	kqRWallFunction	omegaWallFunction
front	*empty*/**symmetryPlane**	*empty*/**symmetryPlane**	*empty*/**symmetryPlane**
back	*empty*/**symmetryPlane**	*empty*/**symmetryPlane**	*empty*/**symmetryPlane**

(*) Alpha: a variable that accounts if the cell has water, air, or a portion of both, used to calculate the position of the free surface according to the VOF Method.

3.3 Initial Conditions

In the analyzed cases, there are two types of initial conditions considered, one of them consist in a constant level and the other one is a sequential type; each type is considered depending on whether or not the simulation of different input flows is carried out while preserving the same spillway geometry.

The initial condition of a constant water level is specified through the Alpha field (a variable that accounts if the cell has water, air, or a portion of both, used to calculate the position of the free surface according to the VOF Method) when a constant elevation is assigned up to the peak level of the crest (an unit value of alpha is specified in all the cells located below the crest and upstream of it). On the other hand, zero pressure is indicated throughout the domain and the initial velocity was defined uniform throughout the domain and calculated as $u = Q / (H0 + P)$ where H_0 is the design load and P the height of the upstream face of the dam. For the turbulence models, initial conditions for the variables k and ω were defined considering the recommendations given by Strandenes (2017). The initial condition defined as sequential type is specified by mapping the results of another case (with a lower flow rate) in such a way that the final values of a simulated case are used as initial values in the new case.

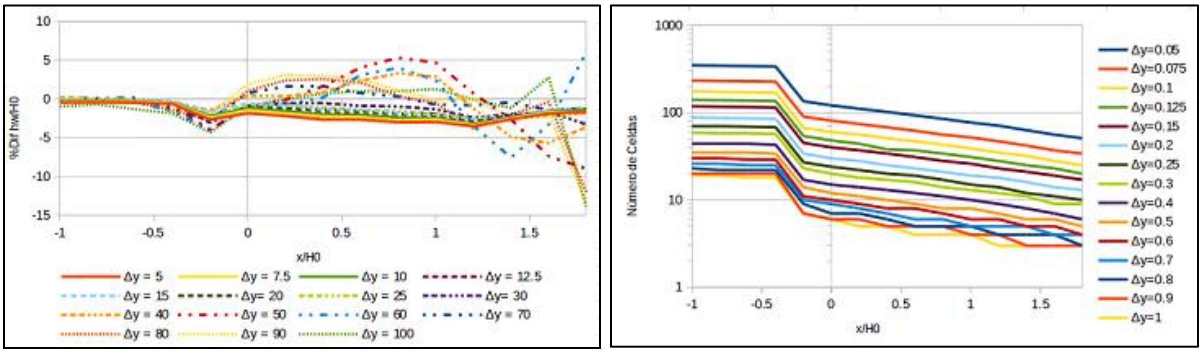
4 MESH SIZE STUDY

In this case the objective was to measure the sensitivity of the OpenFOAM numerical results for both, the depth of the water and the pressures in the crest, to the changes in the size of the cell of the computational meshes used; this was done in order to determine the ideal maximum size of the grid cell to use in the next cases.

Two spillway crest geometries of the WES type were defined for design loads (H_0) of 2.5 m and 4.0, both with a vertical face and a downstream slope of 0.65H: 1V. Those Ho values are in some way arbitrary, but its relation to the mesh sizes is what it is important. In each geometry several mesh sizes were evaluated. The maximum sizes of the meshes were defined varying in the range between 100 and 5 cm. The case was a quasi-three-dimensional type with the boundary and initial conditions specified in the previous section. In both cases, a single flow, coinciding with the design flow rate ($H / H_0 = 1$) and a relation $P / H_0 = 2.5$ was used.

First, the results of the upper nappe flow profile obtained with both cases were compared against the reports of the Hydraulic Design Charts 111-11. The OpenFOAM program does not directly show the value of the water depth, it has to be obtained with an integration of the alpha variable over the height; Once the numerical results were established, percentages of difference were calculated with the Eq. [1], and then the number of cells containing water was determined for both geometries. Figure 1 shows the results for the case of the simulation with the dam of size of 4 m.

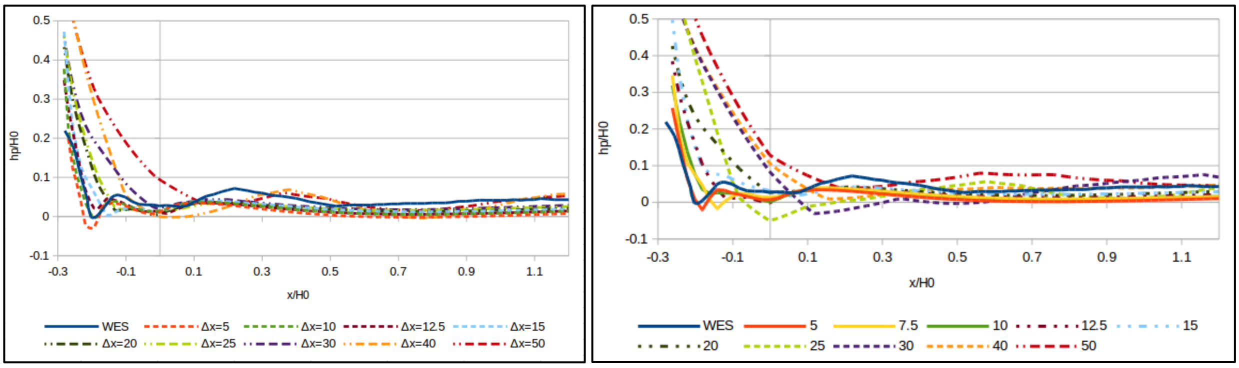
$$\%Dif = \frac{hw/_{H0_{CFD}} - hw/_{H0_{WES}}}{hw/_{H0_{WES}}} * 100 \qquad [1]$$



(a) (b)

Figure 1. Results of the H_0=4m design crest case (a) Percentage of difference in the Upper Nappe Flow Profile and (b) Number of Cells below the water free surface by nominal size of the mesh.

For the 4 m design head geometry, the lowest values of percentages of difference were obtained for mesh sizes of 15 cm and below; by simultaneously comparing the values of error percentages and number of cells, it can be interpreted that a minimum number of cells of at least 15 cells in depth in the vertical direction could be recommended as a limit. Similar values were obtained for the case of the 2.5 m design head geometry. Figure 2 shows the values of the crest pressure for both geometries and their comparison with the HDC 111-16 of WES.



(a) (b)

Figure 2. Crest pressures results for (a) H_0=4m (b) H_0=2.5m

According to the results, for the case of design head H_0 = 2.5 m, the mesh size with the best precision of the pressure results is 7.5 cm (12.5 cm in the case of H0 = 4m), so a recommendation of the maximum horizontal size of the cells could be determined as a ratio to the design load $\frac{H_0}{\Delta x_{max}} \sim 35 - 40$.

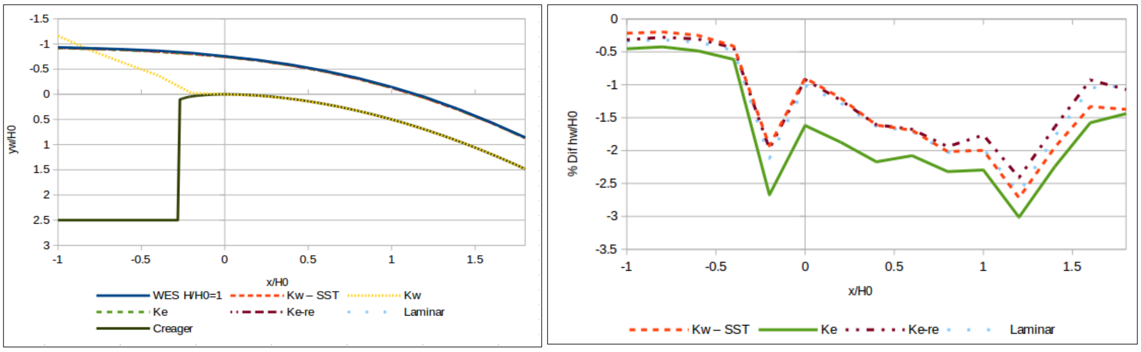
5 EVALUATION CASE: CHOICE OF TURBULENCE MODEL

The objective of this case was to test the sensitivity of the numerical results of the depth of water and the pressures on the crest before the use of different turbulence models, in order to determine which is suitable to use in subsequent cases.

The geometry chosen consists of a spillway with a crest designed with the WES criteria, defined for a design load (H_0) of 4 m, vertical upstream face and downstream slope of 0.65H:1V; and taking into account a maximum size for the mesh cells of 10 cm. The case was a quasi-three-dimensional type with the boundary and initial conditions specified in the previous section. A single flow rate coinciding with the design flow rate (H/H_0 = 1) was used. The incoming velocity was low due to a defined P/H0 = 2.5 for the spillway.

A total of 4 turbulence models were evaluated including: k-ε, k-ω, Realizable k-ε and k-ω SST, and a simulation without turbulence (laminar) was also considered. As in the case presented above, the upper nappe flow profiles and the crest pressure values were compared with the reports in the HDC 111-11 and HDC 111-16 of WES, respectively. The initial conditions for the turbulent variables were established according to the recommendations of Strandeness (2017).

Figure 3a shows a chart with the dimensionless upper nappe flow profiles numerically obtained for each turbulence model, and the profile according to WES; it can be seen that the k-ω profile presented instabilities and did not converge to expected results, while the others presented an imperceptible difference to the WES profile. Again by means of equation [1], there were established percentages of difference as shown in Figure 3b.



(a) (b)

Figure 3. Numerical Results for (a) Upper Nappe Flow Profile (b) Percentage of difference with various types of turbulence models.

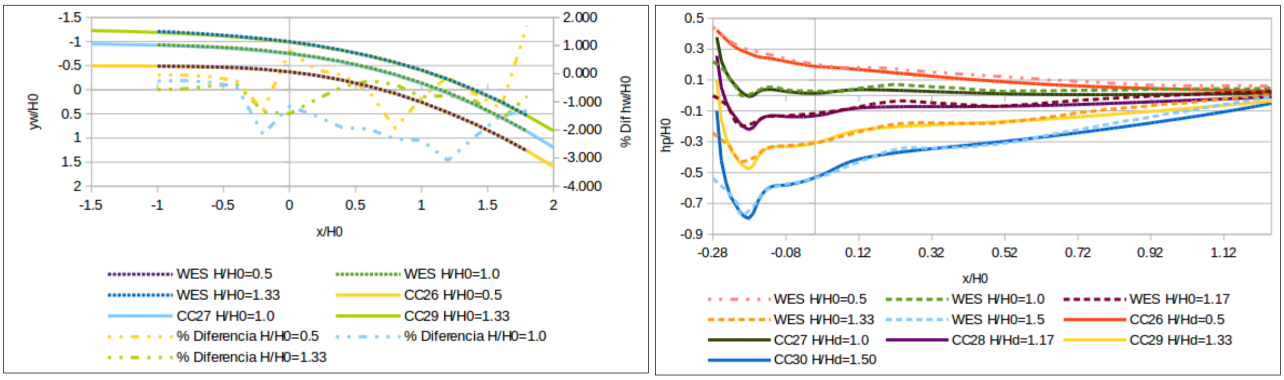
According to the numerical results, upper nappe flow profiles shown and the comparative results of the crest pressures, it is considered that the k-ω SST is the turbulence model that better fits the expected results following the HDC WES. However, when the results of the laminar model are compared to the ones obtained with turbulence models, it is seen that the consideration of one or the other model is not that determinant, for the case studied; so the final choice of the turbulence model to choose is left to the modeler's criteria, discarting the k-ω model from the beginning due to its numerical instabilities.

6 UPPER NAPPE FLOW AND CREST PRESSURE PROFILES COMPARISON FOR A WES TYPE SPILLWAY WITHOUT PIERS

The case consisted in the simulation of the flow over a standard ogee type spillway, with the objective of comparing the results of the upper nappe flow profiles and the crest pressures obtained numerically with the OpenFOAM simulations with respect to those reported in the Hydraulic Design Charts from WES.

The geometry considered consists in a spillway whose crest was defined according to the WES criteria with a design head H_0 = 4.0 m and a maximum cell size of 10 cm. The spillway sides consist in a vertical upstream face and a downstream slope of 0.65H: 1V. The case was also a quasi-three-dimensional type with the boundary and initial conditions specified in the previous section. Five flow rates were used given by the head to design head rates H / H0 reported by WES (1.5, 1.33, 1.17, 1.0, 0.5) and four different P / H0 ratios: (2.5, 1.0, 0.5, 0.25) to consider various incoming velocities.

In order to make a comparison of the numerical results with respect to those published in the WES reports, the water depth values were calculated in the same positions as those specified in the Hydraulic Design Charts, this means that the x/ H0 positions in the range between -1 and 1.8 were considered. For giving an example, the numerical results obtained for the position of the free surface (upper nappe flow profile) in the case of spillways with negligible arrival velocity represented by the sub-case with P / H0 = 2.50 and H / H0 = 1.0 are shown in Table 2. These results are plotted in the charts shown in Figure 4a where, they are shown in conjunction with the profiles calculated according to the dimensionless values published by WES for the specific cases of H / H0 = 0.5, 1.0 and 1.33. On the other hand, Figure 4b shows the crest pressure profiles obtained from cases with P / H0 = 2.5.



(a) (b)

Figure 4. Numerical results for (a) Upper Nappe Flow Profiles and Percentages of Difference of Flow Depth and (b) Crest pressure Profiles for Spillways with an approximation depth of P/H₀=2.50

A very good fit can be observed between the curves obtained with the numerical model and those of the experimental model (WES). As it can be seen in Figure 6a, there is a maximum percentage of difference of 3% for the data case shown in Table 2. In the cases with a head to design head rate, H / H0, of 0.5 and 1.33, even smaller differences were obtained. On the other hand, in the case of the crest pressure values a very good adjustment was found in all H / H0 the subcases, the numerical values and the results reported by WES in HDC 111-16 are very similar in magnitude and position of the minimum pressure. It is considered that, for low arrival velocity, the values of the flow depths and pressures calculated with CFD are adequate in magnitude for design effects.

When evaluating cases with an arrival velocity that is non negligible (lower values of P / H0) it was found that the percentages of difference, with respect to the WES values (HDC 111-11), increase as the arrival speed increases, as it can be seen in Figure 5.

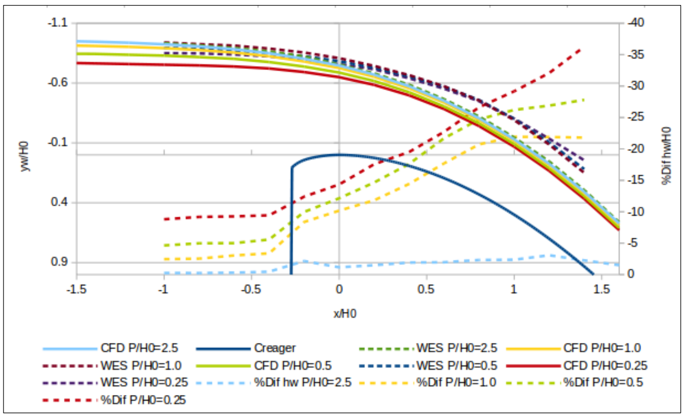


Figure 5. Numerical results for Upper Nappe Flow Profiles and Percentages of Difference of Flow Depth considering spillway geometries defined for different P/H0 and a single rate of H/H0=1.0

Table 2. Specific Boundary Contours for Each Variable

Position		CC27, H/H_0=1.0			WES, H/H_0=1.0			Comparison	
x/H_0	x (m)	yw (m)	yw/H_0	hw (m)	yw/H_0	yw (m)	hw (m)	Δ hw (cm)	% Difference hw/H_0
-1	-4	13.697	-0.924	13.697	-0.933	13.732	13.732	-3.548	-0.258
-0.8	-3.2	13.626	-0.907	13.626	-0.915	13.660	13.66	-3.354	-0.246

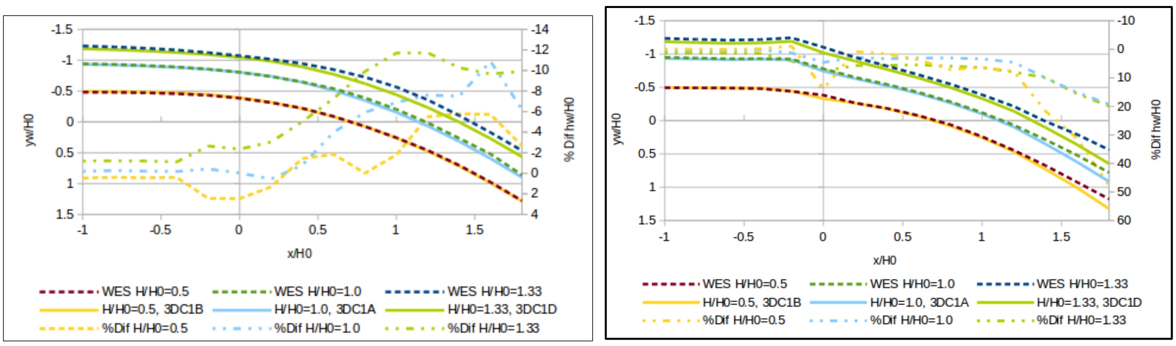
-0.6	-2.4	13.531	-0.883	13.531	-0.893	13.572	13.572	-4.098	-0.302
-0.4	-1.6	13.398	-0.849	13.398	-0.865	13.460	13.46	-6.222	-0.462
-0.2	-0.8	13.210	-0.802	3.3815	-0.821	13.284	3.4559	-7.443	-2.154
0	0	12.985	-0.746	2.985	-0.755	13.020	3.02	-3.502	-1.160
0.2	0.8	12.682	-0.670	2.7836	-0.681	12.724	2.8258	-4.223	-1.495
0.4	1.6	12.292	-0.573	2.6592	-0.586	12.344	2.7111	-5.195	-1.916
0.6	2.4	11.808	-0.452	2.5856	-0.465	11.860	2.6373	-5.177	-1.963
0.8	3.2	11.220	-0.305	2.5431	-0.32	11.280	2.6036	-6.045	-2.322
1	4	10.519	-0.130	2.5189	-0.145	10.580	2.58	-6.113	-2.369
1.2	4.8	9.701	0.075	2.5028	0.055	9.780	2.5823	-7.948	-3.078
1.4	5.6	8.766	0.308	2.4935	0.294	8.824	2.5511	-5.758	-2.257
1.6	6.4	7.710	0.572	2.4816	0.563	7.748	2.5195	-3.782	-1.501
1.8	7.2	6.539	0.865	2.4723	0.857	6.572	2.5051	-3.279	-1.309

7 UPPER NAPPE FLOW AND CREST PRESSURE PROFILES COMPARISON FOR A WES TYPE SPILLWAY WITH AN INTERMEDIATE TYPE II PIERS

This case consisted in the simulation of the Flow over a standard Ogee spillway whose crest was defined according to the WES Criteria. The spillway's sides are vertical for the upstream face and a downstream slope of 0.65 H:1V. The spillway also has two intermediate type II piers at the half thirds. The geometries were defined for a design head of 4m, considering the geometries shown in the HDC 111-13 and 13/1 in the WES (1987) reference. The objective is to compare the numerical results of the upper nappe flow profile and crest pressures profiles obtained with the OpenFOAM with respect to those reported in the HDC of WES (111-12 and 12/1 in the case of the flow profiles and 111-16 / 1 and 16/2 in the case of pressures).

The case has the same crest geometry as the previous case, but two type 2 piers, spaced 1.1 * H0 from each other, are added. Simulations were performed for 4 different P / H_0 ratios (2.5, 1.0, 0.5, 0.25) and 5 flow values derived from the ratios H / H_0 reported by WES (1.5, 1.33, 1.17, 1.0, 0.5) in a similar way to the previous case. It is a three dimensional case, so the contour conditions in front/back faces were changed as discussed.

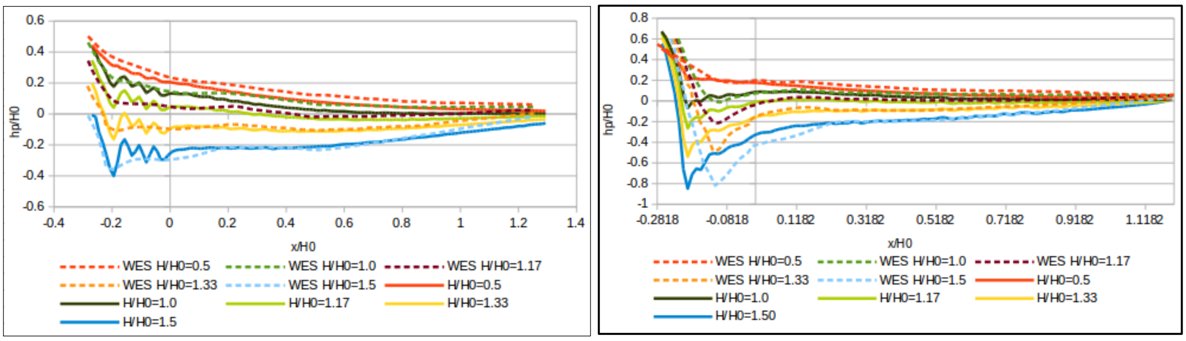
As in the previous case, the water depth values were calculated in the same positions as those specified in the HDC of WES, x / H_0 between -1 and 1.8. For giving an example, the numerical upper nappe flow profiles compared with those published by WES for the center of the span between piers and along the piers, respectively, are shown in Figure 6a and Figure 6b.



(a) (b)

Figure 6. Numerical results for Upper Nappe Flow Profiles and Percentages of Difference of Flow Depth for (a) Bay Center and (b) Along Piers, P/H_0=2.50

As in the previous case, good adjustments were obtained for the nappe upper flow profiles (compared with the WES reports in HDC 111-12 and 12/1), and relatively low percentages of difference in the flow depth. On the other hand, Figure 7a and Figure 7b show the profiles obtained for the crest pressure in the center of the span between piers and along the edge of the piers for cases with P / H0 = 2.5. In the case of pressure profiles along the piers, there are similar magnitudes for each case, but the location of the minimum pressure is in a different station, which could be due to the fact that the geometry of the piers evaluated is type 2, and the reports of the HDC for the case of pressure are type 3.



(a) (b)

Figure 7. Numerical results for Crest Pressure Profiles for (a) Bay Center and (b) Along Piers, P/H_0=2.50

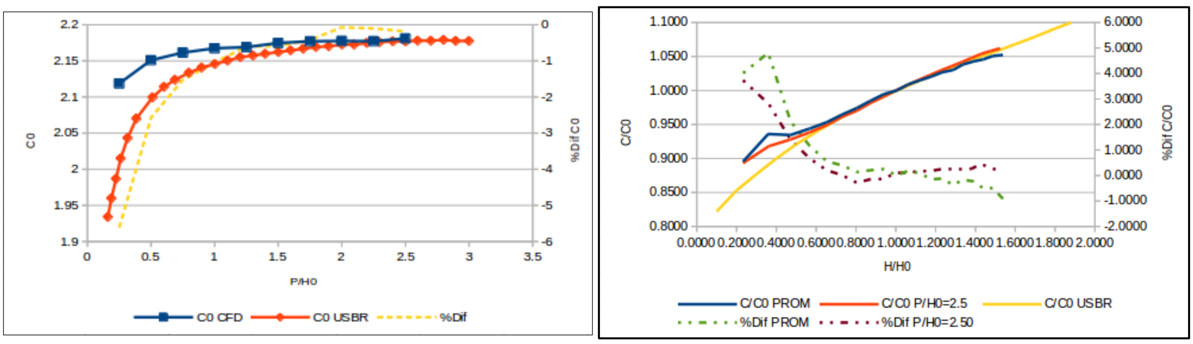
8 DISCHARGE CAPACITY

This case consisted in the simulation of flow over an ogee type spillway with 4 different upstream slope values and 10 different P / H0 ratios. Each dam geometry is evaluated for a series of 20 flows (in range between 10%-200% of the design flow), in order to determine the variations in the discharge capacity, measured through the discharge coefficient, product of the variations of P / H0 and the upstream slope. Then the simulated capacity of discharge of the spillway compared to the literature is calculated though the comparison between the discharge coefficients calculated with the OpenFOAM with those reported in the literature, specifically the USBR curves that contemplate the base discharge coefficients (dam with vertical face and effect of relation P / H0), correction curve by effect of the slope of the vertical face and correction curve for loads different from H_0.

A total of 20 flows with 10 different P / H0 ratios for each slope (4 different: 0, 0.33: 1, 0.66: 1 and 1: 1) for a total of 800 cases were simulated. For each one there was extracted the value of the depth of flow at an upstream point where the vertical velocity was practically zero, so that the assumptions of hydrostatic pressure were met and the discharge coefficient could be estimated by means of the expression Cd = Q / (B * H1.5), in such a way that relationships of discharge coefficients and geometric variations could be established. Taking all the values of discharge coefficients of the cases with vertical upstream face and head equal to the design head, the variation of the coefficient was expressed as a function of the relation P / H0 (indirect measure of incoming velocity). Figure 8a shows this variation and its comparison with the base discharge coefficient according to USBR. A better fit and a low percentage difference is notorious for those cases with P / H0 greater than or equal to 1.

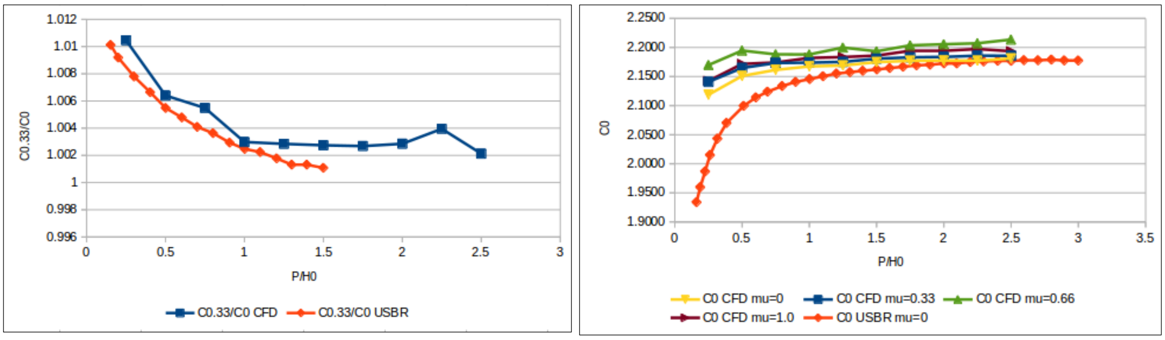
In the same way, the cases of vertical upstream face and negligible arrival speed were taken and compared with each other in order to establish the variation of the discharge coefficient as a function of the real head ratio to design load (H / H0). . This was also done for the other P / H0 ratios and finally an average relationship was made as shown in Figure 8b, from which it can be seen that, for H / H0 ratios greater than 0.6 a good adjustment was obtained with respect to the curves of correction suggested by USBR.

Finally, a comparison of the discharge coefficients obtained for different slopes of the upstream face was established, removing the effects of the corrections for loads different from the design and the base coefficient. For each slope, there were obtained comparisons of the correction factor for slope with respect to the curves recommended by USBR. For example, Figure 9a shows the comparison for the case of the slope of 0.33H: 1V, noticing a good adjustment. Figure 9b shows the comparison of the discharge coefficients for the different slopes, from which, as denoted by USBR suggestions, in the case of numerical results, the slope of 0.66H: 1V is also the one that has a greater capacity of discharge.



(a) (b)

Figure 8. Results of Comparison for (a) Base Discharge Coefficient and (b) Discharge Coefficient Correction for Head Different that Design Head



(a) (b)

Figure 9. Results of Comparison for (a) Discharge Coefficient Correction for 0.33H:1V upstream slope and (b) Comparison for Discharge Coefficients for all slopes considered in simulations

9 CONCLUSIONS

1. Given the large number of simulated cases (with different geometries and parametric variations thereof), it proved the usefulness of numerical simulations with respect to physical models, because it is possible to perform a high number of different simulations in an expeditious and economical manner, at least for the case of the simulation of the flow over a ogee type of spillway with free discharge.
2. The choice of OpenFOAM as the program to be evaluated is considered appropriate given its condition as an open access and source program and the dedicated forums. The process of assembling cases in the OpenFOAM program is not simple and is quite manual since it lacks of an official graphical user interface.
3. According to the results of the OpenFOAM, to increase the trust in the results if only the study of the water depth is of interest, it is recommended to use a maximum cell size of Hw / 15 where the value of Hw is the approximate head of water measured upstream and above the crest level, while if it is important to know well the pressure in the crest, it would be advisable to lower the horizontal size of cell to Hw / 40.
4. Of the turbulence models evaluated, the k-ω presents a completely unstable behavior, so its use is not recommended. In the other models, the closer results to those reported in the literature were obtained with the k-ω SST.
5. For the range of stations whose depth of flow and pressures were evaluated (between -1 <x / H0 <1.8) a significant influence of the roughness was not detected, given that it was not included in the simulations and also the results obtained were very close to those reported in the literature.
6. For dams with very low arrival velocity heads (P / H_0 = 2.5 or greater), OpenFOAM represented the profiles of the upper nappe flow and crest pressures profiles quite accurately and close to the results reported in the literature. For dams with high arrival velocity loads (P / H_0 less than 1.0) OpenFOAM results present stability problems that increase as speed increases, so its implementation is not recommended with the configurations used in this work. For dams with intermediate velocity loads ($1.0 < P / H_0 < 2.5$) the results of OpenFOAM behave in a stable manner and converge to a solution of flow profiles and pressures within expected ranges according to the data reported in the literature. The numerical results can be relied upon, although it should be taken into account that there may be errors of less than 10% in the depth values of the water. These errors will be lower as the P / H_0 ratio increases.
7. The results of the base discharge coefficients present a difference of less than 1% with respect to those recommended by USBR, for P / H0 ratios greater than 1.0. For lower values, OpenFOAM calculates a much higher discharge capacity, which increases more as the P / H0 ratio decreases.
8. The results of the discharge coefficients, obtained with OpenFOAM, for cases with heads different from the design heads, are well adjusted with respect to the curves of the literature, if they are in the range 0.6 <H / H0 <1.5. For ratios smaller than 0.6, numerical discharge coefficients obtained are much higher than expected according to the literature, so their use in these cases is not recommended. It is possible that in this case the results are influenced by a mesh size effect, which was very large for low H / H0 cases, since, for simplification purposes, meshes of constant size were generated in the case. The reliability of the results obtained is greater as the incoming velocity is lower, this is evidenced in the better adjustment of the curve of numerical discharge coefficients to that reported by the literature for values of P / H0 greater than 1.0 . The OpenFOAM is able to simulate in an acceptable way the influence of variations in the slope of the face upstream, which would allow the application of the program for simulations of dams with slopes different from those reported in the literature. In addition, the OpenFOAM corroborates that the inclinations of the vertical facing tend to increase the discharge coefficient, however, it was detected that for the slope of 2: 3 higher values of the discharge coefficients were obtained, above those of slope 1 : 1, which coincides with the reports in literature.

ACKNOWLEDGEMENTS

We thank the hydraulic engineers Ph.D. José Pablo Porras and Ph. D. Alberto Serrano Pacheco for their great contributions in the follow-up during the development of this academic work and suggestions for analyzing cases that were simulated with OpenFOAM.

REFERENCES

CFD Support. (2017). *OpenFOAM Training.* Praga: CFD Support s.r.o.

ENGYS. (2012). A Comprehensive Tour of snappyHexMesh. *7th OpenFOAM Workshop.*

Olsen, N. R. (2014). A Three-Dimensional Numerical Model for Simulation of Sediment Movements In Water Intakes with Multiblock Option: User's Manual. *Department of Hydraulic and Enviromental Engineering: The Norwegian University of Science and Technology*.

OpenFOAM. (2016). User's Manual.

Strandenes, H. (06-12-2017). NTNU HPC GROUP. Taken from OpenFOAM Tutorial: http://www.hpc.ntnu.no/pages/viewpage.action?pageId=442368

USACE. (1990). EM 1110-2-1603 Hydraulic Design Of Spillways. Washington: U.S. Army Corps of Engineers

USBR. (1987). Design Of Small Dams. *Bureau Of Reclamation: U.S. Department of Interior*

WES, W. E. (1987). Hydraulic Design Criteria. *United States: Army, Corps of Engineer*s