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Investigating Scale Effects of a Hydraulic Physical Model with 3D CFD

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SYNOPSIS In the present study, the three-dimensional (3D) Computational Fluid Dynamics (CFD) Volume of Fluid (VOF) method is validated to reproduce hydraulic free surface flows over a labyrinth weir and a spillway for several flow rates using the open source toolbox OpenFOAM 3.0.1 and the commercial CFD package ANSYS Fluent 17.2. The CFD solvers are employed to simulate the 1:25 scale Froude number similarity physical model of the scheme, with validation conducted using experimental observations and measurements. It is found that both solvers are capable of accurately reproducing the velocities and depths measured in the physical model and are also able to capture complex flow features. The models are applied to simulate the prototype hydraulic flows so that scale effects from the physical model can be quantified. Results show the overall decrease in water depth and increase in velocity in the prototype can be up to 15% and 10%, respectively, for the lower flow rates, with scale effects reducing for larger flow rates. The prototype scale simulations also exhibit some variation in the labyrinth weir rating curve when compared to the scaled case; showing lower heads upstream of the crest for the same discharge. As theory would suggest, discrepancies in the rating curve at the two scales are more pronounced for low flow rates.

INTRODUCTION

The effects of climate change are becoming more apparent with extreme rainfall events intensifying and, in some instances, doubling in parts of the UK in the last four decades (Fowler and Kilsby, 2003). Flooding is the natural disaster with highest occurrence (Jonkman, 2005) and is expected to further increase in the future as a consequence of the climate change. In the context of these circumstances the design of new, and upgrade of existing, hydraulic infrastructure such as weirs and spillways is of paramount importance. Such structures play a key role in providing safety for developed areas and the natural environment. In the recent years the implementation of labyrinth weirs has been increasingly proposed internationally as an alternative to linear weirs (Paxson and Savage, 2006). Interest in such designs has intensified both their research and application (Ribeiro et al., 2013). Given the high efficiency of these structures they have frequently been selected for reservoir rehabilitation schemes.

The typical hydraulic modelling approach for the design of hydraulic infrastructure has involved the construction of a scaled physical hydraulic model. A physical model is typically constructed with similitude based on dimensional analysis, which dictates that a model is fully similar to the prototype if there is geometric, kinematic and dynamic similitude between the prototype and the model. Full dynamic similitude between prototype and model is not physically possible when using the same fluid and therefore the most relevant force ratio is chosen and matched in the prototype and model. In hydraulic structures this is typically the Froude number, since gravity effects are highly relevant. This induces scale effects, which are discrepancies arising due to force ratios being unequal in the prototype and model (Chanson, 2009). Physical models are designed to try and minimise these scale effects, but they cannot be eliminated entirely. As such, scale effects can constitute one of the main disadvantages of physical hydraulic models and it is essential to minimise them by complying with the available established criteria. A number of studies have investigated scale effects present in Froude number physical models and determined limits in force ratios or flow variables to be applied in the physical modelling of several phenomena. Some of the most prominent examples can be found in Pfister and Chanson (2012), Pfister et al. (2013) or Erpicum et al. (2016).

Over recent decades the hydraulic modelling community has experienced a growing interest in three-dimensional (3D) Computational Fluid Dynamics (CFD) models to simulate hydraulic free surface flows. Improvements in computer processing power have enabled the development of several CFD modelling techniques. Such models are capable of simulating the prototype scale and provide the mapping of the quantity fields across the entire modelling domain. One of the most established CFD models to simulate free surface hydraulic flows is the Volume of Fluid (VOF) by Hirt and Nichols (1981). The VOF method involves the application of a volume fraction function to differentiate between the two phases. In order to locate the position of the interface within a cell, a transport equation for the volume fraction function is solved using interface capturing schemes. VOF has been shown to be able to reproduce complex experimental and real free surface flow phenomena. Examples of the application of VOF to simulate flow over labyrinth weirs can be found in Crookston et al. (2012) Paxson and Savage (2006) or Savage et al. (2016). Furthermore, the capability of CFD models to simulate the prototype scale make it possible to utilise numerical simulations to determine scale effects of a physical model.

The objective of this study has been to use the VOF CFD approach to simulate water flowing over a labyrinth weir. Having validated the numerical model using experimental measurements, the prototype scale is simulated so that comparisons between the numerical outputs at the two scales can be made. A range of flow rates over a physical model, constructed for the design of a flood alleviation scheme, are used for validation.

CASE STUDY AND PHYSICAL MODEL

The hydraulic structure used in the study consists of a flood alleviation scheme, comprising an embankment dam, a labyrinth weir and a spillway. The scheme is designed to provide protection for a flood event with a return period of 100 years. The layout of the scheme and a photograph of the physical model are shown on Figure 1 and Figure 2 respectively. The length of the spillway channel from the labyrinth weir to the stilling basin is of approximately 150 m. At the top of the spillway the labyrinth weir stretches across the full 32 m width of the channel, which is the widest part of the spillway. The labyrinth has a depth of 5.1 m with 4 cycles. The spillway presents four different gradients along the channel. 75 m downstream of the weir, the spillway channel narrows to 20 m wide and increases in gradient. 9 m further downstream, the spillway gradient presents a second change in gradient and the channel becomes gentler and constant until it merges with the stilling basin which has a horizontal bed.

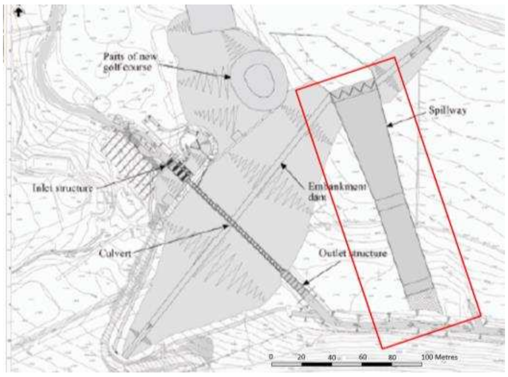

Figure 1: Layout of the hydraulic structures from Brinded et al. (2014)

Figure 2: Photograph of the physical model

A 1:25 scale physical hydraulic model based on Froude number similarity was commissioned for the design of the scheme as described in Brinded et al. (2014). By geometric similitude, the length ratio is equal to this model scale λ, as indicated in Eq. (1) where L_m is the characteristic length in the model and L_p is that in the prototype. Eq. (2) presents the velocity equivalence, where v_m is the water velocity in the model and v_p is the equivalent in the prototype. The correlation of the flow rate in the model Q_m and in the prototype Q_p is defined in Eq. (3). The time equivalence is indicated in Eq. (4) where T_m is the time in the model and $T_p$is the real time.

$$\lambda = \frac{L_p}{L_m} \tag{1}$$

$$v_p = v_m\sqrt{\lambda} \tag{2}$$

$$Q_p = Q_m\lambda^{5/2} \tag{3}$$

$$T_p = T_m\sqrt{\lambda} \tag{4}$$

Depth and velocity measurements were collected at several locations along the spillway channel. Depth measurements were taken with a steel ruler and velocity was measured with a total head pitot tube. The accuracy of the depth and velocity measurement instruments is reported to be not higher than 0.001 m and 0.01 m/s respectively which correspond to 0.025 m and 0.05 m/s in the prototype. Accounting for errors associated with locating the measurement equipment, the measurement error is estimated to be closer to 0.01 m (0.25 m in the prototype). Accurate schematic representations of the flow features were also captured and reported in physical model diagrams.

NUMERICAL MODEL

A 3D geometry comprising the labyrinth weir and the spillway was extracted from CAD drawings of the structure and the modelling domains were constructed and meshed appropriately. Figure 3 a) and b) present the outline of the two modelling domains created for the present work. These consist of a primary domain comprising the approach channel, the labyrinth weir and several meters of spillway channel downstream (which here is referred to as “weir” domain) and a secondary domain covering the approach channel, the labyrinth weir and the whole length of the spillway channel and stilling basin (referred to as the “channel” domain). The channel domain enables the execution of model validation with physical model measurements of water depth and velocity as well as details of the wave structures. The secondary weir domain is created for the computation of the weir rating curve and crest velocities with a reduced geometry.

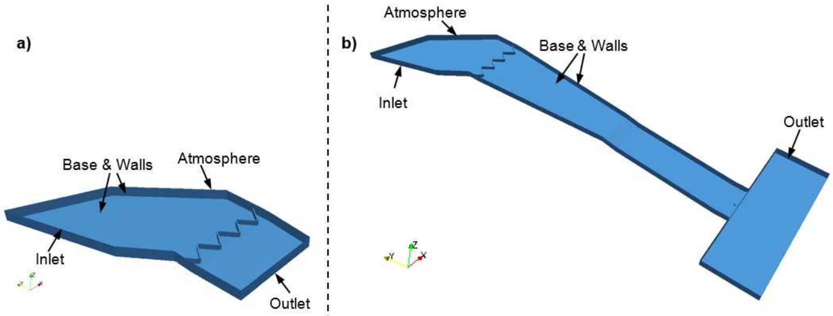

Figure 3: Modelling domain with boundary conditions of: a) the weir geometry and b) the channel geometry

The weir domain was meshed such that it would be possible to measure the water depth upstream of the weir with appropriate precision. The approach channel was meshed with a cell size of 0.004 m and similarly the labyrinth weir and its vicinity with a cell size 0.002 m for the entire volume (equivalent to 0.1 m and 0.05 m in the prototype respectively). The channel domain was meshed with an inflation layer at the base of the spillway to accurately represent the flow features along the whole channel. A mesh convergence study was conducted with the channel domain using three hexahedral meshes with main cell sizes 0.02 m, 0.008 m and 0.004 m (equivalent to 0.5 m, 0.2 m and 0.1 m in the prototype) at the area surrounding the free surface, and these are reduced at the base of the spillway. These meshes had 0.6, 2.9 and 7.9 million elements respectively. Mesh dependency was analysed in bases on the Grid Convergence Index (CGI) methodology as described in Celik et al. (2008). The study demonstrated that OpenFOAM presented higher sensitivity to cell size than Fluent. For the simulations at model scale, the mesh of intermediate resolution was chosen for the Fluent simulations and the finest mesh for those with OpenFOAM. The study was also completed at prototype scale, and showed that the two solvers present mesh independent results with the mesh of intermediate resolution, which was the one chosen at such scale. The cell size of the weir domain was also informed by the outcomes of such study.

Scaled and prototype simulations were conducted using a collocated Finite Volume Model (FVM) discretisation on hexahedral cells and the VOF approach for multiphase modelling. Two well-known solvers were utilised to perform the numerical simulations in order to allow for performance comparison. These are the open source platform OpenFOAM 3.0.1 and the commercial CFD solver ANSYS Fluent 17.2. The three-dimensional turbulent nature of the flow in this case required solving the 3D Reynolds Averaged Navier-Stokes (RANS) equations. Turbulence was modelled with the Standard k-ε model. The near-wall flow region was modelled with a standard wall functions. The free surface was resolved with the VOF method. The VOF solves only one set of equations within the domain and the values of density and dynamic viscosity at the interface are computed by using the values of α at the interface. The interface capturing scheme employed in Fluent is a geometrical reconstruction approach based on the Piecewise Linear Interface Calculation (PLIC). In OpenFOAM the corresponding algorithm utilised is the algebraic reconstruction scheme MULES (Multidimensional universal limiter for explicit solution). No additional equations are implemented to model the aeration phenomena smaller than the mesh cell size. This means that air entrainment and the associated bulking of the flow are not considered in the model.

RESULTS AND DISCUSSION

Model Validation: Simulating the Physical Model

Four flow rates were simulated at model scale, these are 40 m^3/s, 79.8 m^3/s, 119.6 m^3/s and the PMF of the site which is 159.5 m^3/s. These were scaled down to physical model size appropriately as per Eq. 3. The reported values from the physical model are the maximum recorded. In the physical model a constant flow rate was applied until an effective steady state was achieved, and the same approach was used in the numerical simulations. The time series point data of the numerical simulations indicated that steady state occurred after approximately 90 s. Results presented are all extracted from simulations at times between 100 and 150 s, when the monitored predictions had remained stable for a minimum of 10 s. Time-averaged results are averaged within a time window typically between 10 and 30 s.

Flow rates 40 m^3/s and 79.8 m^3/s

Results show the complex configuration of cross-waves generated by the labyrinth weir are well reproduced by the two solvers for the shallow flow of 40 m^3/s. Figure 4 a) shows the physical model diagram with the location of the measuring locations and free surface features. Figure 4 b) shows the physical model cross-waves patterns and Figure 4 c) and d) present those predicted with OpenFOAM and Fluent, respectively. In the physical model, the intersecting cross-waves generated by the weir propagate until the change in gradient point, at which point they begin to fade. This situation is also reproduced in the numerical predictions from the two solvers. Figure 4 e) shows water surface profiles across the spillway channel (along a section through A) with the predictions from both solvers being well correlated with the depth measurements. Figure 4 f) shows the time-averaged values of velocity at different locations along the channel, which confirm velocity predictions from the two solvers are consistent and in line with measured values. Figure 4 g) shows the free surface features obtained for the 79.8 m^3/s case in the physical model diagram and numerically predicted with OpenFOAM. In this case, the complex configuration of cross-waves generated by the labyrinth weir are also well reproduced by the numerical model. The cross-waves crests are indicated with dark lines and they demonstrate a good correlation with the wave positions shown in the physical model. Velocity cross sections at several locations down the spillway channel are plotted on Figure 4 h), where it is shown there is especially close agreement between the numerical predictions and physical model measurements at all sections.

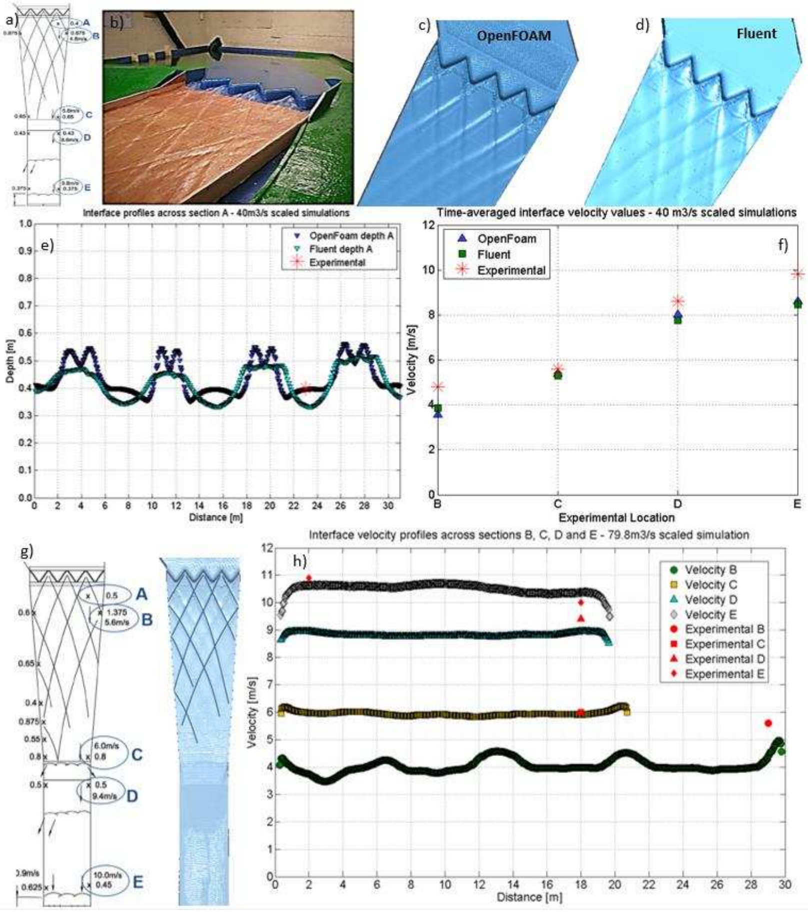

Figure 4: 40m^3/s: a) Model diagram; b) Physical model photograph; c) Free surface generated with OpenFOAM and d) with Fluent; e) Cross-sectional depth profiles through section A; f) Time-averaged velocity values; 79.8m^3/s: g) Model diagram and numerical predictions of free surface features; h) Interface velocity profiles at different sections

Flow rates 119.6 m³/s and 159.5 m³/s

In the modelling of the two largest flow rates, it is observed that predictions from Fluent indicate more pronounced wave's crests than predictions from OpenFOAM. Figure 5 a) presents the 119.6 m³/s water depths across sections A and B, located across the intersecting cross-waves. In this area of large depth and velocity variations, the Fluent predictions demonstrate closer agreement with the physical model measurements. The depths in the cross-waves area are very variable and therefore, although there is certain differences between the measurements and the numerical predictions, these are considered acceptable. Figure 5 b) shows time-averaged velocity values at the different measurement locations. The velocity predictions from both solvers present more consistency than those of depth.

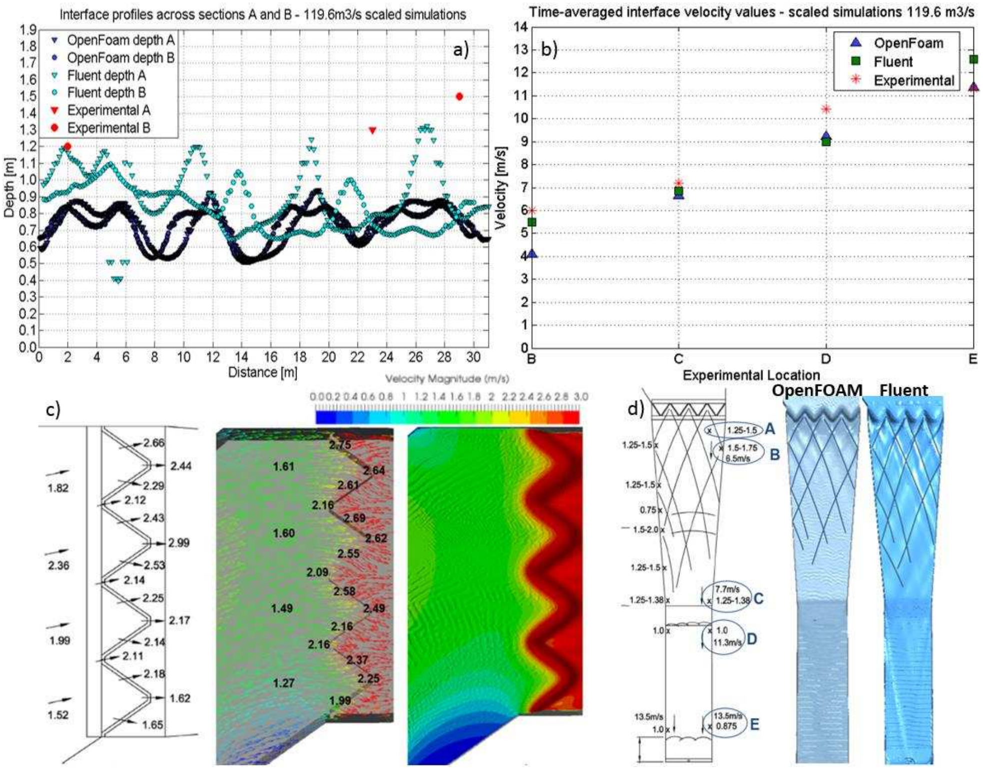

Figure 5: a) 119.6 m³/s profiles across sections A and B; b) 119.6 m³/s time-averaged velocity point data; c) 159.5 m³/s labyrinth weir velocities and numerical predictions; d) 159.5 m³/s physical model diagram and numerical predictions of free surface features

The PMF simulations show similar results, where the Fluent predictions exhibit larger depths and more prominent waves; and hence closer agreement with the physical model. In Figure 5 c) the PMF velocities measured upstream and at the crest of the labyrinth weir are shown along with the numerical predictions. Overall predictions are in reasonable agreement with the physical model measurements. Figure 5 d) shows the physical model diagram with the wave structures and those predicted with the two solvers. Despite the differences in wave crest prominence, the cross-wave configuration is generally well predicted in both solvers. The small discrepancies between the results from the two solvers are attributed primarily to the different interface capturing schemes utilised and slight variations in the algorithms of the two solvers.

Simulation of the prototype and Comparison with Model Scale

Velocities and Depths at the Spillway Channel

Prototype simulations for the four flow rates were undertaken and compared with those at physical model scale. Discrepancies between model and prototype scale simulations consist of increases in velocities and decreases in depth in the prototype scale with respect to the model scale. This is observed in the simulations from both solvers and for generally all flow rates, with discrepancies being reduced for increasing flow rate. The fact that discrepancies in depths and velocities decrease for the largest flows is in line with theory, which indicates that the scale effects are larger for lower depths and velocities, causing viscosity and surface tension forces to become more relevant in the physical model (Heller, 2011). Depths and velocities were averaged across sections B and D in order to quantify the variations at the two scales. Table 1 shows the percentage difference in the prototype scale values with respect to those at the model scale at sections C and D. The percentage difference in water depths at sections C and D correspond to $dh_{C,}$ and dh_D respectively. The velocity percentage differences are $dv_{B,}$ and $dv_{C,}$ respectively. In it is observed that the decrease in water depth and the increase in velocity in the prototype predicted by the two solvers is consistently largest in the 40 m^3/s case and it reduces for increasing flow rate. The OpenFOAM simulations show this consistent trend. The Fluent simulations also exhibit a decrease in discrepancies for increasing flow rates, although the 119.6 m^3/s shows lower differences at the two scales than the PMF case.

Table 1: Percentage difference in depth and velocity in the prototype respect of model scale

	OpenFOAM Simulations				Fluent Simulations			
Q [m^3/s]	dh_B [%]	dv_B [%]	dh_D [%]	dv_D [%]	dh_B [%]	dv_B [%]	dh_D [%]	dv_D [%]
40	-15.1	18.4	-16.4	7.1	-12.8	12.7	-11	3.1
79.8	-14.5	12.6	-13.2	2.2				
119.6	-12.9	11.6	-2.7	2.7	-0.04	0.2	5.4	3.3
159.5	-9.0	10.8	-0.36	2.9	-5.7	3.6	-6.3	3.0

Labyrinth Weir Rating Curve

The labyrinth weir rating curve of the physical model was compared to that that produced numerically at model scale. Subsequently, the curve at prototype scale was compared to that at model scale. The physical point in the weir where the experimental measurements were taken for the rating curve is not known. Given the location of the inlet is on the right side of the approach channel, the water head upstream of the weir presents variations within the approach channel and weir crest. In order to plot representative values of such depth the values were extracted and averaged along three cross-sections upstream and parallel to the weir. The numerically predicted and experimental curves are shown on Figure 6 where it is confirmed there is generally good agreement between the numerical predictions at model scale and the experimental measurements. The greatest difference between the predictions from the two solvers is for the 40 m^3/s case, and they show increasing agreement for the larger flow rates. In the intermediate flow rates there is good agreement between physical and numerical results. For 159.5 m^3/s, there is approximately 0.1 m difference between the experimental and the numerically computed curves. The 159.5 m^3/s flow rate presented the largest depth variation along the weir crest due to the inlet position, which was of up to 0.2 m in OpenFOAM and 0.4 m in Fluent. The prototype scale rating curves compared to those at model scale are shown on Figure 7. These exhibit a decrease in depth upstream of the weir for all flow rates. The decrease in depth is largest for the lowest flow rate and is minimal for the PMF. As previously stated, this situation is also expected from a scale effects point of view.

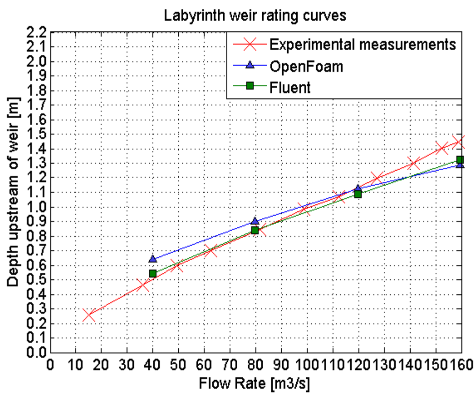

Figure 6: Rating curve of the labyrinth weir in the physical scale model and computed with the two solvers

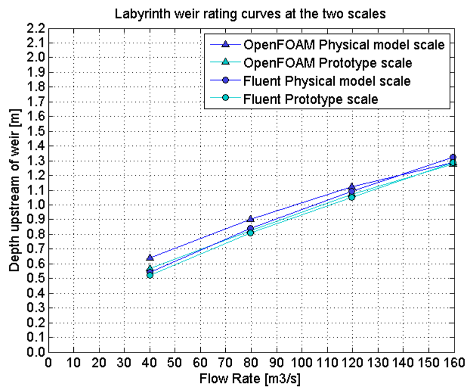

Figure 7: Rating curves at the two scales computed with the two solvers.

Literature recommends a minimum head of 0.03 m to correctly measure rating curves in physical models (Erpicum et al., 2016). In this case, in the

40 m^3/s the scaled head is 0.025 m which is under the limit, therefore discrepancies between the values at the two scales are expected. However, the 79.8 m^3/s case with a scaled head upstream crest of 0.036 m still appears to have approximately a 10% difference in the depth between the two scales. Further simulations of an extended scale range currently being conducted since they are necessary to determine an appropriate head limit for this particular case.

CONCLUSIONS

In this study, 3D CFD VOF simulations of hydraulic flows over a prototype labyrinth weir and spillway were conducted using the ANSYS Fluent and OpenFOAM solvers. Numerical simulations of the physical scale model were first undertaken four flow rates: 40 m^3/s, 79.8 m^3/s, 116.9 m^3/s and the PMF of the site 159.5 m^3/s. Results show there is good agreement achieved between the numerical and physical models. There is greater consistency between predictions from both solvers for the lowest flow rates. In the largest flow rates, the Fluent simulations present closer correlation with the physical model measurements. Discrepancies between solvers' predictions are mainly attributed to the different interface capturing schemes implemented in the two solvers. The comparison between scaled and prototype predictions shows the prototype flows exhibit lower free surface depths and higher velocities. The depth discrepancies between scaled and prototype flows are larger for the lowest flow rate; being of approximately 16% for 40 m^3/s and of 5% for the PMF. The increase in velocity also reduces for increasing flow rate, with a difference of approximately 13 % for 40 m^3/s and about 6 % in the PMF. The labyrinth weir rating curve at the two scales also exhibits differences. At the prototype scale the curve presents lower upstream depths for the same discharge, and such differences also decrease significantly with increasing flow rate. The observed scale effects are in line with the theory that the impact of viscosity and surface tension forces becomes relevant in low depths and velocities of Froude physical models. Further investigations are currently being undertaken in order to determine limits to minimise scale effects for this structure.

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