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NUMERICAL MODELING OF FLOW IN THE VERTICAL DROP WITH INVERSE APRON

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Drops are hydraulic structures that are commonly used in irrigation and waste water collection networks. A vertical drop balances the elevation difference between the channel slope and ground slope. Earlier investigations on this structure have mainly focused on experimental studies of the hydraulic characteristics. In this paper, the hydraulic characteristics of vertical drops with inverse apron have been studied numerically with used of Fuent software to solve the finite volume method. The volume of fluid (volume of fluid) was used for modeling the free surface. Flow characteristics such as downstream depth, pool depth and energy loss were calculated and compared with the experimental values. Different turbulent models and grids have been studied. The numerical results with a 52745-node grid, 1.5 meter downstream channel length, standard k-ε turbulence model and standard wall function showed the best agreement and the numerical downstream depth, pool depth and energy loss followed the theoretical equations very well. Finally the numerical impact velocities were compared to empirical equation for different cases and showed little discrepancy, therefore velocity characteristics of falling jet were calculated.

Keyword: Drop Structure, Numerical modeling, Flow characteristics, Turbulent model, Velocity characteristics.

INTRODUCTION

Drops are hydraulic structures that are commonly used in irrigation and waste water collection networks. A vertical drop balances the elevation difference between the channel slope and ground slope. The structure causes an either sub- or supercritical flow passing over a vertical fall and descends into a stilling pool downstream from the drop. Thus the flow structure is comprised of a falling jet (free overfall), a sliding or skimming jet and a circulating or mixing zone. This pattern causes the significant portion of flow energy to be dissipated through jet impact and turbulent mixing.

Earlier investigations on this structure have mainly focused on experimental studies of the hydraulic characteristics (Bakhmeteff [1], Moore [10], White [12], Gill [5], Rajaratnam and Chamani [11], Chamani and Beirami [2], and Chamani et al. [4]). Chamani et al. [3] investigated the hydraulic characteristics of vertical drops with adverse apron and upstream subcritical flow. They showed that the relative pool depth and relative downstream depth for adverse apron drops were larger than those with horizontal apron. The energy loss also increased as the invert angle changed from zero to 5 degrees.

Assuming a steady 2D irrotational and frictionless flow, Marchi [9] derived general equations for the lower profile of the nappe and the brink depth. He also presented two formulas for the free surface profile of the upstream from the brink depth in both sub- and supercritical cases.

Lin et al. [7] investigated the characteristics of mean velocity fields and flow patterns in the falling jet, the sliding jet and the pool of a free overfall using laser Doppler velocimetry and flow visualization techniques. Their results confirmed Marchi's equations for the nappe profile and energy loss. They also developed some unique similarity profiles of the mean velocity at different locations of the flow and proposed characteristic velocity and length scales of the deflected jet in the pool. Lin et al. [6] classified the flow pattern over a vertical drop pool without ventilation and tail water into a napped flow, transitional flow, a periodic oscillatory flow and a skimming flow based on discharge and height of the end sill.

The characteristics of shear layer structure between the sliding jet and the pool for skimming flow over a vertical drop pool were investigated by Lin et al. [8]. They analysed the distribution of measured velocity and obtained a similarity for the profile of the mean velocity at different cross sections along the shear layer.

Elaborated studies were made on different properties of the drop structure mostly by experimental modelling. However, it is well known that laboratory experiments not only suffer from constraints on the range of applicable physical parameters and scaling effects, but also the cost associated with performing careful experiments could be quite high. Recent powerful Navier Stokes (NS) solvers have the potential to simulate flow in hydraulic structures for better understanding the physical processes and providing engineering tools to design these structures. Few numerical models have been developed to investigate the flow characteristics over the vertical drop.

In this study the complex flow pattern in the vertical drop with adverse apron was studied numerically. The two dimensional RANS equations accompanied with volume of fluid (VOF) method are applied. The results of the simulation are then compared to experimental results of Chamani et al. [3]. The details of energy loss, velocity profiles in different locations are also scrutinized.

NUMERICAL MODEL APPLICATION

Numerical model

Two dimensional unsteady RANS equations were solved numerically using Finite Volume Method. The PISO scheme was applied for the velocity-pressure coupling. The mostly used two-equation turbulence models k-ε and k-ω were chosen to model Reynolds shear stress term. The power law scheme was used for discretization of momentum, k, ε, and ω equations. The VOF method (geometrically reconstruction algorithm) was adopted for interface simulation.

Description of test cases

In this study were used data set presented was measured by Chamani et al. [3]. Their experiments were conducted in a ventilated vertical drop with subcritical flow at the upstream channel and sloping aprons at the downstream channel. Flow characteristics such as pool depth, downstream depth, and energy loss were measured in an 11 m length, 0.401 m width flume. The drop height was 0.21 m and inverse slope was set at 5 degrees (Fig. 1).

In Fig 1., drop height (H), brink depth (Y_b), critical flow depth (Y_c), critical flow velocity (V_c), downstream flow depth and velocity (Y_t,V_t), impact velocity (V_i), apron angle (θ), pool depth (Y_p), and jet deflection length (L_p), for case is schematically illustrated.

Boundary and initial conditions

Instead of setting the depth and velocity, at the upstream end of the channel, a tank was set up so that the contracted flow depth and the average velocity (after the gate) match the selected critical depth and velocity. Pressure outlet boundary conditions (BC) were set at top of the channel, the channel outlet and at the air vent (Fig. 2). No slip BC and standard wall function were used at the walls for the laminar and turbulent conditions, respectively.

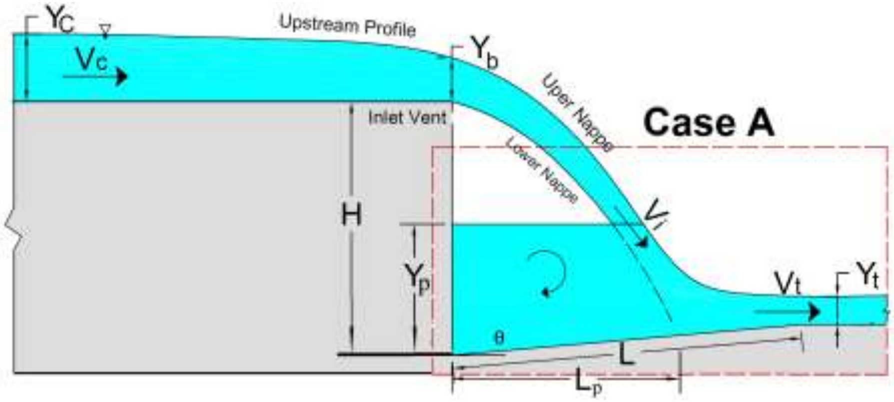

Figure 1. Schematic view of the drop structures

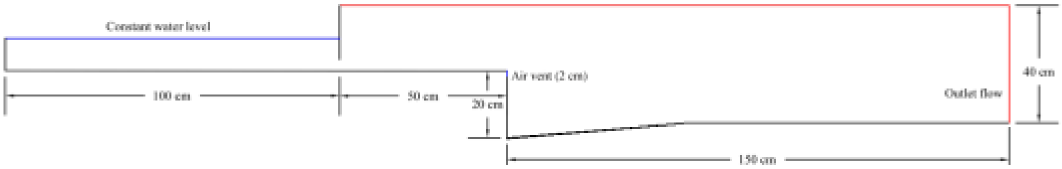

Figure 2. Adopted boundary conditions for the numerical modeling of the flow over the vertical drop.

Numerical grids

Structured grids were generated to discretize the flow domain including the drop structure and downstream channel as can be seen in Fig. 3.

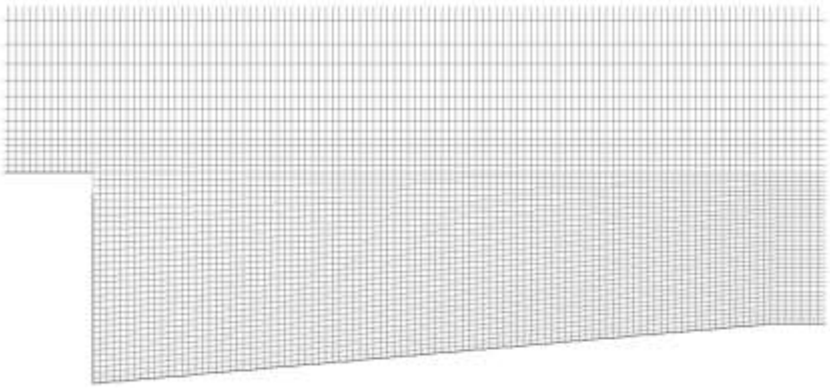

Figure 3. A sample structured grid used for the vertical drop with adverse apron

RESULTS AND DISCUSSION

Four different grids (7908, 18901, 32729 and 57512 nodes) with identical flow properties were used. The flow depth results were converging and a good agreement with experimental data was observed with the two smallest grids. However, to access better resolution, the 57512-node grid was preferred and grids with almost the same cell size were adopted for other numerical simulations.

To study the effects of downstream channel length on the flow modelling, the pressure outlet BC was set at different distances (1.5, 3, and 6 m) from the vertical wall of the drop. The results showed that the flow was developed at about 1.5 m and extra length was not influencing the flow properties. Moreover, it was observed that after 20 seconds the steady condition almost prevailed.

To approximate a better upstream velocity profile, the flow led to the channel underneath a gate. With trial and error, the water level at the tank and gate opening was set up so that the contracted flow depth and the average velocity (after the gate) match the selected critical depth and velocity. Using this method the model results were significantly enhanced.

The laminar model did not produce satisfactory flow depth and velocity along the drop structure. The results of the most commonly used two-equation turbulence models (k-ε and k-ω) were identical. Furthermore, the standard wall function produced better results compared to non-equilibrium wall function. Thus, for other simulations, the standard k-ε with the standard wall function was preferred. The results of this research can be categorized into: (1) comparison of flow depth and velocity in different parts of the drops with existing experimental data and empirical relations, (2) investigating the velocity characteristics of falling jet.

Comparison of computed and measured flow depth, velocity and energy

The computed flow depth, averaged velocity, and the flow energy in different parts of the drops were compared to their analogous experimental data (Tables 1 and 2). The results reveal that the numerical model mimicked the overall experimental flow characteristics.

Some empirical equations based on surface jet theory have been reported by Chamani et al. [3] for the adverse apron drop as functions of $Y_c/h^{'}$, such as

$$\frac{Y_t}{h'} = 0.516\left(\frac{Y_c}{h'}\right)^{1.184} \theta^{0.054} \qquad \text{(relative energy loss at the drop)} \qquad (1)$$

$$\frac{Y_p}{h'} = 0.89\left(\frac{Y_c}{h'}\right)^{0.765} \theta^{0.347} \qquad \text{(relative pool depth)} \qquad (2)$$

$$\frac{\Delta E}{E_0} = 0.173\left(\frac{Y_c}{h'}\right)^{-0.602} \theta^{-0.079} \qquad \text{(relative pool length)} \qquad (3)$$

Where $h' = h - L \sin\theta$,

Table 1. Comprison of the numerical and experimental flow depth and velocity (in SI units).

Parameter	H	L	$h^{'}$	Q	Y_c	V_c	Y_b	Y_p	Y_t	V_t	L_p
Num.	0.21	0.64	0.054	0.026	0.041	0.624	0.026	0.086	0.022	1.220	0.151
Exp.	0.21	0.64	0.054	0.026	0.041	0.636	0.029	0.087	0.021	1.222	0.149

Table 2 reveals that the numerical results were in very good agreement with these equations. This indicates that the numerical set up (grid size, boundary and initial conditions) was set appropriately and the numerical results can be extended to other flow and geometry conditions (Fig. 4). Therefore, the numerical model with this initial and boundary conditions could be confidently used to investigate the flow properties over the drops.

Table 2. Comprison of the numerically, experimentally and empirically obtained flow energy (in SI units).

Parameter	E_1	E_2	Y_c/H	Y_p/H	Y_p/h'	Y_t/H	Y_t/h'	L_p/H	$\Delta E/E_1$
Num.	0.271	0.097	0.196	0.409	0.561	0.102	0.140	0.641	0.717
Exp.	0.272	0.098	0.196	0.415	0.570	0.102	0.140	0.641	0.711
Em. Eq.	-	-	0.196	-	0.570	-	0.117	-	0.683

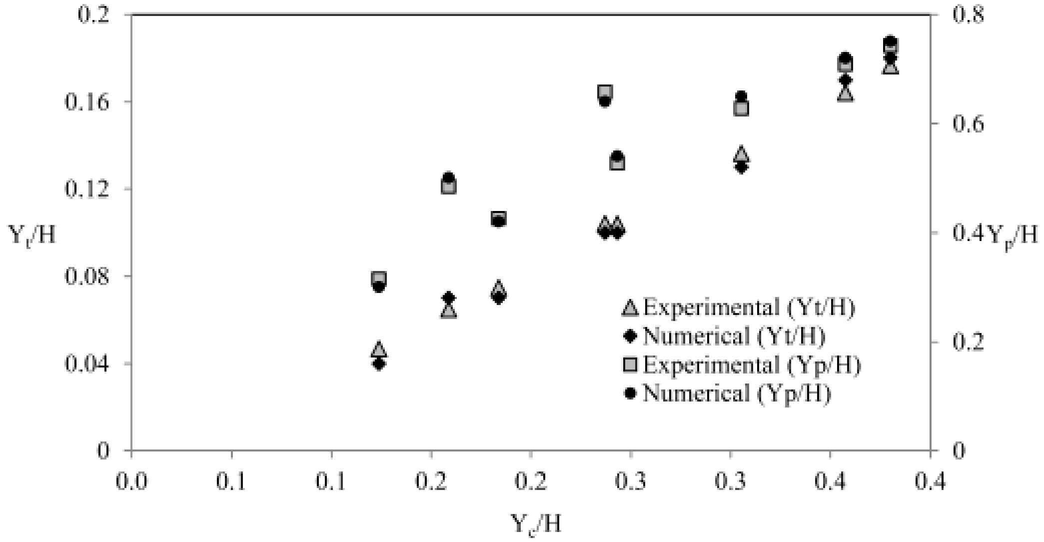

Figure 4. Comparison of the numerical and experimental results for different flow conditions.

Velocity characteristics of falling jet

Consistent with Lin et al. [7], the detailed velocity characteristics were studied in falling jet. According to experimental analyses of Lin et al. [7] two coordinate systems were adopted in this study. One was the Cartesian coordinate system (X,Y) with the origin at the lower corner of the drop, and the other was a local coordinate system (S, y_r) which was constructed along the upper surface of the sliding jet with S being tangential to the upper surface of the jet and y_r pointing outward normal to the surface. Here, S represents the arc length along the upper surface of the sliding jet between the brink end, with S=0 being the upper jet surface at X=0, and the end of the pool (the upper jet surface at X=L). Furthermore, u and U represent the velocity in S and X direction, respectively.

The modelled time-averaged velocity profiles of the falling jet at five cross sections for Y_c/H = 0.146 for adverse apron has been shown in Fig. 5. The locations of the five cross-sections, marked as “a” to “e”, start from the arc length of S = S_a (a very short distance upstream of the intersection of the falling jet and the pool at Y = Y_p), to near the bottom of the downstream flow.

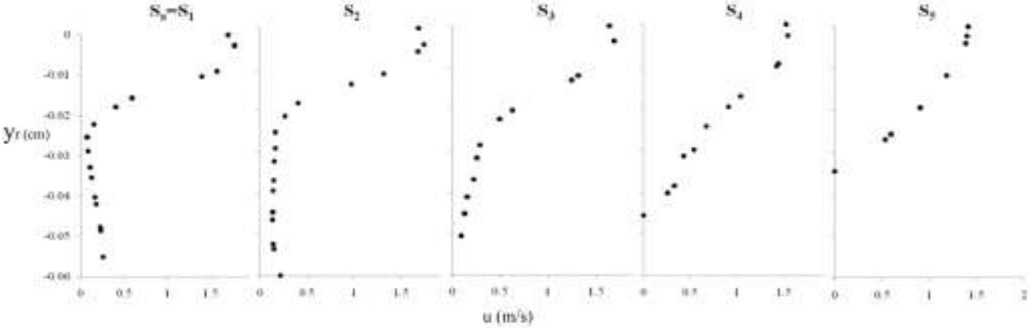

Figure 5. Comparison of jet mean velocity profiles of the case $Y_c/H = 0.146$ for adverse apron drop

Consistent with the Fig. 5, the large velocity gradient near the sliding jet pool intersection decreases as the jet moving further downstream, which is mostly due to the entrainment effect caused by turbulent mixing along the shear layer. This diffusion-like mechanism decreases the velocity gradient as well as momentum exchange as the jet moves downstream, and results in energy exchange between the jet and the pool as well as energy dissipation due to turbulence [7]. Therefore, the model results can be analysed where ever the measurement of the flow characteristics need special tools and technology. However, the dissipative nature of the two-equation turbulence model caused the velocity gradient dispersed as the jet moves towards the downstream channel.

CONCLUSIONS

The characteristics of the complex flows over a vertical drop with adverse apron were studied numerically using a RANS solver. The flow properties over a vertical drop with adverse apron were investigated. Grid study showed that numerical results of a 57512-node grid had the best agreement with the experimental values. The desired downstream channel length was preferred to be 1.5 meter, and the standard k-ε turbulence model produced the best results in an adverse apron drop.

The numerically calculated velocity profiles reveal the large velocity gradient near the sliding jet pool intersection decreases as the jet moving further downstream, which is mostly due to the entrainment effect caused by turbulent mixing along the shear layer. Using enhanced turbulence model will decrease discrepancies in this region.

It can be concluded that the 2D numerical model is able to produce satisfactory results in order to design and evaluate a vertical drop with adverse apron, which in turn can aviate the need to endeavor too much effort and financial cost to construct a suitable experimental model in the laboratory.

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