Numerical Investigation of Flow over Rectangular Side Weir in a Circular Channel

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Abstract

Side weir is one of most important structures in drainage system, irrigation, flood protection, and urban sewage systems. Therefore, the hydraulic behavior of side weirs received a level of interest by many researchers. The water surface profiles over rectangular side weirs in circular channel were investigated experimentally by many researchers in past. In present study, hydraulic behavior of a side weir is simulated by FLOW-3D software. RNG model for turbulence simulation and VOF model for water surface simulation were applied. At first, the water surface profiles and the discharges performances from CFD analyses were validated with the experimental results. The results show good agreements between CFD and experimental results in the subcritical regime. Then free surface flow and flow pattern over a side weir is simulated and effects of upstream Froude number on them are investigated. Various turbulence models were tested to determine the sensitivity of the free surface over a rectangular side weir. The results showed, RNG k- ε turbulence model can be used to predict the various characteristics of the side weir flow and give close results compared to other turbulence models.

Keywords: Side weir, CFD analysis, Free surface flow, Turbulence model, Circular channel.

1. INTRODUCTION

Side weirs are the hydraulic structures that have been used in drainage system, irrigation, flood protection, and urban sewage systems. A side weir is installed on the side wall of main channel to divert the flow. Flow over side weir is a typical case of spatially varied flow. The importance of channels with side weir and the passing flow over side weir were investigated experimentally and numerical by many researchers. There are several studies on side weirs, most important experimental studies in a sharp-crested rectangular side weir in rectangular channels are as follows:

De Marchi (1934), was one of the earliest investigators who gave equations for flow over side weirs and developed an equation for the water profile across a side weir on the assumption that total energy along the side weir is constant [1]. Then several researchers have developed an equation for the discharge coefficient of De Marchi until today; For instance Frazer (1954), Collinge (1957), Chow (1959), Subramanya and Awasthy (1972), El-kashab (1975), Ranga Raju et al. (1979), Ramamurthy et al. (1980), Hager (1987), Uyumaz and Smith (1991), Singh et al. (1994), Swamee et al. (1994), Swamee et al. (1995), Jalili and Borghei (1996), Vatankhah and Bijankhan (2009), Emiroglu et al. (2010), Emiroglu et al. (2011), Bagheri and Heidarpour (2012), Novak et al. (2013), Bagheri et al. (2014), Emiroglu et al. (2016), [1-21].

Although the behavior of side weir received the level of interest for many decades, there are few contributions aimed to study the hydraulic characteristics of the flow along side weirs in circular channels. Allen (1957) was the first one who conducted a laboratory study on the passing discharge over a rectangular side weir on a circular channel [22]. Uyumaz and Muslu (1985) investigated some experimental and analytical methods on the passing flow over side weirs on circular channels in both supercritical and subcritical flow conditions. Some discharge coefficient relationships were presented for supercritical and subcritical regimes [23]. Hager (1994) determined the flow features of a side weir in a circular channel in supercritical flow conditions and hydraulic jump was studied with a modified momentum approach [24]. Oliveto et al. (2001) obtained the results from theoretical and experimental study conducted along the side weir located in a circular channel when the flow along the weir is supercritical while upstream flow is subcritical and theoretical relations derived for the average lateral outflow velocity along a side weir [25]. Vatankhah (2012) using computational tool for the evolution and design of rectangular side weirs in open circular channels and introduced an analytical solution for flow profile computation over the side weir on a circular channel [26]. Granata et al. (2016) an experimental study of the flow field in a circular channel along a side weir using a Particle Image Velocimetry (PIV) system. In this research only the components of the velocity in planes parallel to the axis of the channel were measured [27].

Today, numerical methods (Computational Fluid Dynamics, CFD) with their advantages of lower cost and greater flexibility can reasonably predict the mean flow characteristics such as velocity distributions, pressure distributions, and water surface profiles of complex problems in hydraulic engineering; For instance, Aydin (2012) used VOF model to describe the free surface flow over the triangular labyrinth side weir for different Froude numbers [28]. Aydin and Emiroglu (2013) used CFD to analyze the discharge capacity labyrinth side weir for various Froude number, dimensionless nappe height, dimensionless weir width, and weir included angle [29]. Azimi at al. (2014) simulated the flow free surface and the passing flow through a rectangular side weir in circular channel in supercritical conditions by commercial software [30]. Aydin (2015) determined hydrodynamics properties of flow on the sill and effects on the discharge. It was seen that the using a sill located in a suitable place considerably increases outflow discharge of the side weir [31]. Aydin et al. (2016) investigated to determine hydrodynamic characteristics experimentally, theoretically and numerically of siphon in subcritical flow condition [32]. Aydin and Emiroglu (2016) used CFD to determine the discharge capacity of two-cycle trapezoidal labyrinth side weir. The results indicated that the discharge coefficient decreased with an increase in Froude number and the best performances were obtained with side weir angle, α=30° and weir height, p=20 cm among tested values [33].

In this paper, the free surface flow and the flow pattern over a rectangular side weir in a circular channel is simulated by using FLOW-3D software. The influences of the upstream Froude number on subcritical flow conditions are investigated. The knowledge of the above characteristics expanded the knowledge on the operation of side weir in a circular channel.

2. Governing Equations

A High Performance Computer (HPC) was used to simulate the CFD models in FLOW-3D software. Flow field of a non-compressible fluid solved in the continuity equation and Reynolds-averaged Navier–Stokes equations are used as follows:

$$\frac{\partial(\rho u_j)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_i} = -\frac{\partial p_s}{\partial x_j} + \frac{\partial}{\partial x_i}\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) + \rho g_j + F_j \quad (1)$$

Where ρ is fluid density, μ is dynamic viscosity of fluid, u is velocity vectors, P_s is pressure, g is gravitational acceleration and F is body force.

$$\frac{1}{\rho_q}\left[\frac{\partial}{\partial t}(\alpha_q \rho_q) + \nabla.(\alpha_q \rho_q \vec{v}_q) = S_{\alpha q} + \sum_{p=1}^{n}(m_{pq} - m_{qp})\right] \quad (2)$$

In which m_{qp} and m_{pq} is mass transfers between phases, α_q is volume fraction of fluid in a cell, and $S_{\alpha q}$ is source term, which is by default zero. The value of α_q depends on whether the cell is empty or full, If $\alpha_q = 0$, the cell is empty, if $\alpha_q = 1$, the cell is full, and if $0 < \alpha_q < 1$, the cell contains the interface between two fluid phases [33].

3. Numerical Model

The Uyumaz and Muslu's (1985) experimental data were used in this study to validate the numerical models [23]. The Laboratory model of the rectangular side weir in circular channels are also illustrated in Fig.1. The laboratory model is composed of a circular main channel 0.25 m wide and 10.9 m long, with a discharge collection channel 0.85 m wide and 0.30 m deep perpendicular to the main channel. A sluice gate was fitted at the end of the main channel to control flow depth. A sharp side weir is installed at the middle section of the main channel side wall.

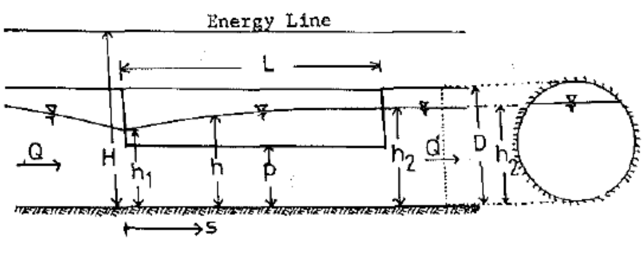

Figure 1. Geometry and characters of rectangular side weir in circular channel (Uyumaz and Muslu, 1985)

4. BOUNDARY CONDITIONS AND GRID LAYOUT IN NUMERICAL MODEL

The boundary conditions are provided to analyse the flow characteristics consist of, the inlet boundary at the inlet section with a known volume flow rate; the outlet boundary was defined as the out flow used at the side weir boundary and at the end of channels and a sluice gate was fitted at the end of the main channel to control flow depth. The symmetry was applied at the boundaries above of main channel. The wall boundary condition presents an option which ensures to easily describe the bottom and the surface levels of the main channel. The typical view of 3D model and boundary conditions are given in Fig. 2 and Fig. 3.

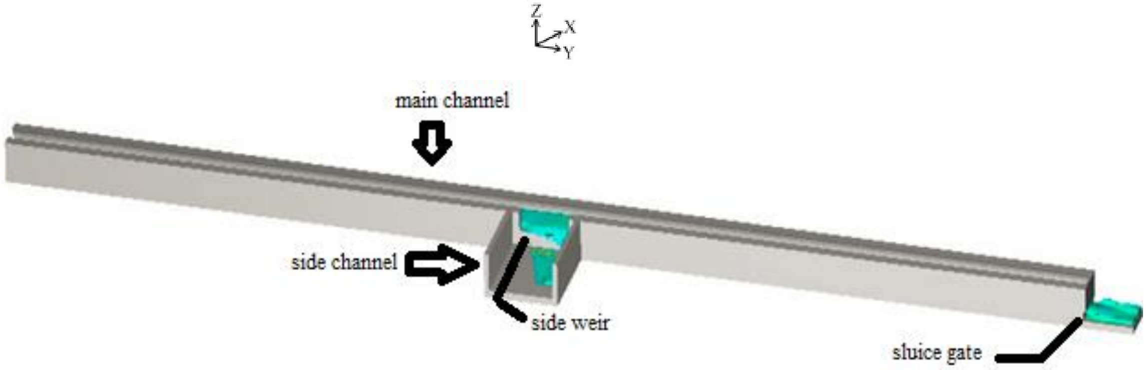

Figure 2. 3D view of rectangular side weir in circular channel in numerical model

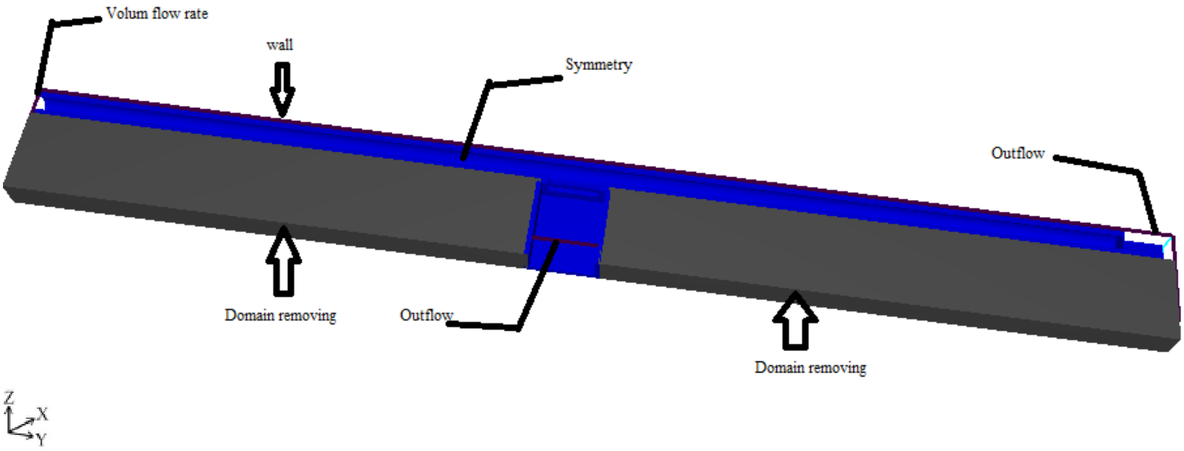

Figure 3. Boundary conditions of rectangular side weir in circular channel in numerical model

Generation of a good quality grid is one of the basic part of the numerical modeling and the greater the number of cells in the mesh grid, the more accurate will be the modelling results. The region of the side weir and some part of the downstream channel were made finer to accommodate dividing streamline, stagnation point and flow separation zone with acceptable accuracy. Grid independence study was done initially for the coarse mesh size. However, the computing time increases with mesh density. Hence we tried to find a balance between quality of results and computation time, settling on 685 000 computational cells and for reduce of time used doming remove. The grid of CFD model is depicted in Fig.4.

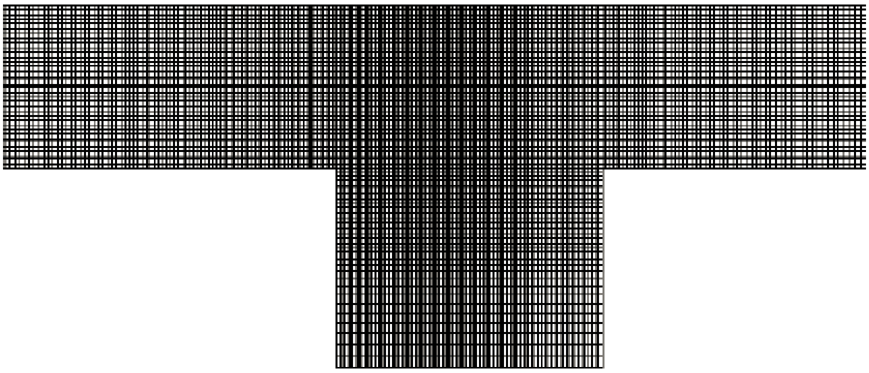

Figure 4. numerical mesh structure in the main channel and side channel

5. Results and Discussion

5.1. Effect of turbulence

In this study, similar free surface over a rectangular side weir are used for verification of the numerical model. Whereas, turbulence models may also have effects the results of CFD simulations. Various turbulence models were tested to determine sensitivity of the free surface over a rectangular side weir to turbulence. RNG k-ε turbulence model can be used to predict the various characteristics of the side weir flow and give close results besides other models (Fig.5). Very good agreement is achieved between the CFD and experimental results. These results all show that the numerical simulation can be considerable to be reliable.

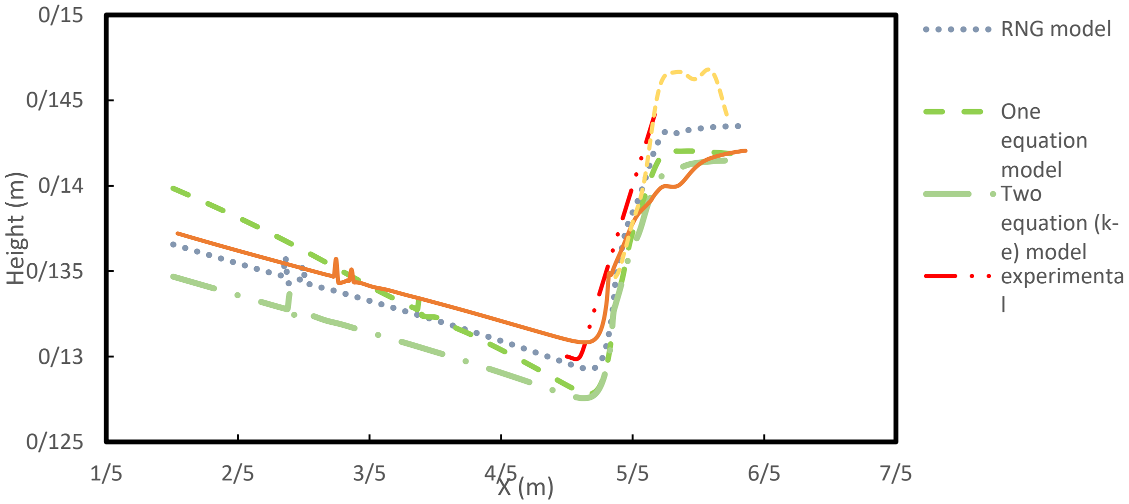

Figure 5. Free surface profiles provided from CFD simulations for p = 0.1 m, L = 0.5 m, Fr =0.42

5.2. Velocity profiles

Inside the main channel and at the downstream end of the side weir, there is a stagnation zone. Stagnation point has the highest water surface elevations. Due to the collision of the flow with the wall of the downstream of the channel and assuming a constant specific energy at this zone, the minimum longitudinal velocity appears with the highest water surface elevations. Therefore, a stagnation point is formed and the amount of shear stress near the bed of the main channel is zero. If the sediment is carried by flow, the sediment particles are trapped and, due to the absence of shear stress and low velocity of the flow, the sediment particles are deposited.

The velocity contours on the free surface are specified in Fig.7. The stagnation points in downstream edge of side weir, vortices, stagnation zone near to the left side wall of the main channel downstream were apparent. On the other hand, Fig.7 shows that velocity head decreases 10 mm from the upstream toward downstream. The maximum velocities along main channel on the surface occur in the part between centerline and the opposite side wall.

Emiroglu et al. (2011), the primary reason for this may be the intensity of secondary flow created by lateral flow turbulence and velocity streamlines that is oriented toward the side weir. By the orientation of the velocity streamlines toward side weir, the occurrence of the stagnation zone plays an important role in flow interactions. As mentioned above, the strength of the secondary flow created by the lateral flow was affected by the length of the side weir crest height of the side weir and the Froude number. An increase in the secondary flow causes the growth of the deviation angle and kinetic energy toward the side weir when the relative length of the side weir increases [17].

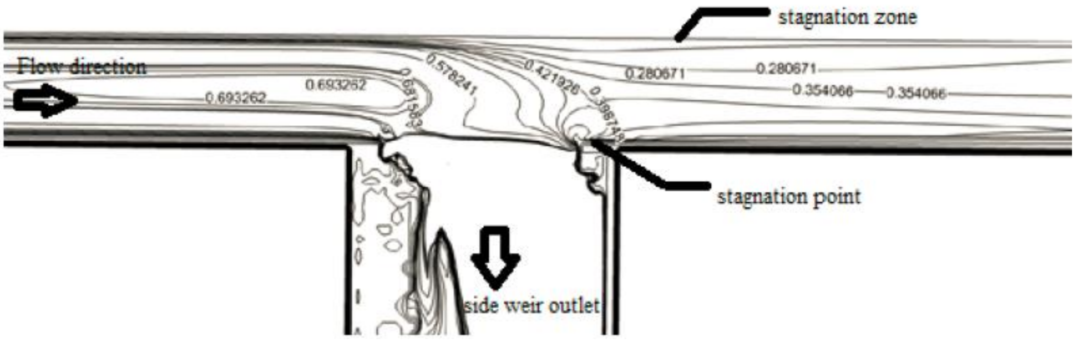

Figure 7. Velocity contours on the free surface for p = 0.1 m, L = 0.5 m, Fr =0.42

5.3. Free surface profiles

Water surface profiles were obtained computationally along side-weir in the centerline of main channel in Fig.6. As shown in these figures, the water level along the side weir drops slightly at the upstream end of side weir, then rise quickly toward the downstream end of the weir. The drop of water level is probably because of the side weir entrance effect at the upstream end. Additionally, besides side weirs, a vortex or circular motion occurrence in the circular channel can also causes a drop of water level at the upstream of weir.

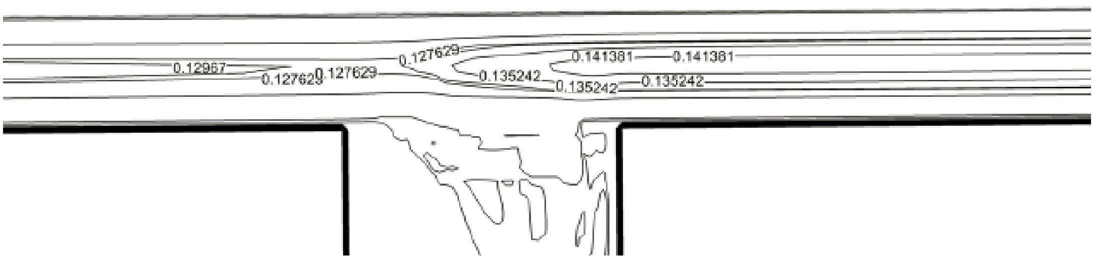

Figure 6. The contours of free surfaces for p = 0.1 m, L = 0.5 m, Fr =0.42

6. Conclusions

In the present study, the CFD analyses of rectangular side weir on a circular channel were simulated by Flow-3D. The simulations results agree reasonable with experimental data. The sensitivity of tturbulence models were checked with different turbulence models. The RNG recommended in literature were selected as the turbulence model because RNG k- ε turbulence model can be used to predict the various characteristics of the side weir flow and give close results compared to other turbulence models. The results in this study showed that the CFD simulations can help to determine the flow characteristics such as free surface flow, stagnation point, vortex region.

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