Numerical Detection of Energy Dissipation in Different Shapes of Stepped Spillways

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Abstract

To reduce the size of the dissipation basin, the stepped spillways have been consideredasone of the most powerful hydraulic structures. The present paper deals with the energy dissipation rate in two types of stepped spillways with different horizontal face angles: traditional, and V-shaped. The flow is simulated by the three dimensional numerical model. The governing equations are solved by the finite volume method, and the realizable k-ε model is used for estimating the turbulence closureof the mean flow system. The Fluent software is used forflow simulations. The flow regime is skimming that energy dissipation is affected by vortices formed at the corner of the step.Results show that step shape is effective in energy dissipation. Moreover, the energy dissipation rate is increased inV-shaped stepped spillways than the traditional stepped spillway.

Keywords: V-shaped stepped spillway, Numerical simulation, Fluent, Energy dissipation

1. INTRODUCTION

Spillwaysare such important hydraulic structures designed to prevent overtopping of dams and provide sufficient safety and stability during floods. Stepped spillways have long been used in water related projects owing to its high efficiency of energy dissipation and air entrainment.Stepped spillways can be used in different types of dam such as Roller-Compacted Concrete (RCC) dam which is widely expanded in recent years. In these spillways, vortices create in the flow (Amador et al., 2006; Chen et al., 2002; Sorenson, 1985) that results in high energy dissipation and aeration than that of smooth spillways. Moreover, it can release high speed flood flows while reducing and preventing dangerous scour and cavitation (Terrier et al., 2015).

Various studies have been conducted on the types of regimes on stepped spillways (Alghazali and Jasim, 2014), the pressure distribution in stepped spillways (Zhang et al, 2012), energy dissipation in various types of stepped spillways: horizontal steps, inclined steps, and steps with end sills (Chinnarasri and Wongwises, 2006), and the effects of step roughness on flow properties (Gonzalez, 2008).

By reviewing previous studies, it can be found that the effects of variations in the step shape have received little attention. Bai et al.(2017) investigated pressure distributions of stepped spillways with different horizontal face angles.Moreover, studies have confirmed that by replacing numerical simulations with experimental studies, great economic benefit will be produced.In this paper, three dimensional numerical model of the traditional stepped spillway ofSalmasi (2009) is simulated using Fluent software. Then,the shapes of the traditional steps are changed to the V-shape steps. And the flow in the V-shape stepped spillway are simulated. Finally, the results of energy dissipations in these two shapes of stepped spillways are compared together.

2. Physical model

The properties of the physical modelof Salmasi (2009) are considered for the traditional stepped spillway as follows. Stepped spillway has 0.25 meters width, and 0.3 meters height. Number of steps is three with slope 1V:2H. Therefore the height of each step is 0.1 meters and the length of each step is 0.2 meters. In the second numerical model, the traditional steps of Salmasi (2009) are changed to V-shape stepped spillway with horizontal face angle,$\theta = 30°$.

3. Numerical model

Gambit software has been applied to expand the numerical models fordifferent shapes of stepped spillway. The size of the stepped spillways was identical to the experimental model of Salmasi (2009). Determining the appropriate grid size is an important part of any numerical simulation. The Grid size can affect not only on the accuracy of results, but also on the simulation time. TriangularGrids have been used for all models. Figure 1 shows the situation of grid meshing proposed for the numerical model. Due to the high sensitivity of the flow, it has been attempted to increase the mesh density near walls and on the spillway surface.

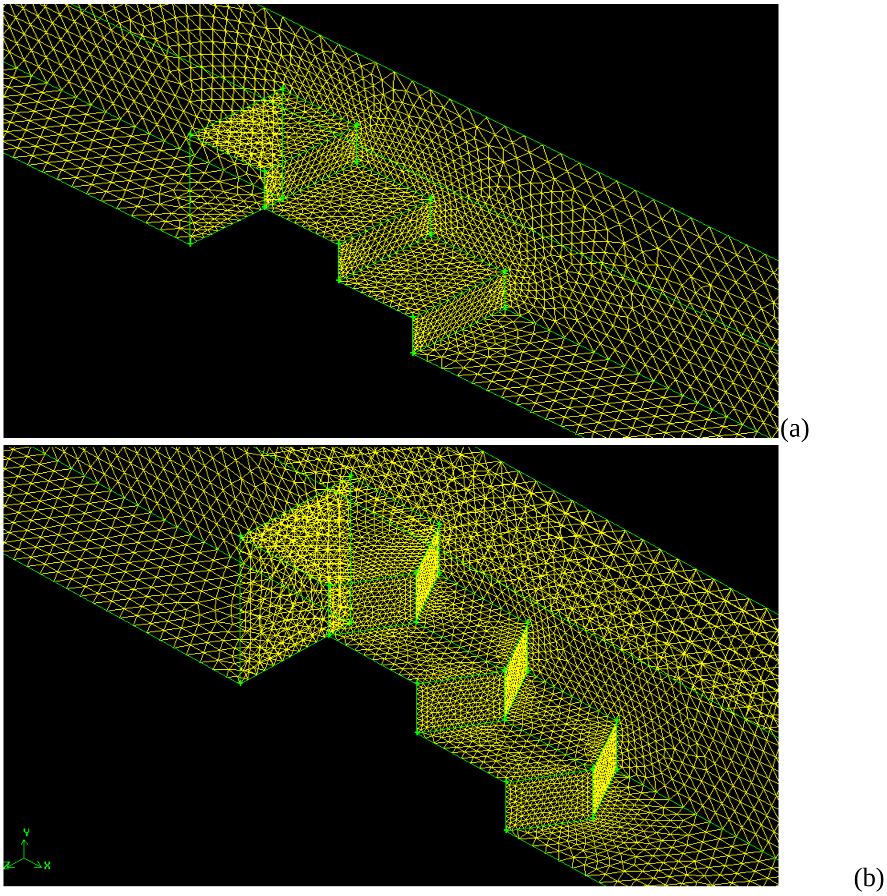

Figure 1. The grids for (a) the traditionalstepped spillway and (b) V-shaped stepped spillway

4. Governing equations and solution models

Fluent software has been used to simulate flow over spillway, using the Finite VolumeMethod (FVM). Continuity and momentum equationsare as follows:

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho u_i}{\partial x_i}=0 \qquad (1)$$

$$\frac{\partial \rho u_i}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho u_i u_j\right)=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left[(\mu+\mu_t)\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right](2)$$

Where ρ = volume fraction average density; t = time; u_i = velocity component in x_i coordinate; μ = volume fraction average molecular viscisity; and p = modified pressure.The Volume of Fluid (VOF) model was used to track the air-water interface.In each computational cell, the sum of the volume fractions of air, α_a, and water, α_w, is unity and can be given as

$$\alpha_w+\alpha_a=1; \qquad 0\leq\alpha_w,\ \alpha_a\leq 1 \ (3)$$

The realizable (Rl)κ-ε turbulence model presented by Shin et al(1995) was used for considering turbulence effects. The equations of turbulent kinetic energy, κ, and its dissipation rate, ε, are as follows:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho k u_j\right)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon-Y_m+S_k \quad (4)$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho\varepsilon u_j\right)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+\rho C_1 S_\varepsilon-\rho C_2\rho\frac{\varepsilon^2}{k+\sqrt{\nu\varepsilon}}+C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b+S_\varepsilon \quad (5)$$

Where$C_1 = \max[0.43, \eta/(\eta+5)]$ and $\eta = Sk/\varepsilon$, $S=\sqrt{2S_{ij}S_{ij}}$, where $S_{ij} = 0.5(\partial u_j/\partial x_i + \partial u_i/\partial x_j)$; ν is the turbulent kinematic viscosity; $C_{1\varepsilon} = 1.44$, C_2=1.9, $\sigma_k = 1.0$, and $\sigma_\varepsilon = 1.2$ are the empirical constants.

To complete the modeling process, pressure equation discretization in body force weighted method was used. The pressure-velocity coupling algorithm was usedbyPISO method. In this paper, time step size was considered 0.01 s.

5. Boundary conditions

Setting the appropriate boundary conditions has a significant effect on whether the numerical results are reflecting the actual situation. The boundary conditions have been considered as follows:

- Inlet boundary: inlet velocity, which is set as 0.236 m/s.
- Outlet boundary: pressure outlet; the normal gradient of all variable is 0.
- Wall boundary: no-slip velocity boundary condition; the near wall regions were analyzed using the method of standard wall function.
- Free surface: pressure inlet, the pressure value is P = 0.

6. Numerical results and analysis

6. 1.Flow pattern and field velocity

Figure 2 shows the situation of the spillway at the beginning of the analysis,which represents how water flows through stepped spillway. In this figure, blue color represents the water phase and red represents the air phase.Figure 3 also shows the flow velocity vectors overtraditional and V-shaped stepped spillway in the axial plane and walls.In this figure, it is quite obvious that the vortices created in steps corner will cause more energy dissipation as mentioned earlier.Also, skimming flow regime is also observed on the steps. The majority of the energy dissipation in this regime is caused by these vortices under the pseudo bottom.The pseudo bottom is imaginary line joining two adjacent step edges.In the traditional stepped spillway, vortices are almost small and identical in near walls and the axial plane. In a V-shaped stepped spillway, vortices are larger near walls, decrease when approaching the axial plane, and finally disappear.In this type of spillways, transverse velocityis also formed.

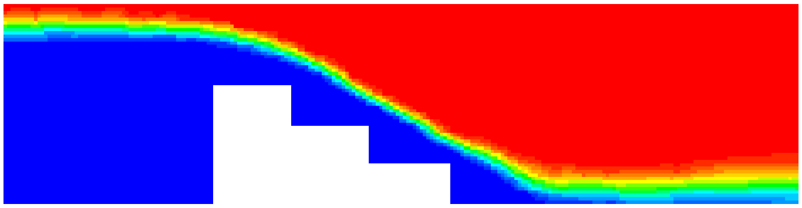

Figure 2. Flow pattern on stepped spillway

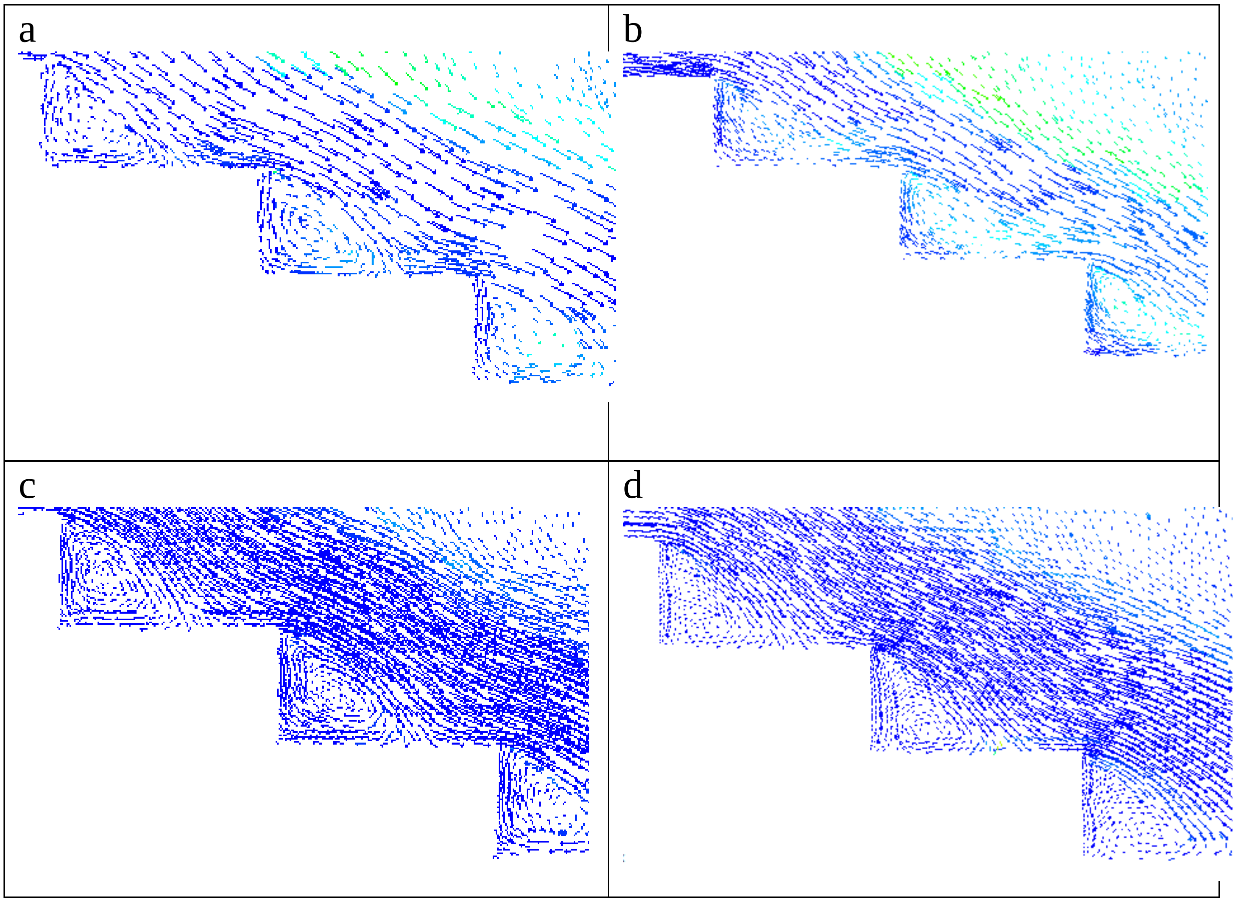

Figure 3. Flow velocity vectors: a) axial plane of traditional spillway; b) near wall of traditional spillway; c) axial plane of V-shaped spillway; d) near wall of V-shaped spillway

6. 2. Energy dissipation rate

To evaluate the accuracy of the numerical model, the traditional stepped spillway numerical model results were compared with experimental results of Salmasi (2009) in table 1.By simulating the flow depth over the stepped spillway and obtaining the rate energy loss through the relations8,9, the difference between the numericalresults and the experiment data was acceptable.

$$\frac{\Delta H}{H_0}=\frac{H_0\text{-}H_1}{H_0}\times 100 \quad (6)$$

$$H_0=H+y+\frac{q^2}{2gy^2} \quad (7)$$

Where H_0 and H_1= the upstream and downstream total energy respectively; H = the spillway height; q = 0.0945 $\boldsymbol{m^2 s^{-1}}$,the unit discharge; y= the depth of flow and g= the gravitational acceleration.The energy dissipation rates of the V-shaped and traditional stepped spillways have been presented in table 2.

Table 1. The amount of energy dissipation in traditional stepped spillwayfor$q$=0.0945$\boldsymbol{(m^2 s^{-1})}$

Experimental model	Numerical model
20.5 %	19%

Table 2. Energy dissipation rates

Traditional shaped	V-shaped
19 %	25%

According to table 1, the energy dissipation rate of the traditional stepped spillway is lower than the V-shaped stepped spillway.It can be found that changing the step shape is effective for increasing the rate of energy dissipation.

7. Conclusions

In this study, flow overtraditional and V-shaped stepped spillway was simulated using the Fluent software.According to results of the simulation, the following conclusions can be drawn:

- Due to the transverse velocity formed in the modelingV-shaped stepped spillway, it was considered three-dimensional simulation. The three-dimensional model is more accurate than the two-dimensional model because of the consideration of parameters changes in spillway width.
- The numerical modeling results showed acceptable with the experimental results. As a result, it can be simulated in larger-scale spillways before construction.
- In V-shaped stepped spillway, vortices are larger near walls. Therefore,more water trap on the steps and the energy dissipation increase.
- By comparing therate energy loss of the two types of spillways, it was concluded that changing the horizontal face angle of the step increases the energy loss. Consequently, in the construction of dams, this can help reduce costs in the construction of the basin.
- It seems that changing the traditional stepped spillway to the V-shape can be a solution in dam rebuilding.

8. References

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