Investigation of Energy Dissipation in Stepped Chute with Concave Steps

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Abstract

A stepped spillway is an incorporated piece of the dam that permits the entry of overtopping flows, and it is defined as a spillway with stairs on the chute to improve the energy dissipation. In this study, three models of stepped chutes, including plain steps, quarter cut steps, and concave steps are investigated to improve energy dissipation. The amount of energy dissipation on chutes under different discharges was investigated by numerical experiments using InterFOAM code in the OpenFOAM software. The results indicate that the energy dissipation decreases with increasing the discharge, and the concave steps are more effective compared with plain steps.

Keywords: stepped spillway; OpenFOAM ; InterFOAM; energy dissipation.

الملخص

المسيل المائي المدرج يعتبر جزء مهم من السد يستخدم للسيطرة على منسوب المياه من خلال تصريف المياه الفائضة وتحويلها من مقدم المجرى المائي إلى مؤخر المجرى المائي، ويتم تعريفه على أنه مسيل مائي يحتوي على درج على طول قناة المسيل لتحسين تبديد الطاقة. هذه الدراسة عبارة عن محاولة لزيادة تحسين تبديد الطاقة من خلال اختبار قيم مختلفة من التدفق المائي فوق عدة نماذج من قناة المسيل المائي المدرج، بالإعتماد على مجموعة من التجارب العددية باستخدام كود InterFOAM الموجود في برنامج OpenFOAM. التجارب تم اجرائها على عدة اشكال من الدرجات باستخدام ثلاث نماذج

من المسيل المدرج. النموذج الأول استخدم فيه الدرج العادي، والنموذج الثاني استعمل فيه درج ربع مقطوع، وفي النموذج الأخير تم أختيار جزء الدرجة النائمة بشكل مقعر على طول قناة المسيل المائي. تشير النتائج إلى أن تبديد الطاقة يتناقص مع زيادة التدفق المائي في جميع النماذج، كما بينت النتائج أيضا أن الدرج مع استعمال جزء النائمة بشكل مقعر يكون أكثر كفاءة مقارنة بالدرج العادي.

Introduction

The common problem in the design of spillways is the amount of energy dissipation. The energy created by high water velocity that rushes downstream face of the spillway, can cause erosion and subvert the downstream toe of the structure (Chanson, 2001; Felder, 2013; Gonzalez and Chanson, 2007). In the traditional design theories, a standard stilling basin or another dissipater at the outlet of the spillways was used (Boes and Hager, 2003). The stilling basin can be very big and costly to build, especially if more excavation is required (Chen et al., 2002; Kositgittiwong, 2012; Murillo, 2006; Shahheydari et al., 2015). Beside damages to the spillway, the high velocity of the flow can increase the risk of cavitation (Boes and Hager, 2003b; Chanson, 1993). Spillways with steps are suggested to reduce the energy along the channel bed to decrease these problems (Shahheydari et al., 2015). The energy dissipation of stepped spillways are reliably better than the traditional smooth spillways. Regardless of the presence of many design rules, information on energy dissipation stays deficient because of a complex air-water flow on each step.

The flow over stepped spillways has been investigated mostly with physical model (e.g., Boes and Hager, 2003; Chamani and Rajaratnam, 1994; Chanson, 1993; Chanson, 2013; Chanson and Felder, 2010; Chinnarasri and Wongwises, 2006; Felder, 2013; Felder and Chanson, 2016; Gonzalez and Chanson, 2007; Rajaratnam, 1990; Zhang and Chanson, 2015a,b; Zhang and Chanson, 2016). These studies are expensive and might lead to different issues, issues related to measurement devices and scaling factors. With the recent developments in computer technology the fluid dynamics problems utilizing different mathematical equations can easily be solved. Computational fluid dynamics (CFD) is the numerical modelling approach to investigate fluid stream issues. Numerical modelling is much faster and cheaper than physical modelling and in moreover, it is easier to apply changes in the design of an existing model. Moreover, in compare to physical modelling, CFD helps users to obtain flow information at any specific point in the flow domain rather than just at select positions where devices are installed. CFD has been used in many studies related to flow over stepped spillways with a high degree of accuracy (e.g.,Bayon et al., 2017; Bombardelli et al., 2011; Chen et al., 2002; Cheng et al., 2014; Kositgittiwong et al., 2013; Li and Zhang, 2018; Li et al., 2018; Lopes et al., 2017; Shahheydari et al., 2015; Tabbara et al., 2005; Toro et al., 2016).

The experimental and numerical examinations have been investigated in the literature about the energy dissipation in uniform stepped spillways for different slopes, numbers of steps, and flow rates. However, there are few studies on spillways with concave steps length. Therefore, it seems necessary to investigate the energy dissipation for semicircular steps treads of stepped spillways. With the help of InterFOAM code in the OpenFOAM software and by using the volume-of-fluid technique and Realizable k-ε turbulent model, three stepped spillway configurations with plain, cut and concave steps lengths have been investigated.

Methodology

Material Properties

Material properties, such as: viscosity, density, and wall must be characterized as an input for the numerical simulations. For phases (water air), the keyword transportModel is set to Newtonian. A Newtonian flow, such as air -water is defined by a consistent kinematic viscosity which is kept unaltered with the rate of deformation (Finnemore et al., 2002). During this investigation, water at 20 °C was picked, which represents the ideal room temperature of the laboratory. The physical properties of the cases were determined as: ρ_{water}=1000 kg/m^3, ρ_{air} = 1.2 kg/m^3, ν_{water} = 10$^-$

^{6} m^2/s and v_{air} = 1.45 × 10^{-5} m^2/s. The surface tension between air and water was considered as sigma and its value was set to 0.07 N/m. Moreover, the channel material was selected considering Zhang and Chanson (2015a,b) and Felder (2013) physical models as a smooth plywood-made bottom in which roughness effect is negligible, where roughness height is equivalent to uniform sand roughness of the channel surface (k_s = 0.5 mm). When using wall functions, a smooth no-slip boundary condition is used to the wall contours of the model, because the roughness effect of the physical model in the experimental study was negligible.

Mesh Generation and Boundary conditions

In the present work, GMSH software was used to create the numerical mesh due to its practical availability, as well as it is a free source software. Moreover, mesh size has been determined carefully to obtain accurate results. The computation domain was discretized within structured mesh with size of 0.01 × 0.01 m^2 quadrilateral cells as shown in Figure 1.

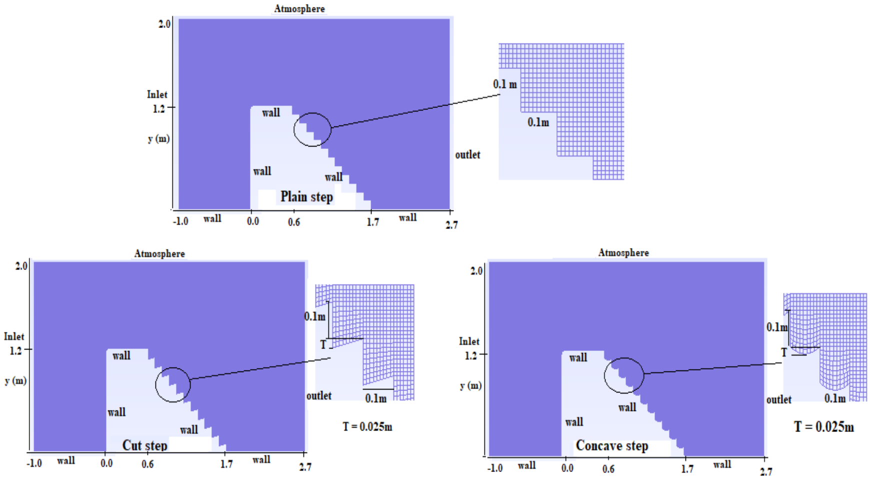

Figure 1. Structured mesh of models of stepped chute

The boundary conditions were imposed as follows; inlet, wall, atmosphere, and outlet (Figure 1). At the inlet boundary, the water inflow boundary is set as velocity-inlet condition that was obtained based on the flow rate. The walls represent “no slip” boundaries (the velocity is zero at the wall). Additionally, the air boundaries were defined as an inlet pressure in the atmospheric pressure and the outlet boundary condition was defined as an outlet pressure so the water can flow out freely.

Governing Equations

The governing equations were discretized by the Finite-volume method on a Cartesian grid system. The continuity and Navier-Stokes equations were used to simulate flow over the stepped chute.

$$\nabla . u = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u) + \nabla . (\rho u u) - \nabla . \left(\mu_{eff} \nabla u\right) = -\nabla p^{*} - gh \nabla \rho + F \tag{2}$$

The Volume of Fluid (VOF) method introduced by (Hirt and Nichols, 1981) was used in the simulation. In this method, the advection equation of fluid fraction is as below:

$$\frac{\partial \alpha_w}{\partial t} + \nabla (u \alpha_w) = 0 \tag{3}$$

In all the computational cells, a fraction of water (α_w) and air (α_a) is considered such that: $\alpha_a = 1 - \alpha_w$. Therefore, the density (ρ) and molecular (μ) viscosity can be described by Equations (4) and (5), respectively:

$$\rho = \alpha_w \rho_w + (1 - \alpha_w) \rho_a \tag{4}$$

$$\mu = \alpha_w \mu_w + (1 - \alpha_w) \mu_a \tag{5}$$

where, ρ_w and ρ_a are the density and μ_w and μ_a are the molecular viscosity of water and air, respectively. The maximum and minimum values of α_w are 1 and 0, demonstrating that the given cell is filled up with water or air, respectively.

In order to model the flow over a stepped chute by Equations (1) and (2), a turbulence closure is required. The realizable *k – ε* model is a modification over the standard *k– ε* model that is given for a higher Reynolds number in the turbulence flow. The governing equations for this model; one for *k*, the other for *ε* are given through the following Equations (6) and (7).

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon-Y_M+S\frac{\partial}{\partial x_{j_K}} \qquad (6)$$

$$\begin{aligned}\frac{\partial}{\partial t}(\rho\varepsilon)+\nabla(\rho\varepsilon u)\\ &=\nabla\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\nabla\varepsilon\right]+\rho C_1 S\varepsilon-\rho C_2\frac{\varepsilon^2}{k+\sqrt{\upsilon\varepsilon}}\\ &+C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b+S_\varepsilon\end{aligned} \qquad (7)$$

$$C_1=max\left[0.43\frac{\eta}{\eta+5}\right],\eta=S\frac{k}{\varepsilon},S=(2S_{ij}S_{ij})^{0.5}$$

where: υ = kinematic viscosity, G_k is added because of the impact of the turbulence on the kinetic energy because of the mean velocity in the gradients, G_b is the generation of turbulent kinetic energy because of buoyancy, Y_M is used as the fluctuating expansion that is given in the turbulence. The equations incorporate some adjustable constants as: S_ε, S_k that are user-defined source terms, $C_{1\varepsilon} = 1.44$, $C_{3\varepsilon} = 1.0$, $\sigma_k = 1$, $\sigma_\varepsilon = 1.2$, and $C_2 = 1.9$.

Energy Dissipation Calculations

The main aim of the current paper is to determine the energy dissipation for each stepped spillway, $\Delta E/E_t$, at the downstream end of the stepped spillway (Felder, 2013; Zhang and Chanson, 2015a), where ΔE is the total head loss ($\Delta E = E_t - H_{res}$), E_t is the maximum upstream head, and H_{res} is the residual energy calculated as:

$$H_{res}=\int_{y=0}^{y90}(1-C)dy\times cos\theta+\frac{{q_w}^2}{2\times g\times\left(\int_{y=0}^{y90}(1-C)dy\right)^2}+Z \qquad (8)$$

where, C is the void fraction, y is measured perpendicular to the pseudo-bottom formed by the step edges, y_{90} is the depth where the local air concentration is 90% and Z is the step edge elevation above the datum.

Results and Discussion

Figure 2 shows a volume fraction of water simulated for $Q = 0.112 m^3/sec$. As can be observed, the entrainment air within the flow occurs when the level of turbulence is high, and thus, the volume portion of water turns out to be smaller than unity. Moreover, high turbulences of the flow reduce the velocity and then the total energy of the flow.

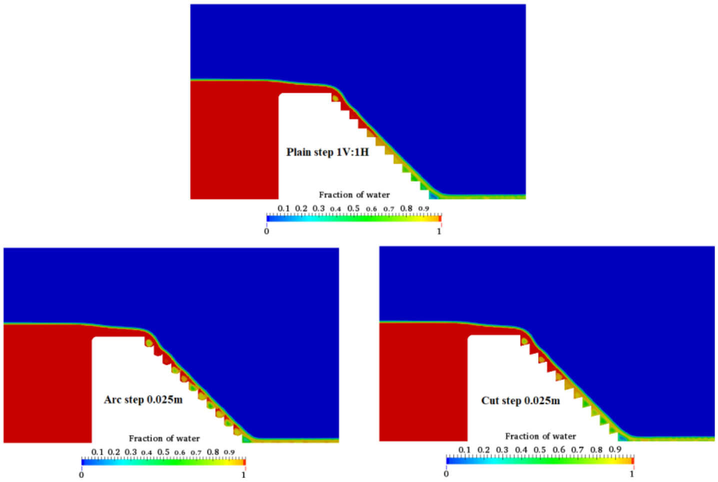

Figure 2. Flow on a stepped chute at slope 45° for $Q = 0.112 m^3/sec$.

In Figure 3, a simulation of velocity field is described, where the zone of highest velocity, for instance, can be seen easily. As can be observed, the recirculation flow is adequately regenerated, which corresponds to the negative horizontal velocity that can occur within the steps. The velocity distributions in the overflow are changed through exchanges with such vortices, and energy is dissipated through the process.

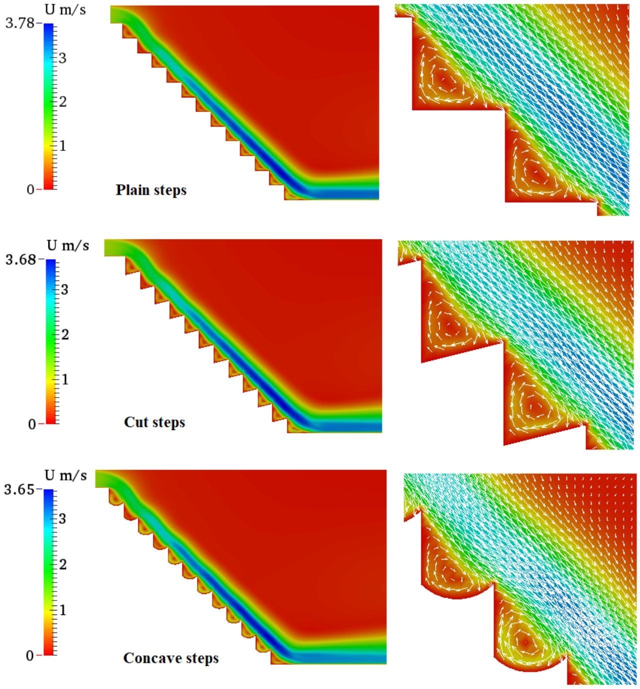

Figure 3. Velocity vectors distribution on stepped chute models at Q = $0.112 m^3/s$.

Figure 4 shows the effect of the stepped spillway with plain, cut and concave steps on the energy dissipation performance. It can be seen that, the energy dissipation has an inverse relationship with the discharge. As the flow rate increases, the energy dissipation at the end of the chute decreases. The results show that, concave steps have better dissipation than cut steps; and, cut steps have better dissipation than plain steps. In which the total energy dissipation for concave steps ranged from 50 to 69%, cut steps ranged from 50 to 62%, and plain steps ranged from 50 to 60%.

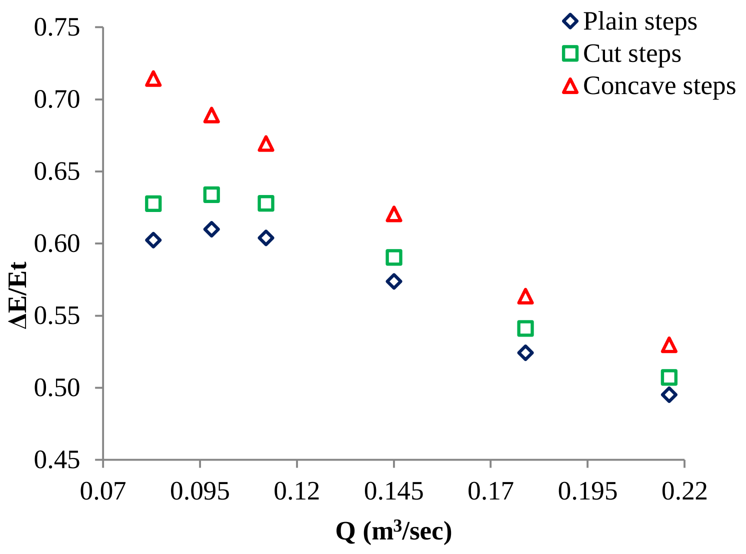

Figure 4. Effect of concave steps on the rate of energy dissipation

Conclusions

In the present research, many numerical experiments were conducted on various stepped spillway models for plain, cut, and concave steps. For all stepped configurations, the height of the spillway was considered constant. Numerical experiments were performed by the InterFOAM solver in the Open FOAM package using the VOF method and Realizable k-ε turbulence model. The results indicated that among the three configurations tested, the concave steps were the most effective, such that the energy dissipation was improved up to 7%.

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