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Effect Of Pooled and Flat Stepped Spillway on Energy Dissipation Using Computational Fluid Dynamics

Shawnm Mudhafar Saleh[*] , **Sarkawt Hamarahim Muhammad** , **Abdulla Abdulwahid Abo**

Water Resources Department, College of Engineering, University of Salahaddin, Erbil, Iraq.

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ABSTRACT

The goal of this research was to determine the impact of a pooled and flat stepped spillway on energy losses. FLOW3D, which is a computational fluid dynamics (CFD) program, with mesh size of 0.015 mm was used for this purpose. First, the code was tested against an available experimental model data for both water flow depth and inception point position. The outcome precisely shows agreement with the available laboratory work. Second, the energy dissipation and residual head of two different types of stepped spillways, flat and pool was computationally compared. The results show that in a pooled stepped spillway, energy dissipation is larger than in a flat step. In addition, the residual head reduces for pooled stepped chutes.

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[*] Corresponding author: E-mail: shawnm.saleh@su.edu.krd , Water Resources Department, College of Engineering, University of Salahaddin, Erbil, Iraq.

تأثير المسيل المائي ذو التدريجات الحوضية والمسطحة على تبديد الطاقة باستخدام CFD

شونم مظفر صالح قسم هندسة الموارد المائية / كلية الهندسة / جامعة صلاح الدين / أربيل - العراق.
سركوت حمەرحيم محمد قسم هندسة الموارد المائية / كلية الهندسة / جامعة صلاح الدين / أربيل - العراق.
عبدالله عبدالواحد عبو قسم هندسة الموارد المائية / كلية الهندسة / جامعة صلاح الدين / أربيل - العراق.

الخلاصة

الهدف من هذا البحث هو تحديد تأثير تصريف المياه المجمعة والمسطحة على فقدان طاقة الماء. تم استخدام برنامج Flow 3D، وهو برنامج حسابي لديناميكا الموائع، مع شبكة بحجم ٠،٠١٥ مم تستخدم لهذا الغرض. اولا، تم اختبار الكود مقابل بيانات متوفرة لنموذج مختبري لكل من عمق تدفق المياه وموضع نقطة البداية. أظهرت النتائج اتفاقا دقيقا بين البرنامج الحاسوبي مع العمل المختبري متوفرة. ثانيا، تمت مقارنة تبديد الطاقة والشحنة المتبقية لنوعين مختلفين من المسيلات المائية المتدرجة المسطحة والحوضية من الناحية الحسابية. بينت النتائج أنه في لمسيل المائي ذو التدريجات الحوضية، يكون تبديد الطاقة أكبر منه في التدريجات المسطحة. إضافة إلى ذلك، فإن الشحنة المتبقية تقل في المسيل المائي المتدرج الحوضي.

1.INTRODUCTION

Spillways designed to convey the flood water from upstream to the downstream of the dam with a very high amount of kinetic energy. This energy may harm the downstream bed of the dam if it's not controlled [1]. A stepped spillway can serve this purpose at a reasonable cost while posing no risk to the structure or the surrounding area. The stepped spillway reduces the kinetic energy of the flow and hence smaller size of stilling basin is required [2]. The invention of rolling compacted concrete (RCC) has made it possible to design a stepped spillway. Generally, steps can be built in flat steps. Sometimes, may be built in pool steps. In a pooled stepped spillway, each step represents a separate mini stilling basin for hydraulic jump. In a stepped chute water flows from one step to the next, resulting in significant energy dissipation [3]. Many factors affect how much energy is dissipated, including step numbers, step shape, spillway slope, flow regimes, discharge, and surface roughness [4]. Several experimental and numerical investigations have been undertaken to calculate the amount of energy dissipation in these two types of stepped spillways (horizontal and pool), but no conclusion can be drawn because in literature the solid conclusions about providing higher dissipation of energy cannot be determined. (Felder and Chanson, 2013) [5] are experimentally investigated the flat and pooled steps spillways for slope=8.9° and discovered that the pooled stepped spillway dissipates extra energy, (Al-Husseini, 2015) [6] achieved the same conclusion in their experimental work, where their study held for three different slopes (27°, 32°, and 40°). Furthermore, (Sholichin, et al., 2016) [2] are experimentally investigated two different step slopes (45° and 30°), each slope with (40 and 20) steps respectively. They examined ten different skimming flow rates over a stepped spillway, ranging from (3.457 to 30.669) l/s, and observed that under all conditions, pooled steps dissipate more energy than horizontal steps. Behind that, (Ma, et al., 2019) [7] numerically compared flat stepped spillway with three different interval-pooled stepped spillways with height (0.025,0.05 and 0.075m) for slope 26.6°. There result indicate that the height of the pool has strong effect on energy dissipation and residual head, as higher residual head happened for interval-pooled high 0.025m. On the other hand, (Hekmatzadeh, et al., 2018) [8] observed that if the slope of the steps is less than 14°, the energy dissipation is greater for pooling stepped spillways, while uniform step is more effective in steeper slopes in terms of energy dissipation. (Ghaderi, et al., 2021) [9] discovered that for slope 26.6°, the flat stepped spillway configuration provides more energy dissipation compared to the pooled stepped spillway options. From this study, the effect of geometry shape on the amount of energy dissipation and residual head investigated for three different discharges.

2.METHODOLOGY

Computational Fluid Dynamics (CFD) model uses the governing equation for solving the fluid dynamics, which they are mass conservation that represented in Equation (1) [10], and the equations of motion (momentum equation) for the fluid velocity components (x, y, z) in the three coordinate directions are the Navier-Stokes equations with some additional terms presented in Equation (2) [11]

$$V_F \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u A_x) + R\frac{\partial}{\partial y}(\rho v A_y) + \frac{\partial}{\partial z}(\rho w A_z) + \xi \frac{\rho u A_x}{x} = R_{\mathrm{DIF}} + R_{\mathrm{SOR}} \qquad \mathbf{(1)}$$

Where: V_F is the volume fraction open to flow, ρ is the density of fluid, R_{DIF} is a turbulent diffusion term, and R_{SOR} is a mass source. The velocity components (u, v, w) are in the coordinate directions (x, y, z). A_x is the fractional area open to flow in the x-direction, A_y and A_z are similar area fractions for flow in the y and z directions, respectively. The coefficient *R* depends on the choice of coordinate system.

$$\frac{\partial u}{\partial t}+\frac{1}{V_F}\left\{uA_x\frac{\partial u}{\partial x}+vA_yR\frac{\partial u}{\partial y}+wA_z\frac{\partial u}{\partial z}\right\}-\xi\frac{A_yv^2}{xV_F}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+G_x+f_x-\frac{R_{SOR}}{\rho V_F}(u-u_w-\delta u_s)$$

$$\frac{\partial v}{\partial t}+\frac{1}{V_F}\left\{uA_x\frac{\partial v}{\partial x}+vA_yR\frac{\partial v}{\partial y}+wA_z\frac{\partial v}{\partial z}\right\}-\xi\frac{A_yuv}{xV_F}=-\frac{1}{\rho}\left(R\frac{\partial p}{\partial x}\right)+G_y+f_y-\frac{R_{\mathrm{SOR}}}{\rho V_F}(w-v_w-\delta v_s)$$

$$\frac{\partial w}{\partial t}+\frac{1}{V_F}\left\{uA_x\frac{\partial w}{\partial x}+vA_yR\frac{\partial w}{\partial y}+wA_z\frac{\partial w}{\partial z}\right\}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+G_z+f_z-\frac{R_{\mathrm{SOR}}}{\rho V_F}(w-w_w-\delta w_s)\quad \mathbf{(2)}$$

Where: (G_x, G_y, G_z) are body accelerations, (f_x, f_y, f_z) are viscous accelerations, and the final terms account for the injection of mass at a source represented by a geometry component. The term $U_w=(u_w,v_w,w_w)$ in the above (momentum) equations is the velocity of the source component, which will generally be non-zero for a mass source at a General Moving Object (GMO). The term $U_s=(u_s,v_s,w_s)$ is the velocity of the fluid at the surface of the source relative to the source itself. It is computed in each control volume from Equation (3) [11]

$$U_s=\frac{dQ}{\rho QdA}n\qquad \mathbf{(3)}$$

Where: *dQ* is the mass flow rate, *ρQ* is the fluid source density, *dA* is the area of the source surface in the cell and *n* the outward normal to the surface. When *d*=0.0, the source is of the *stagnation pressure* type. If *d*=1.0, the source is of the *static pressure* type. Flow 3D is an effective software developed by Flow Science, Inc. for simulating flow streamline through the hydraulic structures. This program was applied for calculating the Reynolds-averaged Navier-Stokes equation with the combination of eddy-viscosity RNG k-ε [12]. For free surface Flow 3D uses advanced algorithm, in problems with one fluid, the air represented as a void rather than a fluid. The interface between phases can be expressed by volume of fraction which is between 0 to 1. Fraction volume of 1 represent cells with full of water, fraction volume of 0 are an empty cell with air, fraction volume between 1 and 0 means that the cells contains both air and water [13]. In present study, RNG model was chosen as its give more accurate results and mostly used than the other models in problems with particles [10, 14, 15].

3.CODE VALIDATION

For this study, an experimental result of (Felder, et al., 2012) [16] were taken and used for validation the numerical model. In their laboratory research they work on 21 steps with uniform step sizes (h=0.05m and l=0.318m) and uncontrolled broad crested width=0.5m. The slope of the stepped chutes was 8.9°. Fig 1 shows the experimental stepped spillway model.

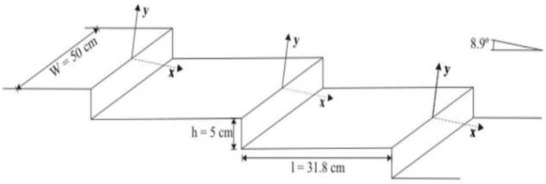

Fig. 1. Stepped spillway model [1]

3.1. *Mesh size*

For validation process study, the grid size of 0.015 mm was used as different grid sizes and mesh numbers tested and after many trails the selected grid size gives better result based on the agreement degrees between experimental and numerical results in terms of flow depth and location of inception point.

3.2. *Boundary condition*

Discharge flow rate (Q) selected for inlet boundary condition at the upstream of the spillway. At the end of the spillway, the boundary condition fixed as outflow (O) to prevent any effect on the last step. For the sides and bottom, wall boundary (W) with no-slip conditions is selected. For the upper part the specific pressure (P) with fluid fraction=0 was used. Fig 2 represent the boundary conditions for the numerical model that used for validation process.

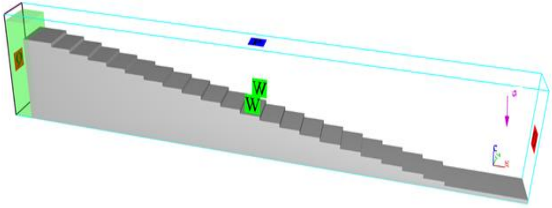

Fig. 2. Boundary conditions that used for validation process.

3.3. *Validation of the experimental work*

The laboratory work of (Felder, et al., 2012) [16] for flat stepped spillway with the same step slopes and dimensions were used for validation of flow simulation over stepped chutes. The flow depth data for discharge (0.076 and 0.117 m³/s) was taken and compared with the numerical results that taken perpendicular to pseudo-bottom. As presented in Fig 3 the flow depths d/dc (d is equivalent clear water depth and dc is critical depth) for experimental and numerical model are very close for both discharges. In addition, the location of inception point takes in consideration. Fig 4 is indicating the location of Inception point for both flow discharges (0.076 and 0.117) m³/s for the numerical. The result shows similar to the experimental result, as it is shown for discharge 0.076 m³/s the inception point produce at step 10, and for discharge 0.117 m³/s the air are enters the water between steps 14 and 15 which are the same locations of inception point for the laboratory work.

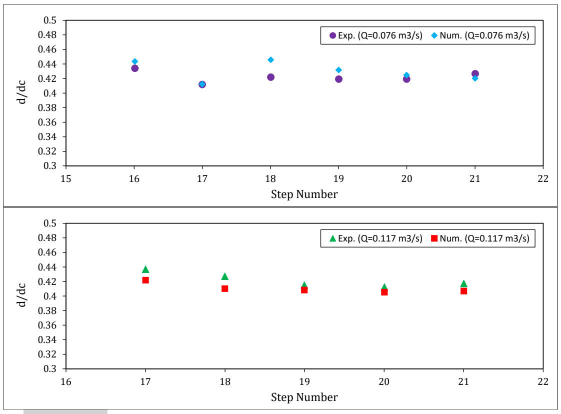

Fig. 3. Water flow depth for exp. And num. results for Q (0.076 and 0.117 m³/s).

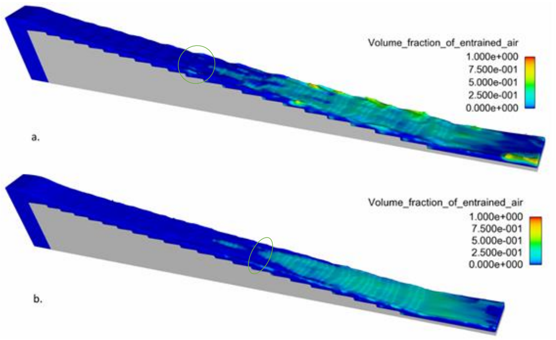

Fig. 4. Location of inception point for (a) Q=0.076 m³/s and (b) Q=0.117 m³/s.

4.RESULTS AND DISCUSSION

For this paper, uniform stepped spillway compared with the pooled stepped spillway with the same step numbers and slope. For construction geometries AutoCAD software was used through .STL file. For uniform stepped chute 16 steps with the slope of 11.2° are chosen and the height of the steps set as h=0.06m and length of spillway l=0.303m. The same step number, step slope, step height, and step length are fixed for the pooled stepped spillway with the key height and length 0.03m and 0.033m, respectively see Fig 5. The length of the broad crest is 0.5m and width of the model set as 0.5m for both flat and pooled step geometries. The same mesh size, boundary conditions, and initial conditions that are used for validation process are applied for the present models.

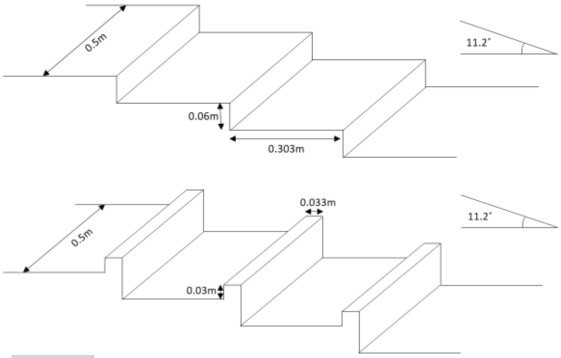

Fig. 5. Sketches of stepped spillway (Flat and Pool) for present study.

In this part, the residual head and energy dissipation were computed at the end of the spillway exactly at the last two steps for both geometries. The amount of energy dissipation through all the steps to the total head at the upstream of the spillway can be expressed by relative energy dissipation ($\Delta H/H_{max}$). Equation (4) [5] can be used for finding total head:

$$H_{max} = 3/2 * d_c + H_{dam} \qquad \textbf{(4)}$$

Where: H_{max} is total head at upstream, d_c is critical depth, H_{dam} is the dam height.

The residual head can be calculated by Equation (5) [9]

$$H_{res} = y * \cos^2\theta + v^2/2g + d_p \qquad \textbf{(5)}$$

Where: V is mean flow velocity, y is flow depth of water, and d_p pool height which is zero for flat step. Then, the total amount of energy loss evaluated from Equation (6)

$$\Delta H = H_{max} - H_{res} \qquad \textbf{(6)}$$

Fig 6 shows the total energy line for both flat and pooled stepped spillway for discharge 0.14 m³/s.

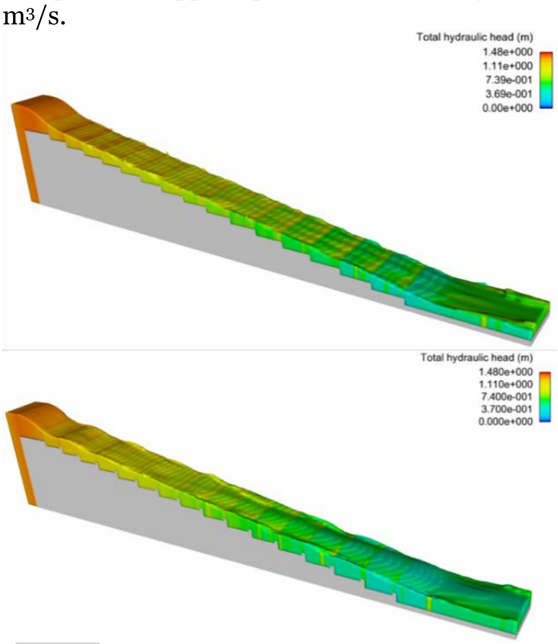

Fig. 6. Total hydraulic head for flat and pool stepped spillway (0.14 m³/s).

The amount of energy losses for three different discharges (0.092, 0.103, and 0.14 m³/s) are predicted in Fig 7.A for the last two steps (15 and 16) against dimensionless function of $\Delta z_o/d_c$, where Δz_o represent the elevation between the step edge and spillway crest, and d_c is the critical depth. According to the figure the amount of energy dissipation is higher for pooled stepped spillway for all skimming flow discharges. For all three discharges 0.092, 0.103, and 0.14 m³/s larger amount of energy dissipated in pooled steps spillway compared to the flat stairs which are about 13-15%, 12-13%, and 20-21%, respectively. Besides, the amount of energy dissipation increases with decreasing flow rates. The results of this research indicate the higher energy dissipation in pooled arrangement steps which has been supported by other works [2, 5, 6]. The residual head in terms of dimensionless parameters H_{res}/d_c and d_c/h are shown in Fig 7.B for both geometries and different discharges at the last two steps. According to the figure, for the pooled stairs spillway the dimensionless residual head was lowest.

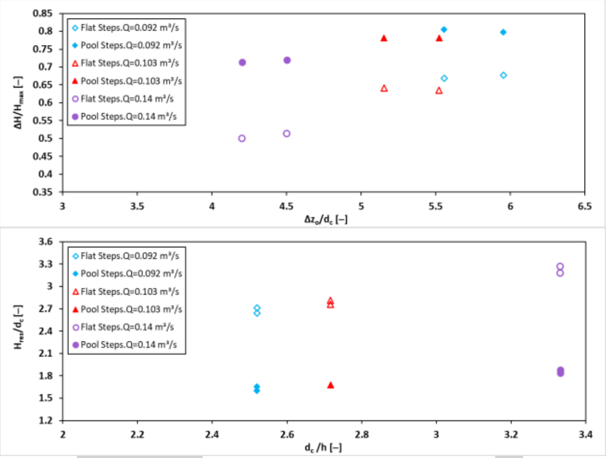

Fig. 7. (**A**. Energy dissipation rate, **B**. Residual head) for flat and pooled stepped spillway at the last two steps for discharges (0.092, 0.103, and 0.14 m^3/s).

5. CONCLUSIONS

For this work, the data of an experimental model was taken and simulated by using Flow 3D program. Firstly, the validation process was analyzed by using the same geometry of the experimental model regarding flow depth and position of inception point. The result gives nearly the identical result for both flow depth and location of inception point. Then, two different step geometries (flat and pooled) stepped spillways were processed to find the amount of energy losses and residual head for the two of them. The outcome indicate that greater amount of energy lost in steps with pooled arrangement steps compared with the flat steps. Which are nearly 13-15% for 0.092m^3/s, 12-13% for 0.103m^3/s and about 20-21% for discharge 0.14 m^3/s. As well as higher residual head achieved for flat stepped spillways.

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