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Computational Fluid Dynamics Modeling of Flow over Stepped Spillway

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Abstract

In present paper, the computational fluid dynamics (CFD - program Flow-3D) was used to analyze and study the characteristics of flow energy dissipation over stepped spillways. Three different spillway heights (P_s) (15, 20 and 25cm) were used. For each one of these models, three numbers of steps (N) (5, 10 and 25) and three spillway slopes (S) (0.5, 1 and 1.25) were used. Eight different discharges ranging (600-8500cm³/s) were passed over each one of these models, therefore the total runs of this study are 216. The energy dissipation over these models and the pressure distribution on the horizontal and vertical step faces over some models were studied. For verification purpose of the (CFD) program, the experimental work was conducted on four models of stepped spillway and five different discharges were passed over each model. The magnitude of dissipated energy on models was compared with results of numerical program under same conditions. The comparison showed good agreement between them with standard percentage error ranging between (-2.01 - 11.13%). Thus, the program Flow-3D is a reasonable numerical program which can be used in this study.

Results showed that the energy dissipation increases with increased spillway height and decreased number of steps and spillway slope. Also, the energy dissipation decreases with increasing the flow rate. An empirical equation for measuring the energy dissipation was derived using the dimensional analysis. The coefficient of determination of this equation (R^2) equals 0.766.

Keywords: Stepped spillway, CFD, Flow-3D, Energy dissipation, Pressure distribution.

نمذجة ديناميكية الموائع الحسابية للجريان فوق المسيل المائي المدرج

الخلاصة

في البحث الحالي تم استخدام برنامج (CFD-Flow 3D) لتحليل ودراسة خصائص تشتيت طاقة الجريان فوق المسيل المائي المدرج. تم في هذه الدراسة استخدام ثلاثة ارتفاعات للمسيل المائي (P_s) (15 ، 20 ، 25سم)، ولكل من هذه النماذج استخدمت ثلاثة أنواع من التدريجات (N) (5 ، 10 ، 25) وكذلك ثلاثة ميول للسطح المدرج (S) (0.5 ، 1 ، 1.25). مرر فوق كل نموذج من النماذج اعلاه ثمانية تصاريف مختلفة تراوحت بين (600 – 8500سم^3/ثانية)، وبذلك بلغ مجموع الاختبارات لهذه الدراسة 216 اختبار تم من خلالها دراسة تشتيت الطاقة لجميع النماذج مع دراسة توزيع الضغط على السطح الافقي والعمودي لبعض التدريجات ولبعض النماذج.

لأغراض معايرة برنامج (CFD)، تم اجراء عدة تجارب مختبرية على أربعة نماذج مختلفة للمسيل المائي المدرج وتم امرار خمسة تصاريف مختلفة فوق كل نموذج، وقورنت نتائج تشتيت الطاقة على النماذج المختبرية مع نتائج البرنامج الرياضي وعند نفس ظروف الجريان. بينت المقارنة توافقا جيدا بين النتائج المختبرية ونتائج البرنامج الرياضي حيث تراوحت نسبة الخطأ بينهما ما بين (2.01- – 11.13%)، لهذا تم اعتماد البرنامج في الدراسة الحالية.
بينت النتائج ان تشتيت الطاقة يزداد مع زيادة ارتفاع المسيل المائي ونقصان عدد التدريجات والميل. كذلك فان الطاقة المشتتة تتناقص مع زيادة التصريف المار فوق المسيل المائي المدرج. تم اشتقاق معادلة وضعية لحساب الطاقة المشتتة للجريان فوق المسيل المائي المدرج باستخدام نظرية التحليل البعدي، وكان معامل التحديد لهذه المعادلة يساوي (0.766).

الكلمات الدالة: المسيل المائي المدرج، ديناميكيات الموائع الحسابية، تشتيت الطاقة، توزيع الضغط.

Introduction

Stepped channels and spillways have been used for more than 3500 years. The ease of construction and the design simplicity have led this structure to be more popular since 1980.

A stepped spillway can be defined as that hydraulic structure in which a series of steps of different shapes, dimensions, and arrangements are built into the spillway surface at some distance from the spillway crest and extended to the toe. The stepped spillway dissipates much more energy than other types of spillways that energy dissipation is caused by steps on the spillway, in which these steps could produce high turbulence and aeration due to the strong interaction between the overflowing water and the surrounding atmospheric air. Stepped chute design is common for over-flow spillways of gravity and embankment dams[1]. Many researchers[2,3,4,5,6], studied energy loss due to steps depends primarily on the ratio of the critical depth of flow passing over spillway to the step height (y_c/h) and the number of steps (N) and the following relationship was suggested to calculate the energy dissipation of stepped spillway in the case nappe flow (when $y_c/h < 0.8$)[3]:

$$\frac{\Delta E}{E_\circ} = 1 - \frac{\left[(1-\alpha)^N\left(1+1.5\left(\frac{y_c}{h}\right)\right)+\sum_{i=1}^{N-1}(1-\alpha)^i\right]}{1.5\left(\frac{y_c}{h}\right)+N} \quad \text{..........} \quad (1)$$

$$\alpha = 0.3 - 0.35\left(\frac{h}{l}\right) - \left(0.54 + 0.27\left(\frac{h}{l}\right)\right)\left(\log\frac{y_c}{h}\right)$$

The finite element computational fluid dynamics module of the ADINA software was used to predict the main characteristics of the flow[7]. Also, numerical model (FLUENT program) to was used to estimate the energy dissipation in simple stepped spillway. It was suggested that in increasing the number of steps, directly increased energy dissipation of spillway and also, decrease of slope in spillway causes more energy to dissipate. Because of limited numerical researches dealing with this problem, the present study aim to compare computational fluid dynamic with experimental model and estimate energy losses.

Experimental Work

In this study, four types of stepped spillway were used. The width and the height of these spillways are (B=30.5cm, P_s=25cm), two slopes of spillways were used (h/l (S)=0.5, h/l (S)=1). For each slope, two number of steps were used (N=5 and 10). So, the heights of steps are (h=5cm, h=2.5cm) respectively. The steps of these samples are horizontal and made from wood and painted with greasy coating to prevent seepage of water into the material model. Each one of these samples has been placed in a flume at a distance of 2.2m from the upstream end. The flume was consisted of 6m long, 30.5cm wide and 40cm high. For each model, five different discharges were passed. The water discharge passing in the flume was calculated for each experiment by using volumetric method. The depth of the water at end upstream and the downstream of stepped spillway were measured by using a point gauge. All laboratory tests were conducted in the hydraulic laboratory of the Environmental Engineering Department at Tikrit University.

Flow-3D Software

Flow-3D is powerful and highly-accurate CFD software that gives engineers valuable insight into many physical flow processes. With special capabilities for accurately predicting free-surface flows, Flow-3D is the ideal CFD software to use in your design phase as well as in improving production processes and Computational Fluid Dynamics (CFD) is a branch of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows. Fluid flow is governed by partial differential equations which represent conservation laws for the mass, momentum, and energy. These equations combine to form the Navier-Stoke equations. In this study, the CFD model included a 3D symmetrical representation of the existing stepped spillway. The commercially-available computational code, Flow-3D Version 10.01 by Flow Science Inc., was used. This package is a finite difference/volume, free surface, unsteady flow modeling system, developed to solve the Navier-Stokes equations in three dimensions. Flow-3D uses an orthogonal coordinate system as opposed to a body-fitted system and can have a single nested mesh block, adjacent linked mesh blocks, or a combination of nested and linked mesh blocks. The software includes several turbulence algorithms that allow for the solving of the RANS equations, the k-e and RNG closure models. These closure algorithms are well suited for the modeling of flow over stepped spillways, because of their suitability in cases where a large amount of turbulence is created.

Numerical Model Set-up

The main set-up for all models was the same. In each case, one fluid, incompressible flow and free surface or sharp interface were applied. The gravity option was activated with gravitational acceleration in the vertical (y-direction) equal (-981cm/s^2). The viscosity and turbulence option was also activated with Newtonian viscosity. Turbulent option with two equation (k-e) model from turbulence options was selected. For wall shear boundary conditions; Non-slip or partial slip was used.

Model Geometry

Numerical model geometry was prepared by drawing stepped spillway models from subcomponent option in the program Flow-3D, see Figure (1).

Mesh Geometry

One of the most important issues to consider when setting up any simulation is how the computational grid should be defined. The number of cells in a mesh is highly dependent upon the size of the defined domain and the number of cells greatly impacts the solution, run-time and accuracy of the problem. Hence, the domain of a problem should be selected with care.

Mesh geometry consists of a number of interconnected elements, or cells. These cells subdivide the physical space into small volumes with several nodes associated with each such volume. The values of the unknowns, such as pressure and velocity were computed in center of each cell. The number and size of the cells are important criteria for numerical model simulation and they limit the accuracy of results and the simulation time.

In this study, the mesh size 1cm used in all directions and then reduced by using a Fractional Area / Volume Obstacle Representation (FAVOR) method[9], to define obstacles and at small step size. Also, reduced for small discharge, to give more accuracy for pressure. For model (a) as an example, the domain in three dimensions is; $-40<X<100$, $0<Y<40$, $0<Z<30.5$, see Figure (2).

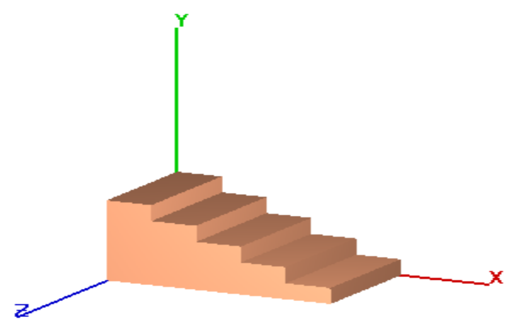


Fig.1. Model geometry

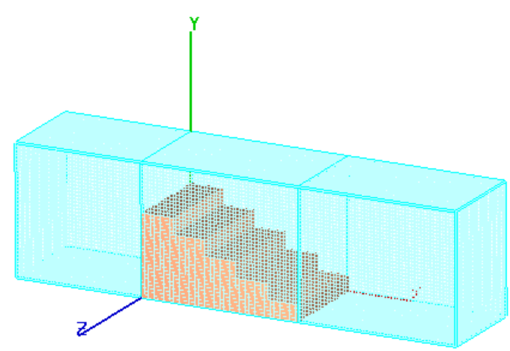


Fig. 2. Mesh geometry

Boundary and Initial Conditions

For all models, the boundary conditions (BCs) are required for all sides of the computational domain and were set as follows: in the x direction, the x minimum boundary was set as volume inflow rate (Q), the x maximum boundary was set as volume outflow (O). In the y direction, the y minimum boundary was set as wall (W), the y maximum boundary was set as atmospheric pressure. In the z direction, the z minimum and z maximum boundaries were set as symmetry, see Figure (3).

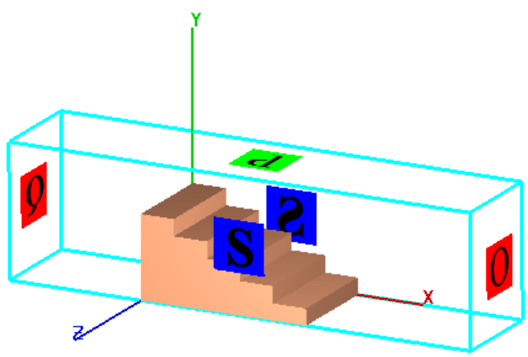


Fig. 3. Boundary conditions of modeling

Model Runs

In this study, 27 models were carried out and these are represent: three different spillway height (P_s) (15, 20, and 25) cm. For each one of these models, three different number of steps (N) (5, 10, and 25) and three different spillway slope (S) (0.5, 1, and 1.25) were selected. The width of stepped spillways was similar to the width of the flume and it is equal to 30.5 cm. In each model, eight flow rates were passed; therefore the total runs of this study are 216.

After the readiness of each model and all options, the model will start simulating, and this process takes long time depending on mesh size, initial conditions and finish time. Then, the result will output for pressures.

Dimensional Analysis

There are six variables which have an effect on energy dissipation of stepped spillway ($\frac{\Delta E}{E_*}\%$): spillway height (P_s), step height of spillway (h), step length of spillway (l), rate of flow passing over stepped spillway per unit width (q), roughness of steps (k_s), the acceleration of gravity (g). The equation relating these variables may be expressed as shown in the following:

$$\frac{\Delta E}{E_*}\% = f(P_s, h, l, q, k_s, g) \quad \text{......................(2)}$$

By using Buckingham pi-theorem, it can be concluded that ($\frac{\Delta E}{E_*}\%$) is a function of the following dimensionless parameters:

$$\frac{\Delta E}{E_*}\% = f(\frac{P_s}{k_s}, \frac{h}{k_s}, \frac{l}{k_s}, F_*) \quad \text{........................(3)}$$

The dimensionless parameter F_* represents roughness Froude number. It is equal to:

$$F_* = \frac{q^2}{\sqrt{g.\sin\theta . k_s^3}} \quad \text{..................................(4)}$$

Where; k_s: roughness of steps (k_s= h.cosθ) and θ: angle of spillway slope ($\theta = \tan^{-1}$(h/l))
The flow passing over stepped spillway per unit width equal to:

$$q = \frac{Q}{B} \quad \text{... (5)}$$

Results and Discussion

Validation of Flow-3D Numerical Program

To validate the use of the Flow-3D numerical program, practical experiments were conducted on four different models in order to measure the energy dissipation for various discharges which were passed over these models. The same details of dimensions of the previous four models and same passing discharge were applied on the numerical model. The energy dissipation results for experimental tests and numerical model were compared as shown in Tables (1) and (2). The comparison shows a good agreement between them. Also, it was observed that the flow divides on stepped spillway in the Flow-3D numerical program as well as in the experimental study into three types of flow which are: nappe, transition and skimming flow. These types of flow depend on the geometries of the stepped spillway and the passing discharge over it. In the case of nappe flow, relative errors between experimental and numerical models were noted, that are less as compared with relative errors in the case of skimming flow. In model 1, by increasing discharge of flow, the energy dissipation decreases. This led to an increase of the error between the experimental and numerical results. The rate of error between the results of experimental tests and numerical model were calculated from the following equation:

$$\text{Error\%}=\frac{\frac{\Delta E}{E_o}\%\,\text{experimental}-\frac{\Delta E}{E_o}\%\,\text{numerical}}{\frac{\Delta E}{E_o}\%\,\text{experimental}} \quad \text{……..(6)}$$

For model 4, the minimum and maximum percentage of errors were observed as (0.15%) and (11.13%) when the discharge of flow equals to 842.98 cm³/s and 7592.91cm³/s respectively.

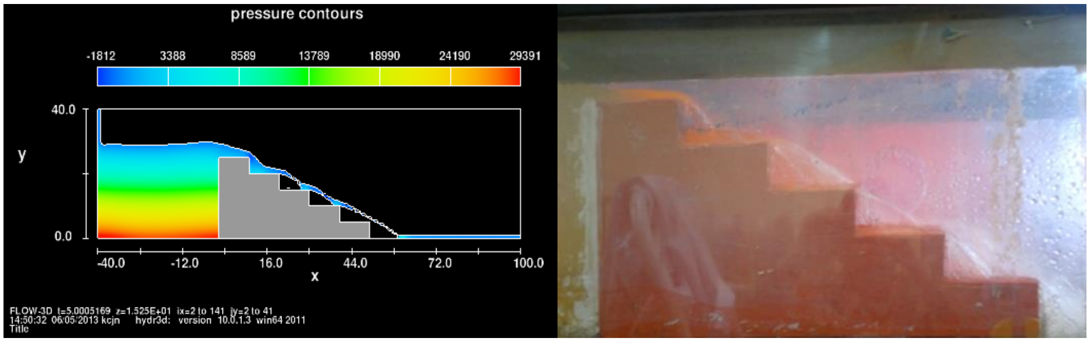
From Figures (4) to (6), it can be seen that the flow patterns which occurred on stepped spillway for experimental model were almost similar to the numerical model for the same conditions. This comparison indicates that Flow-3D numerical program is reasonable software to predict characteristics of dynamic flow, types of flow and energy dissipation over stepped spillway.

Table 1. Comparison of the energy dissipation between results of experimental and numerical models for P_s=25 cm, N=5

No.	S	Q (cm³/s)	$\frac{\Delta E}{E_o}$ % Experimental	$\frac{\Delta E}{E_o}$ % Numerical	Error %
1	0.5	1828.96	91.41	91.63	-0.24
		2788.98	89.01	88.60	0.46
		6074.91	81.24	78.82	2.98
		6421.52	80.70	77.94	3.42
		7368.17	79.24	76.01	4.08
2	1	2015.28	91.11	91.76	-0.71
		2099.03	90.84	91.55	-0.78
		5677.81	82.19	78.89	4.02
		6650.18	79.97	76.93	3.80
		8083.83	78.85	73.08	7.32

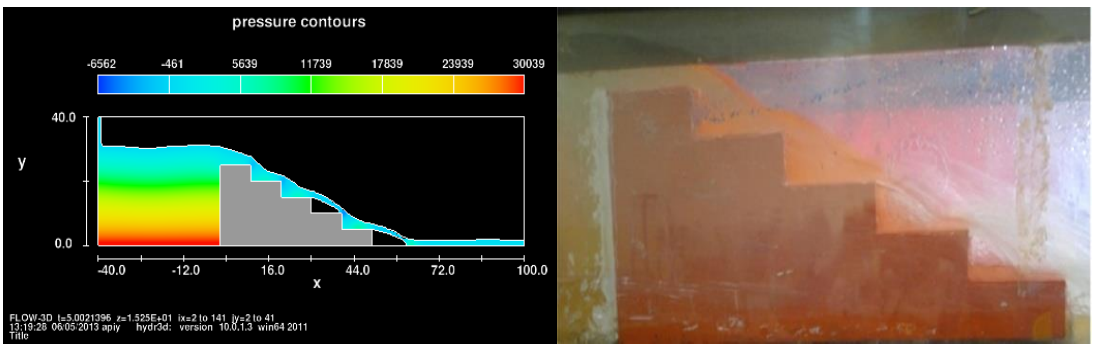
Table 2. Comparison of the energy dissipation between results of experimental and numerical models for P_s=25 cm, N=10

No.	S	Q (cm³/s)	$\frac{\Delta E}{E_o}$ % Experimental	$\frac{\Delta E}{E_o}$ % Numerical	Error %
3	0.5	651.99	95.63	95.87	-0.25
		1043.10	93.72	94.54	-0.87
		3203.02	86.93	87.92	-1.14
		3652.69	87.04	87.25	-0.24
		7500	80.79	73.54	8.97
4	1	389.88	96.74	95.62	1.16
		842.98	94.66	94.52	0.15
		3467.95	84.55	86.25	-2.01
		4390.53	82.90	81.59	1.58
		7592.91	79.68	70.81	11.13



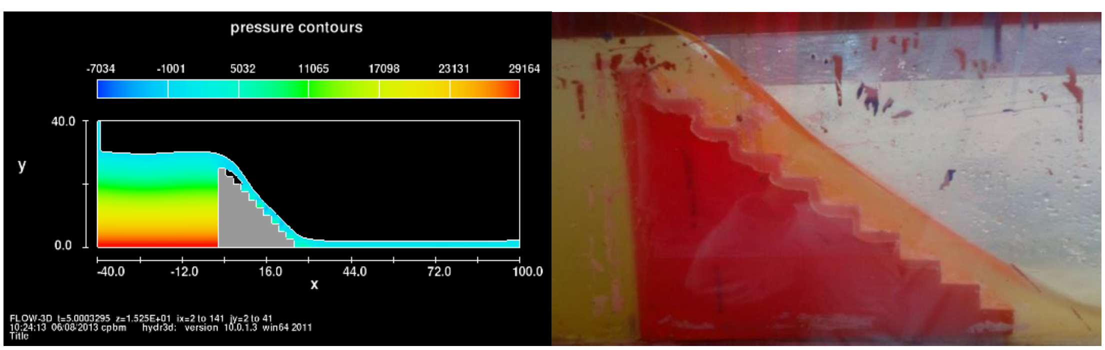
(a) (b)

Fig. 4. Nappe flow on the stepped spillway for P_s=25 cm, N=5, S=0.5, Q=1828.96 cm³/s
(a) Numerical model (b) Experimental model



(a) (b)

Fig. 5. Transition flow on the stepped spillway for P_s=25 cm, N=5, S=0.5, Q=6421.52cm³/s:
(a) Numerical model (b) Experimental model



(a) (b)

Fig. 6. Skimming flow on the stepped spillway for P_s=25 cm, N=10, S=1, Q=7592.91cm³/s:
(a) Numerical model (b) Experimental model

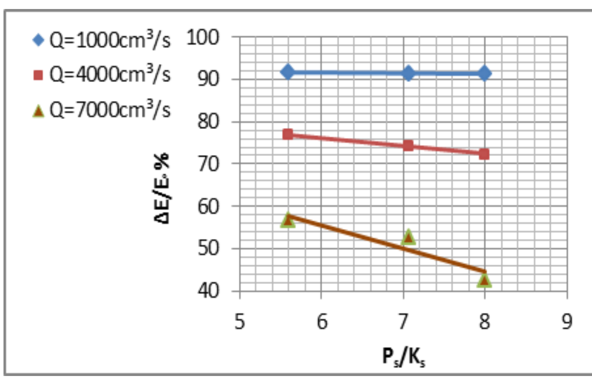
Factors Affecting on the Energy Dissipation

Referring to equation (3), the factors affecting on the energy dissipation of stepped spillway $(\Delta E/E_\circ)\%$ are $(\frac{P_s}{k_s}, \frac{h}{k_s}, \frac{l}{k_s}, F_*)$. The effect of these parameters on the energy dissipation for 27 different models of stepped spillway was studied. Various cases of flow discharges (Q=1000, 4000, and 7000cm³/s) were passed over these models as in the following:

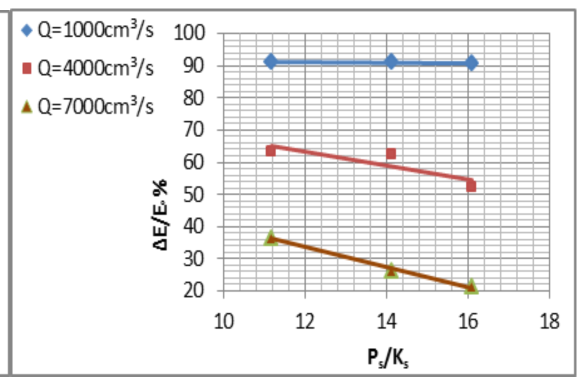
Effect of the Ratio of the Spillway Height to the Steps Roughness (P_s/k_s)

The results indicated that the energy dissipation increases with decreasing the ratio (P_s/k_s) and spillway slope (S). Also, the energy dissipation increases with decreasing the rate of flow (Q). It was observed from results that for a specific step height and spillway slope and fixing flow discharge, the energy dissipation increases with increasing the spillway height (P_s). Figure (7) illustrates the effect of the ratio (P_s/k_s) on $(\Delta E/E_\circ)\%$. It can be concluded from results that by fixing discharge of flow (Q), spillway height (P_s) and spillway slope (S), the energy dissipation refers to increases with decreasing the number of steps (increasing the step height). In a small slope, increasing step height (h) and increasing flow discharge, lead to converts flow from nappe flow to transition flow. Also, Figure (7) shows that the effect of the ratio (P_s/k_s) on $(\Delta E/E_\circ)\%$ in the case of Q equal to1000 cm³/s is so little when other variables (P_s, N) remain constant. This means that increasing or decreasing (P_s), (N), (S) in the case of small discharge, the difference in energy dissipation is very little compared with that of high discharges (Q=4000, 7000cm³/s).

The results indicated a same performance of all stepped spillway when a small discharge (1000cm³/s) passes over these structures where the energy dissipation ranged between (88-95)%. But, when the discharge ranged between (4000-7000cm³/s), the maximum energy dissipation was obtained over the model of (P_s=25 cm, N=5, S=0.5), where it is ranged between (86-77)%.



(a)



(b)

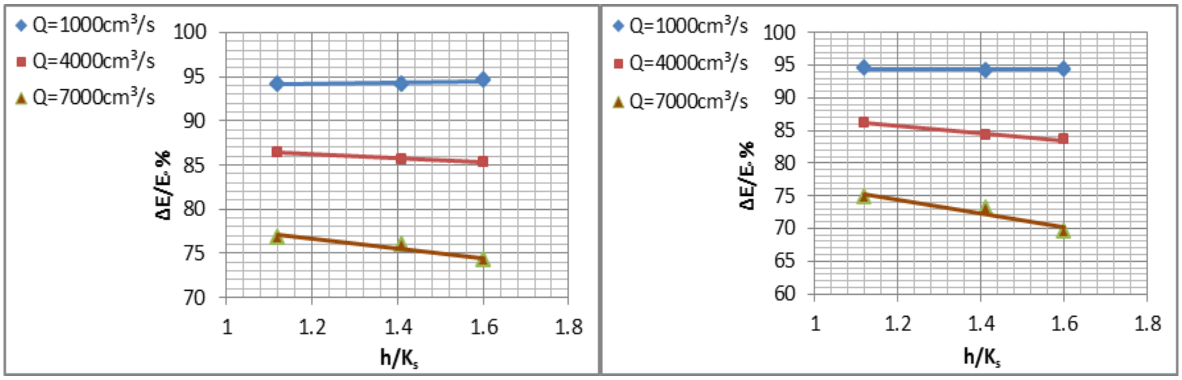
Fig. 7. Relationship between the energy dissipation and the ratio of the spillway height to the roughness of step (a) P_s=15 cm, N=5 (b) P_s=15 cm, N=10

Effect of the Ratio of the Step Height to the Step Roughness (h/k_s)

The results showed that for a certain discharge of flow, the energy dissipation increases with decreasing (h/k_s) due to decreasing in slope of spillway (S). This indicates that (h/k_s) is inversely proportional with $(\Delta E/E_\circ)\%$. For any model, when fixing the value of (h/k_s), the energy dissipation decreases with increasing the flow discharge. The results also showed that at a certain (N), (h/k_s) and discharge (Q), and an increase spillway height (P_s), the energy dissipation increases. It was observed from results that energy dissipation $(\Delta E/E_\circ)\%$ increases with reducing the number of steps (N) at certain height of spillway (P_s) and (h/k_s) and (Q). Also, it was observed that effect the ratio

(h/k_s) on energy dissipation of (Q=1000cm³/s) is little in all types of stepped spillway.

Figure (8) explained typical the effect of the ratio (h/k_s) on ($\Delta E/E_o$)%.



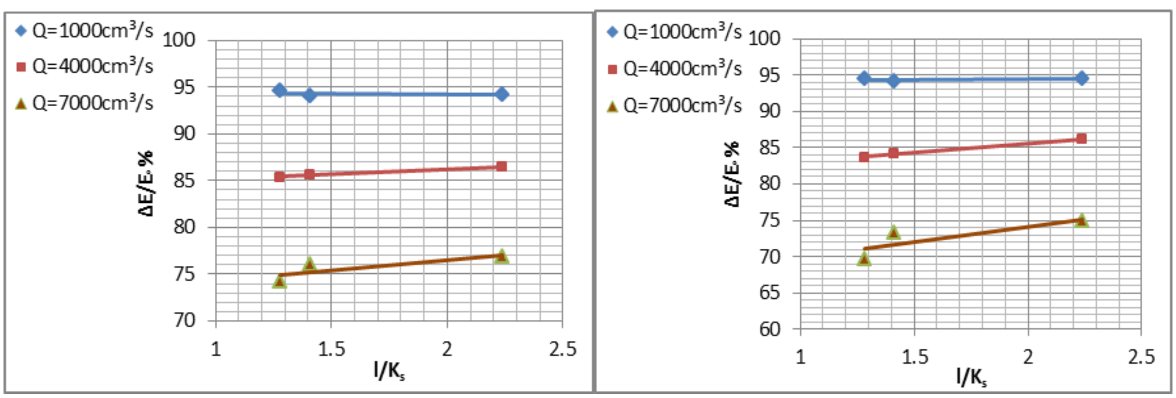
(a) (b)

Fig. 8. Relationship between the energy dissipation and the ratio of the step height to the roughness of step for (a) P_s=25 cm, N=5 (b) P_s=25 cm, N=10

Effect of the Ratio of the Step Length to the Step Roughness (l/k_s)

The results showed that the energy dissipation increases with increasing (l/k_s) and decreasing spillway slope (S). It was noticed from results that at fixed the ratio of the step length to the roughness of step (l/k_s) with number of steps (N) and discharge of flow (4000 or 7000cm³/s), the energy dissipation increases with increasing spillway height (P_s). It was also noticed that ($\Delta E/E_o$)% increases with increasing (h) with fixed other variables (P_s), (l), (Q).

The results indicated that the effect the ratio (l/k_s) on energy dissipation in the case (Q) equal to 1000 cm³/s are few in all types of spillway due to approximate of a values of ($\Delta E/E_o$)%. Figure (9) illustrates typical the effect of the ratio (l/k_s) on($\Delta E/E_o$)%.



(a) (b)

Fig. 9. Relationship between the energy dissipation and the ratio of the step length to the roughness of step for (a) P_s=25 cm, N=5 (b) P_s=25 cm, N=10

Effect Roughness Froude number (F_*)

The effect of different roughness Froude number (eight flow discharge) on energy dissipation indicated that energy dissipation decreases with increasing roughness Froude number. At specific flow discharge, spillway slope and at increasing step height, the values of energy dissipation in the case (N=5) is the largest as compared with that of (N=10 or 25).

It was observed from these figures that energy dissipation in the case P_s=25 cm is the largest Figure (10) shows the effect of the ratio (F_*) on ($\Delta E/E_\circ$)%. But, the effect roughness Froude number on the energy dissipation for different cases of spillway slope is little, due to approximate the values (F_*) and ($\Delta E/E_\circ$)%.

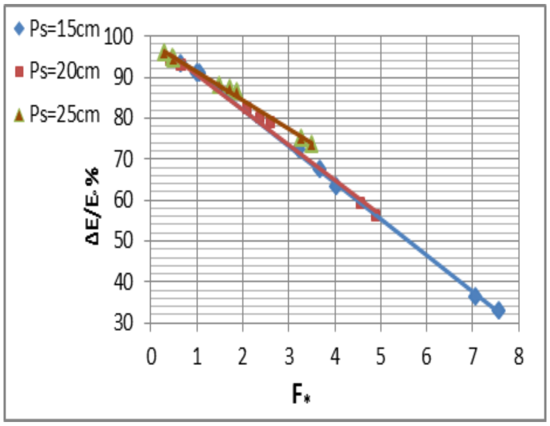


Fig. 10. Relationship between energy dissipation and roughness Froude number for N=10, S=0.5

Equation of Energy Dissipation over Stepped Spillway

After calculating dimensionless parameter ($\frac{\Delta E}{E_\circ}\%, \frac{P_s}{k_s}, \frac{h}{k_s}, \frac{l}{k_s}, F_*$) of each model, about 70% of these results were used in the program SPSS to predicate an empirical equation to determine the energy dissipation of flow over stepped spillways. The following equation is obtained with coefficient of determination (R^2) equal to 0.766:

$$\frac{\Delta E}{E_\circ}\% = 105.574 - 3.074(F_*) + 0.757\left(\frac{P_s}{k_s}\right) - 18.839\left(\frac{h}{k_s}\right) - 1.974\left(\frac{l}{k_s}\right) \quad \text{……………………..…(7)}$$

The remaining 30% values of the dimensionless parameters were used to draw the relationships between the energy dissipation calculated from equation (7) and measured from Flow-3D numerical program as shown in Figure (11). A reasonable agreement between them is indicated, and the standard error between the measured and calculated results equal to 3.40326%.

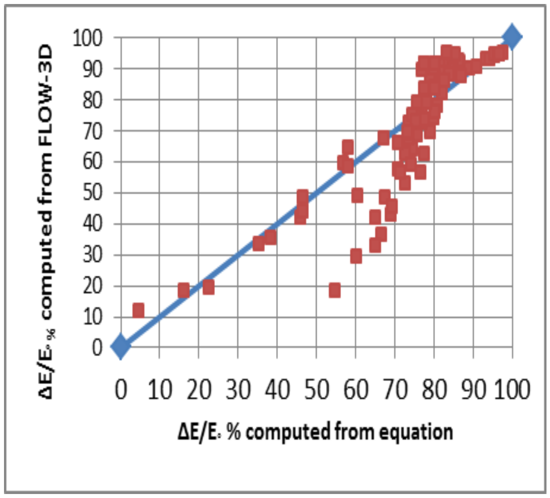


Fig. 11. Comparison between energy dissipation of computed from program FLOW-3D and from equation (7)

Pressure Distribution on the Horizontal and Vertical Spillway Step Faces

The water pressure distribution on the horizontal and vertical step faces at the centerline of stepped spillway was simulated from program Flow-3D for twenty seven models. The height of all these models (P_s) is 15, 20 and 25 cm. Three numbers of steps (5, 10 and 25) and three downstream slopes (0.5, 1 and 1.25) were used. For each one of these models, three different flow rates (Q) (1000, 4000, 7000)cm^3/s were passed. The pressure distribution on the horizontal and vertical faces of steps was measured at three locations of stepped spillway, which are:

-Step 1, 3, 5 for spillway of N=5.
-Step 1, 5, 10 for spillway of N=10.
-Step 1, 13, 25 for spillway of N=25.

These locations represent the beginning, middle and ending of the spillway.

For horizontal faces, the pressures were measured in the center of each cell along these faces. This means that the pressures were measured with different distances (X) along the horizontal face. The distance (X) starts from the beginning horizontal face to center of cell as shown in the Figure (12).For vertical faces of steps, the pressures were measured in the center of each cell along these faces. The distance (y) starts from horizontal face to center of cell, see Figure (12). For this purpose, it was selected a spillway height (p_s=25cm) with three different spillway slopes and number of steps to studying the pressure distribution on these faces.

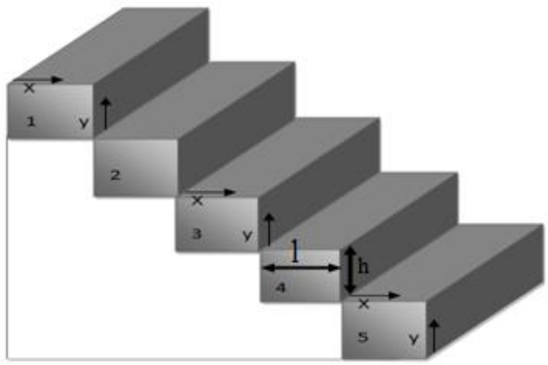


Fig. 12. Details of locations of pressures measuring on faces of spillway steps

It was noticed from results that an increasing in water discharge causes increasing in pressure of water for some models and this leads to decrease energy dissipation. Sometimes, the pressure distribution, at a lower discharge is more than that at a higher discharge; this may be due to the impact of flow on steps.

The positive pressure distribution on the horizontal faces of the first step (step1) was observed when spillway contains less number of steps (N=5), for all slopes (S=0.5, 1, 1.25). These values of pressure distribution be more as compared with that of spillway which contains (N=10 or 25). It is worth to mention the spillways with (N=10 or 25) and steeply slope (S=1 or 1.25) give a lowers pressure distribution and sometimes produce negative pressures in the cases of higher discharges. This may be caused according to the increasing in the velocity of flow. The negative pressure is dangerous on the horizontal faces because leads to erosion step surface.

In the middle of spillway, it was observed that the pressure is more when the lower discharge passes over a spillway with steep slope (S=1.25) and especially when the number of steps (N=5 or 10). For case of passing a higher discharge on the above models, the flow on these models became as a jet which impact the steps after the middle of the spillway. So, in this case the produced pressures on the middle steps will be zero.

For spillway having a number of steps (N) equal to 5 or 10 or 25 with the case of steep slope (S=1.25) and when passing a higher discharge (Q=7000 cm^3/s), it was observed that the values of pressure distribution on the horizontal faces of ending step of the spillway are more than the pressures when the slope of spillway equal to 0.5 or 1.Also, the results show, with passing higher discharge, and when number of steps (N=5), the pressure distribution on the horizontal face of step 5 with (S=1.25), is more as compared with that on step 1 or step 3.

When (N=10), it was observed that the pressure distribution on a horizontal face of step 10 was more, for all spillway slopes (S=0.5, 1, 1.25) and for all discharges (Q=1000, 4000, 7000cm^3/s), as compared with that on step 1 or step 5. Also, the pressure distribution at middle step of spillway (step 5) was more as compared with that at the beginning of spillway (step1).

For (N=25), it was observed that the pressure distribution at the last step (step 25) was more for spillway slopes (S=0.5 or 1) and for all discharges (Q=1000, 4000, 7000cm^3/s) as compared with that on the first step (step1) and middle step (step13).

For vertical faces, the pressure distribution on these faces of the middle or end steps is equal to zero in the case of (N=5), and when low discharge was passed over a spillway with (S=0.5).

It was observed that the behavior of pressure distribution on the horizontal and vertical step faces (at beginning, middle and ending step of spillway) with different discharges are not similar because the regions were taken to measure the pressures are not submerged by water and also, due to a separation of flow which was occurred on this faces.

Conclusions

In the present study the energy dissipation and pressure distribution on the stepped spillway was studied experimentally and using computational fluid dynamic numerical model. The comparison between experimental and numerical results indicated good agreement where the maximum percentage error between them is (11.13%). The following conclusions can be obtained from this study:

1- The results show that energy dissipation ($\Delta E/E_o$)% increased with decreasing the discharge (Q), decreasing spillway slope, decreasing number of steps and increasing the height of spillway.
2- The pressure distribution on the horizontal faces of steps increases with increasing the flow discharge.
3- For all cases of step number (N=5, 10, and 25) and when a higher discharge (Q=7000cm^3/s) was passed over a stepped spillway with (S=1.25), the pressure distribution on the horizontal face of the end step was more than that for the case of (S=0.5 or 1).
4- It was observed from the results that the pressure distribution on the horizontal faces of steps at the middle of stepped spillway equal to zero when the number of steps equal to 5 or 10, in the case of steep slope and higher discharge.
5- The results showed that negative pressure was produced on the vertical faces near the outer edge of steps for some models and discharges.
6- The stepped spillway with (P_s=25cm), (N=5) and (S=0.5) is more efficient than other models for energy dissipation and positive pressure distribution on horizontal faces.
7- An empirical equation for measuring the energy dissipation was derived using the dimensional analysis with the helpful of data which resulted from numerical program for different models of spillway. The coefficient of determination of this equation (R^2) equal to 0.766.

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