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A Study of the Conditions of Energy Dissipation in Stepped Spillways with Λ-shaped step Using FLOW-3D

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Abstract

In the present study, energy dissipation was investigated in a specific type of stepped spillways. The purpose was to achieve the highest level of energy dissipation in downstream of the spillway. It was performed by providing a specific type of geometry for step as a great roughness. Here, steps were recognized as great roughness against flow. Their shape and number were designed in such a way that the maximum flow energy can be minimized in this stage, i.e. over steps before reaching to downstream. Accordingly, it can be stated that the highest energy dissipation rate will be obtained in the structure at downstream. Moreover, thereby, heavy costs imposed by designing and constructing stilling basin on project can be minimized. In this study, FLOW-3D was employed to analyse and obtain energy dissipation rate. The best geometry of the steps, through which the maximum energy dissipation can be achieved, was determined by reviewing related literature and inventing the proposed model in FLOW-3D. To evaluate the proposed method, analyses were performed using trial and error in mesh networks sizes as well as the mentioned methods and the results were compared to other studies. In other words, the most optimal state was obtained with Λ-shaped step at angel of 25 degree with respect to energy dissipation rate compare to smooth step.

Keywords: Stepped Spillway; Energy Dissipation; FLOW-3D; Λ-Shaped Step; Staircase Geometry.

1. Introduction

The volume and energy of water stored in reservoirs is very high. When releasing, this energy can cause irreparable psychological harm and financial loss in downstream of the dams. In this regard, various flow energy dissipation methods are propounded. To control the stored flow energy, hydraulic structure are used. Stepped structures is of important and main structures in hydraulic engineering. In the early 20th century, due to the long period of construction, the high cost of maintenance, and low energy dissipation rate in these structures, using them was decreased and engineers replaced them with other structures. However, with the advent of technology, especially creation of the RCC, duration of construction of these structures has shorten and their maintenance has been more simplified. More importantly, new design has caused the increase of energy dissipation. To this end, during the last thirty years, these structures have been used again; specially, in the last decade, they have changed into the main element in hydraulic designs.

Stepped spillways have a long story (about 3500 years); stepped spillways and channels were previously used to decrease flow velocity [1]. Flow over these structure, especially stepped spillways, gradually dissipate their energy when passing the steps such that most of their energy has been taken at the end of the spillway. Steps are recognized as

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roughness factor at the length of the structure. This fact causes to minimize the need of designing and constructing energy dissipator structures at the downstream of the spillway; therefore, heavy costs imposed to projects by designing and constructing stilling basin at the downstream of the spillways are decreased, leading to project affordability.

Today, stepped structures are constructed for various purposes in various types. Stepped structures are used in flood control, energy dissipation in channels through which sever cloudburst pass. Stepped spillway is a simple sample of waterway with high roughness coefficient, which consists of a number of steps with constant or variable geometry and dimensions, and continues from near to the spillway crest at the structure upstream to the spillway toe at the downstream.

The geometry of steps is one of the most important factors propounded in energy dissipation of flow passing through the stepped spillways. During the recent years, researchers have studied various stepped spillways due to the considerable effect of steps on energy dissipation. With the passage of time and progress of technology, and with respect to high costs of designing and implementing physical models, intelligent software and numerical models have been developed. Such that, the geometry of the considered model is depicted in a software; then, the flow with certain discharge is passed through and the considered parameters are taken at the end of simulation. Afterwards, the obtained data were analyzed to draw the final conclusion.

In the present research, energy dissipation maximization method is investigated in stepped spillway. It is actualized using stepped geometry. The study mainly focuses on energy dissipation. To evaluate the proposed method and compare it with other steps, a computer program was considered. The research, indeed, is an attempt to improve energy dissipation rate in spillways.

2. Literature Review

Various studies have been conducted on energy dissipation on stepped spillways. Many researchers have also studied energy dissipation in stepped spillways as well as geometry of the steps.

For the first time, Cassidy (1965) used numerical method to analyse spillways and obtain energy dissipation. In this study, Cassidy attempted to determine pressure on the crest of an Ogee spillway in two-dimensional domain [2].

Sorensen (1985) compared energy dissipation percentage in Ogee and stepped spillways. Accordingly, energy dissipation rate in stepped spillways was reported about 75% more than Ogee spillways. Also, stilling basin dimensions showed a relative decrease of 84% [3].

Pegram et al. (1999) conducted a comprehensive study to investigate the effect of geometrical characteristics of steps and scale on the type of flow and energy dissipation rate, with the assumption of creating balance conditions at the downstream of the flow. In this research, measuring flow energy in downstream of the stepped and Ogee spillway, which was dimensionally similar, energy dissipation rate in stepped spillway was reported higher. Moreover, the obtained results showed that energy dissipation is decreased by the increase of spillway slope [4].

Tabbara et al. (2005) employed finite element method to compute water flow profile over stepped spillway using ADINA-f software. They also used standard model of K- ε to determine flow turbulence. The computed water flow profile regarding all constructed stepped spillways was qualitatively in accordance to flow characteristics and quantitatively similar to the measured values of free surface flow profile. In addition, relative energy dissipation was computed and compared to the values obtained by the experiment. As revealed, there was a good accordance between the numerical and experimental values [5].

Mansoori and Pedram (2008) studied end sills stepped spillway and presented a relation to determine energy dissipation rate of these spillways. They employed 23 steps made of plexi glass (with the thickness of 10 mm, the length of 17 cm, the width of 55 cm, and the height of 3 cm) from the top connected to a metal skeleton and plexiglass walls. They performed their experiments with discharges of 3.6 $\mathrm{lit/s}$ (Nappe flow) and 25 lit/s (Skimming flow) and took static pressure imposed on floor and its fluctuations with flow velocity and depth. Analysing the obtained data and changing Rajarantnam and Chamani's equation, they could present a relation to determine energy dissipation rate in end sill stepped spillway at Nappe flow regime. They finally concluded that the presence of sill would influences energy dissipation rate in stepped spillways; however, this effect on flow has a different trend and decreased by the increase of discharge. In Nappe Flow regime, width, height and angel of sill at upstream would influence energy dissipation rate; in other words, increasing width and height of sills increase energy dissipation rate and decreasing the angel of sill at upstream would decrease energy dissipation. Therefore, vertical sill compared to curve sill causes higher energy dissipation but in Skimming flow regime, the effect of sills on energy dissipation is very slight due to sills' loss [6].

Naderi Rad et el. (2009) investigated energy dissipation in various types of stepped spillways including simple, sills, and sloped ones using FLUENT numerical model. Totally, 33 numerical models were made including 11 stepped spillway groups. These 11 groups were analysed for 3 discharges and 3 boundary conditions. To analyse simple stepped spillways, five model groups were considered for each of them, three discharges (0.0190, 0.537 and 0.0987 $\mathrm{m^3/s}$, spillway design height (h_d) of 0.05, 0.1 and 0.15 m and critical height (Y_c) of 0.0334, 0.0667 and 0.1 m were analyzed.

For each of the sills and sloped stepped spillways, three model groups were considered. Each group was analysed for three discharges (0.0190, 0.0537 and 0.0987 m^3/s, spillway design height (H_d) of 0.05, 0.1 and 0.15 m and critical height (Y_c) of 0.0334, 0.0667 and 0.1 m were analyzed.

Increasing the number of steps when the height of dam is constant, causes the increase of energy dissipation in stepped spillways. Decreasing stepped spillways' slope when the height of dam is constant causes the increase of energy dissipation. increasing the slope of steps' floor when the dam height, number and size of steps as well as the spillway slope are constant, causes the increase of energy dissipation in the slopped stepped spillways. Increasing discharge in all three states of the stepped spillways causes the decrease of energy dissipation and energy dissipation changes is a kind of independent flow [7].

Mansoori and Soori (2013) compared energy dissipation in Nappe flow regime and Skimming flow regime using FLOW-3D. In addition to investigating the diagnosis of flow type in stepped spillways, they analysed previously reported results. On the other hand, they investigated experimental relation presented to compute energy dissipation. The study was based on the formula presented by Stephenson [8]. Such that, they compared the relative energy dissipation obtained by FLOW-3D with the value obtained by Stephenson's equation. The result obtained by the numerical model and Stephenson's relation was consistent. Finally, in the angel of 8.8^o, the obtained function had higher correlation with Stephenson's formula:

$$\frac{\Delta H}{H_0} = 0.511(Fr_0)^{-0.35} \quad (1)$$

According to the aforementioned, in the modeled spillway design, Pfister spillway dimensions has been used. Using Pfister spillway dimensions and investigating Nappe flow in various discharges and slopes in FLOW-3D, the following equation was obtained to investigate energy dissipation which is practical for spillways with low height in Nappe flow regime [9-11].

$$\frac{\Delta H}{H_0} = \left\{\frac{0.83}{\theta^{0.23}}\right\}(Fr_0)^{-0.33} \quad (2)$$

Hamedi et al. (2016) explored four steps (39 to 42) of a 60-step spillway and analyzed that by the use of FLUENT. The four steps with slope and sill were placed simultaneously. Various sill with different height and thicknesses were tested. In three steps, reverse slopes of $7, 10$ and 12^o were applied. Dimensionless parameter m/h was used to measure energy dissipation. The obtained results revealed that in the discharge of $30\ lit/s$ (discharge per unit width $q = 0.0225\ m^2/s$), which indicates Nappe flow regime, the steps with simultaneous slope and sill (in which the ratio of m/h is less than 0.7) significantly increases energy dissipation [12].

3. Methodology

Numerical simulation of flow field in stepped spillways and in general, hydraulic, spillways and dissipation terminals structures are very important due to the strategies of designing such structures. As various researchers experienced, FLOW-3D outperformed to model such hydraulic structures compared to available software packages. In the present project, FLOW-3D (ver. 10.1) was used to numerically study flow filed on stepped spillways. The experiential stepped spillway model of Sedaghatnejad (2009) was simulated in FLOW-3D [13]. In the following, the geometry of the experimental models is constructed by creating numerical modeling conditions similar to the constructed hydraulic model. Also, hydraulic parameters of flow filed on the stepped spillways with various geometrical conditions were investigated and compared.

3.1. Geometrical Simulation of Various Stepped Spillways Models Based on Hydraulic Model

To simulate the hydraulic model of the stepped spillways using FLOW-3D, entire the spillway's body should be constructed in 3D form using geometrical simulator software such as AutoCAD ‹CATIA, SolidWorks, etc. For the purpose of the present study, SolidWorks 2012 was used.

Geometrical characteristics of the stepped spillways used in the study for calibration in 3D form are as following:

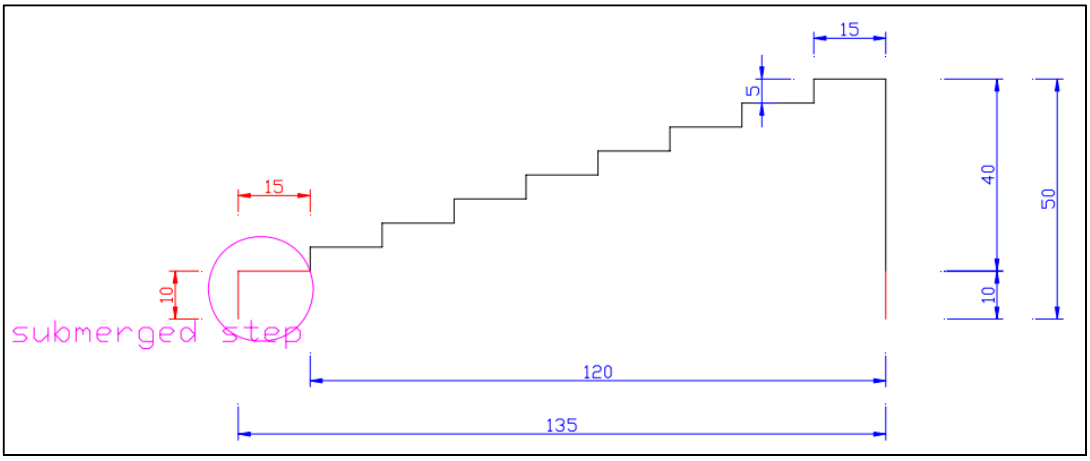


Figure 1. The dimensions of the stepped spillway model simulated in laboratory

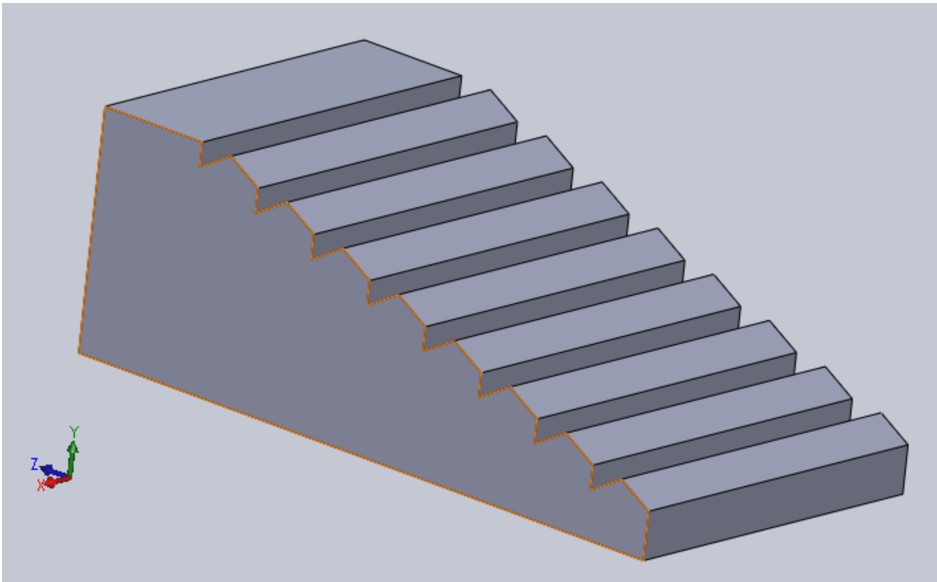
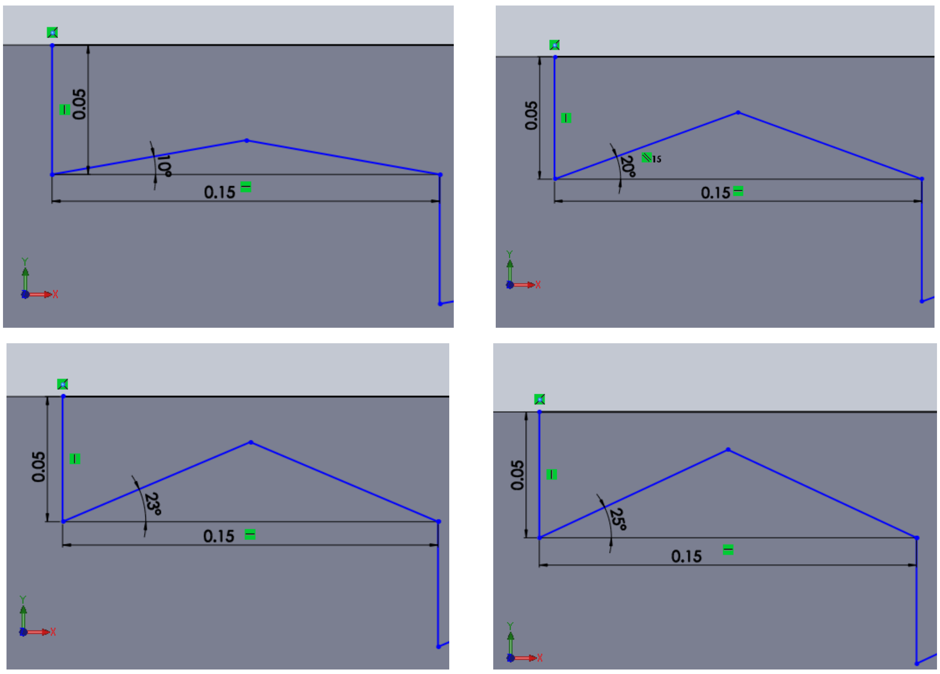


Figure 2. Three-dimensional design of the spillway using SolidWorks 2012

As shown in Figure 3, changing the geometry of the step floor, the six different geometrical models of the stepped spillway were constructed in SolidWorks 2012.



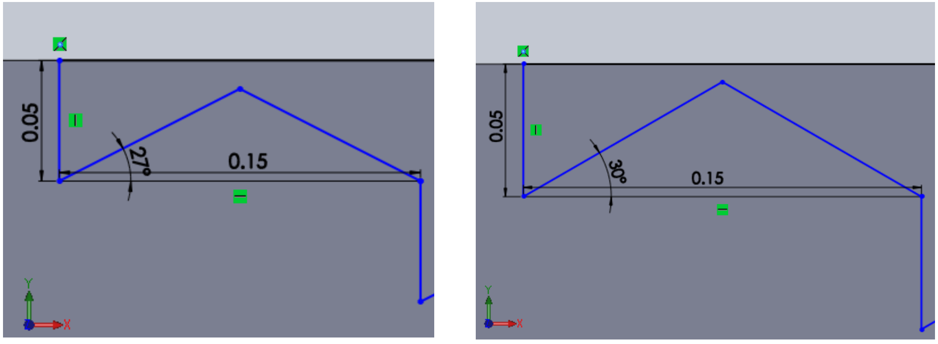


Figure 3. Geometrical characteristics of the Λ-shaped stepped spillway

To investigate flow filed and hydraulic conditions, boundary and initial conditions should be applied to each of the models in FLOW-3D.

3.2. The Process of Flow Simulation on the Stepped Spillways

Given to the geometry type of the model, meshing limits should be determined through mesh blocks, in which all considered size of the structure and free space are defined. As shown in Figure 4, the rigid geometry constructed was added to FLOW-3D. Also, computational environment for the stepped spillways was created in FLOW -3D using mesh bocks.

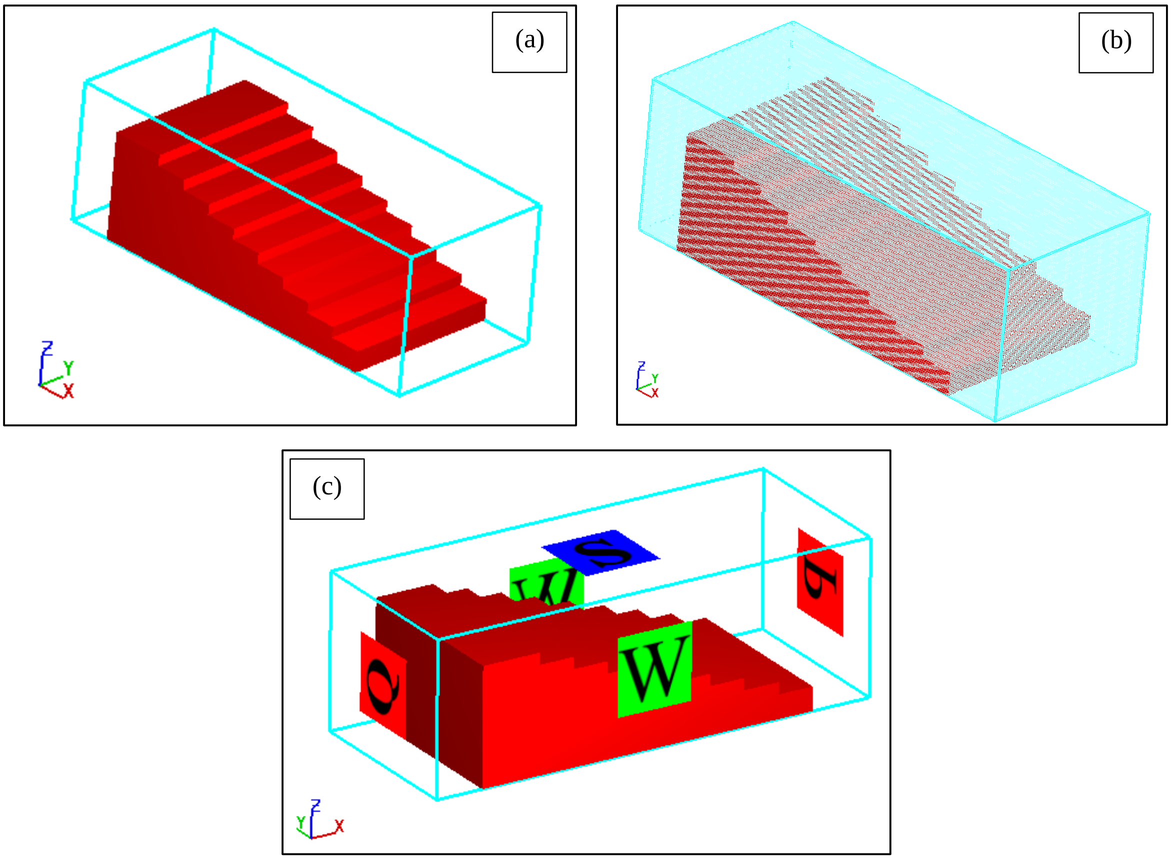


Figure 4. Mesh conditions: a) mesh block; b) computational cells; c) boundary conditions applied in simulation

4. Results and Discussion

In the first stage, the numerical model should be calibrated with experimental data. In other words, the model conditions should be closer to experimental and actual conditions. As mentioned earlier, the present numerical model was simulated based on the experimental data; therefore, the numerical model was validated based on the experimental model. To extract accurate and exact values of an actual or numerical model's data is necessary to achieve steady state conditions. In the available numerical model, after simulating several different models, appropriate time to extract the results was considered 15 seconds. Figure 5. shows how flow passes through the stepped spillway in different times. After 20 seconds, the flow reached steady state on the stepped spillway.

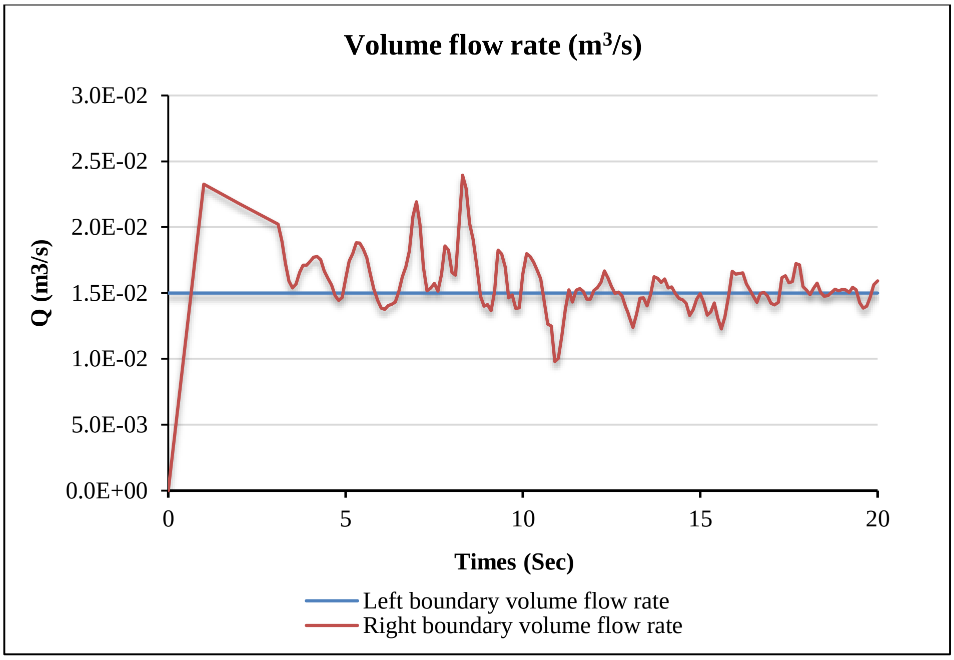


Figure 5. The discharge outflowing at the end of the boundary compared to input boundary

As observed in the figure, after 15 seconds, the discharge in the numerical model reached to 15 lit/s; however, the calibration model was continued to 20 sec to ensure the model validation.

4.1. Validating the Numerical Model Results Using the Experimental Data

To validate the numerical simulation results, the results obtained by the most important hydraulic parameters including flow depth, velocity and energy dissipation in the first step and fifth step of various sections of the spillway were extracted and compared to the experimental results. In this regard, the maximum simulation error was presented. The following figures depict the results pertained to flow depth and flow velocity for the cannel's central axis and stepped spillway.

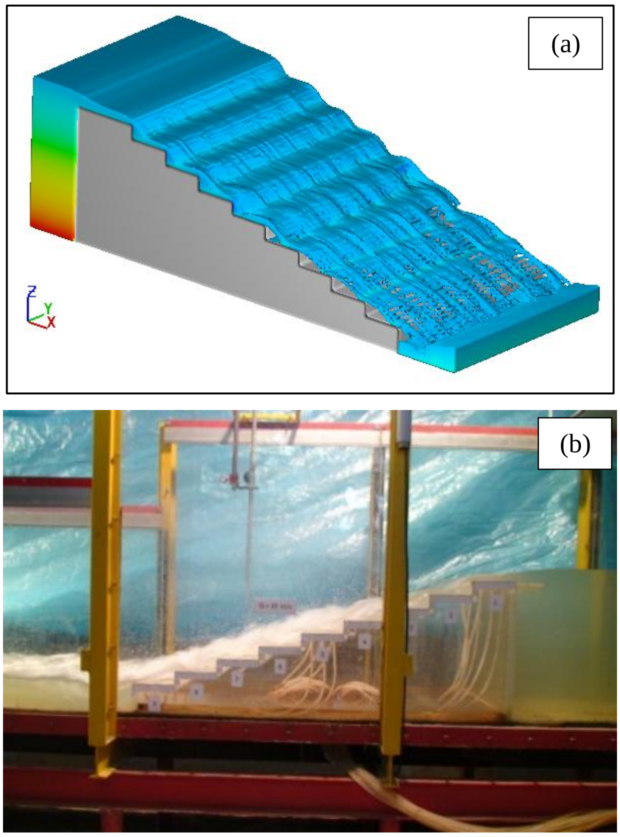


Figure 6. a) 3D Numerical modelling of flow over Spillway; b) 3D experimental modelling of flow over Spillway (with the discharge of 5 lit/s)

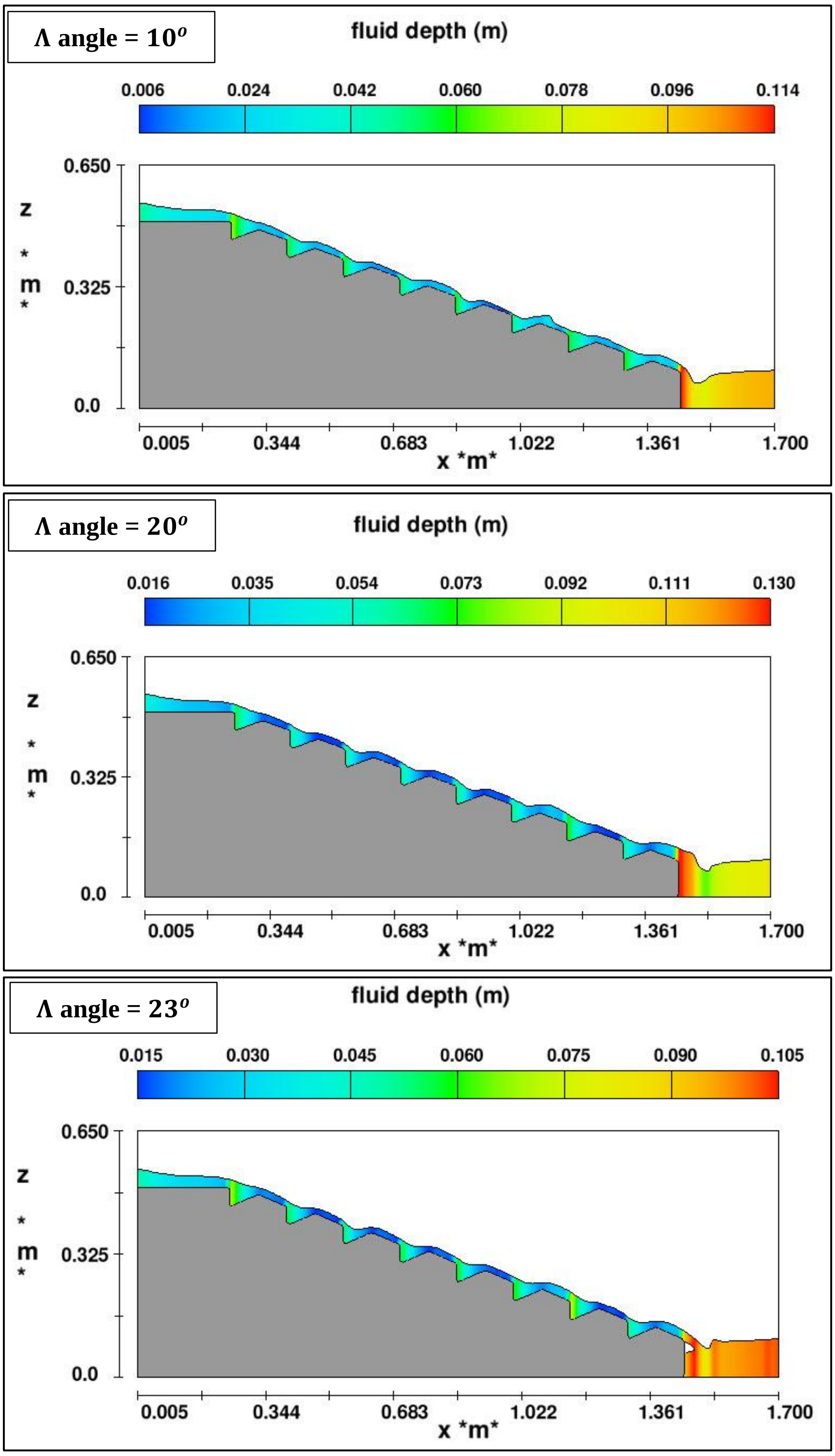
Table 1. compares velocity and depth values in the numerical and experimental modelling and computes error percentage between the numerical and physical models.

Table1. Computing the average error of hydraulic values in the numerical and experimental models

	Flow depth on the first step (cm)	Flow depth on the fifth step (cm)	Flow velocity on the first step (cm/s)	Flow velocity on the fifth step cm/s
Experimental	3.25	3.5	68.35	103.75
Numerical	3	3.4	61.7	110
Error (%)	7.7	2.8	9.7	6.02

4.2. FLOW-3D Modelling Results

The numerical model results for flow depth and velocity have been presented in the following figures:



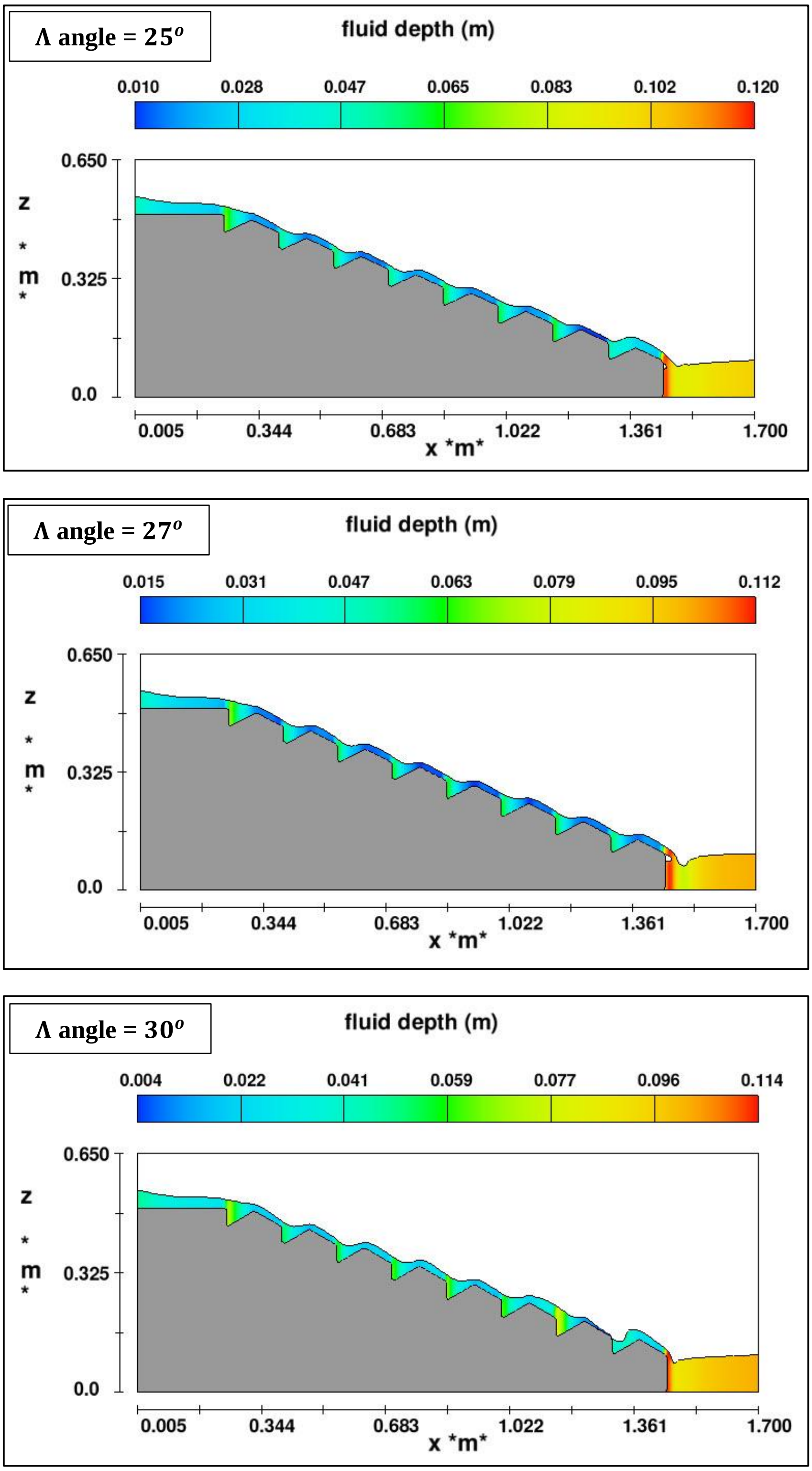
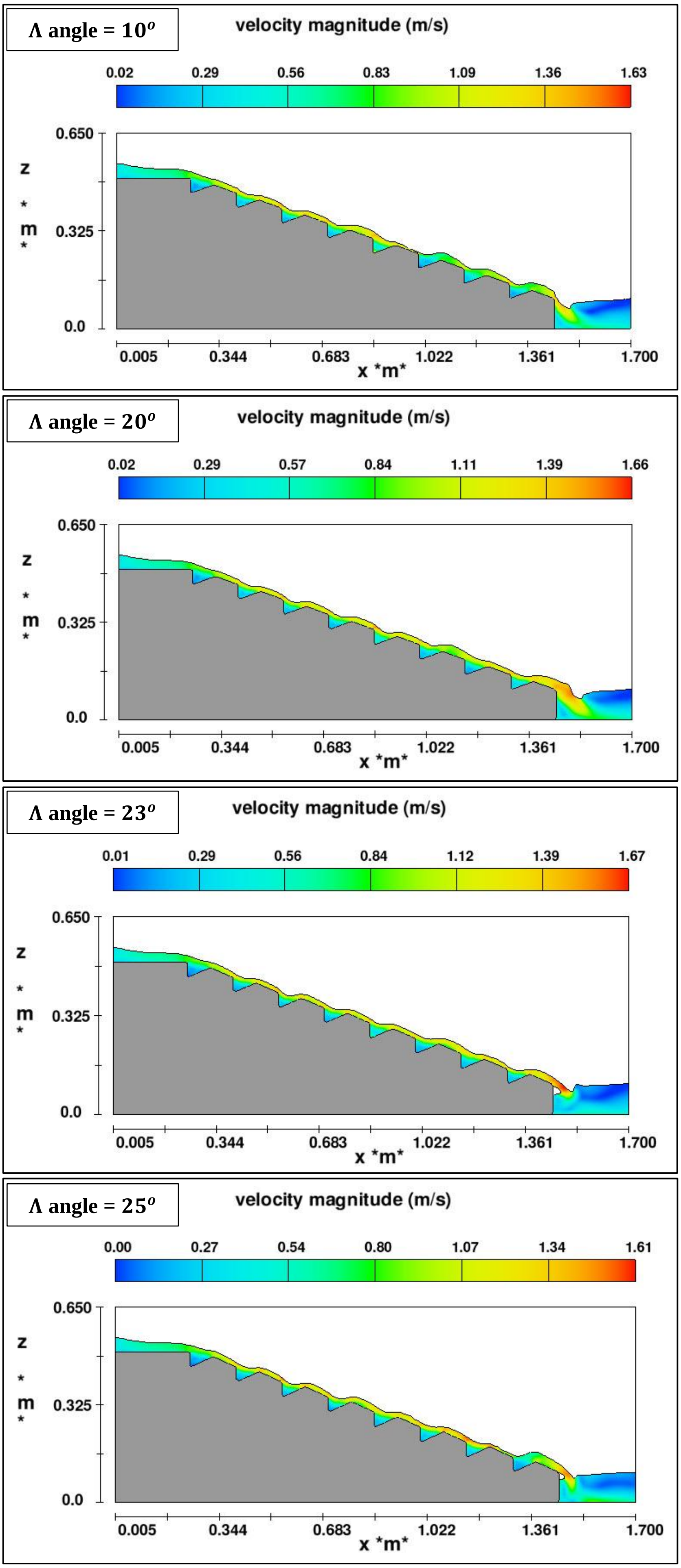


Figure 7. 2D model of flow depth for each angle of the Λ-shaped steps


Λ angle = 10°
velocity magnitude (m/s)
0.02 0.29 0.56 0.83 1.09 1.36 1.63
0.650
0.325
0.0
z *m*
0.005 0.344 0.683 1.022 1.361 1.700
x *m*
Λ angle = 20°
velocity magnitude (m/s)
0.02 0.29 0.57 0.84 1.11 1.39 1.66
0.650
0.325
0.0
z *m*
0.005 0.344 0.683 1.022 1.361 1.700
x *m*
Λ angle = 23°
velocity magnitude (m/s)
0.01 0.29 0.56 0.84 1.12 1.39 1.67
0.650
0.325
0.0
z *m*
0.005 0.344 0.683 1.022 1.361 1.700
x *m*
Λ angle = 25°
velocity magnitude (m/s)
0.00 0.27 0.54 0.80 1.07 1.34 1.61
0.650
0.325
0.0
z *m*
0.005 0.344 0.683 1.022 1.361 1.700
x *m*

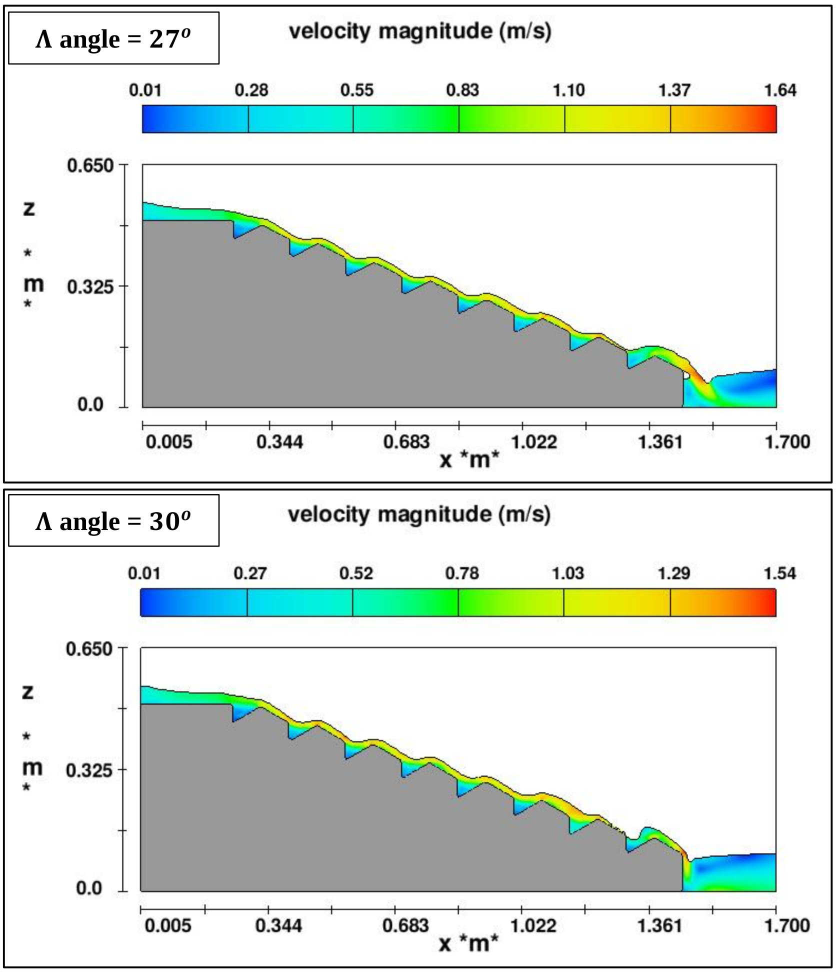


Figure 8. 2D model of flow velocity for each angle of the Λ-shaped steps

Considering Figures 7 and 8, energy dissipation has been computed as following. Firstly, conveying angle was considered equal the slope of the stepped spillway structure ($\theta = 20^o$). Along with this angel, the angles of 10 (0.5θ) and 30 (1.5θ) were modeled and investigated. Given to the obtained results presented in Table 2. and with respect to dissipation rate in the angel of 20^o, in the next stage, the angel of 25^o was targeted; however, due to dissipation reduction in this angel, to obtain the most optimal state, the angles of 23^o and 27^owere also analyzed. Therefore, the most optimal angel of the Λ-shaped steps was obtained.

To compute the experimental energy dissipation, the following relations were employed:

$$E_1 = P + H \tag{3}$$

$$E_2 = d + \frac{v^2}{2g} \tag{4}$$

$$\Delta E = \frac{E_1 - E_2}{E_1} \tag{5}$$

Where E_1 indicates energy extent at the upstream of spillway; P indicates the spillway height; E_2 indicates the energy at the spillway toe; d_m is the average of flow depth at the toe; v indicates velocity at the toe; H indicates water Nappe thickness over the spillway crest, and ΔE denotes energy dissipation rate [1].

With respect to the mentioned relations, the results obtained from energy dissipation computation can be presented as the following:

Table 2. The results obtained from energy dissipation computation

No.	Type	E_1	$H\ (cm)$	E_2	$d_m\ (cm)$	$v\ (cm/s)$	$\Delta E = \frac{E_1 - E_2}{E_1}$
1	Smooth step	43	3	9.6	6.3	80.51	0.777
2	Λ angle = 10^o	43.19	3.19	11.41	7.7	85.32	0.738
3	Λ angle = 20^o	43.07	3.07	11.86	7.9	88.2	0.725
4	Λ angle = 23^o	43.18	3.18	11.88	8.11	86.0	0.724
5	Λ angle = 25^o	43.3	3.3	12.33	8.2	90.0	0.715
6	Λ angle = 27^o	43.15	3.15	11.76	7.9	87.0	0.727
7	Λ angle = 30^o	43.49	3.49	11.66	8.56	78.0	0.732

As shown in Table 2, energy dissipation is increased when the step changes from smooth state to conveying state. Such that, when the step has the angel of 10^o, energy dissipation rate is increased as much 5.01% compared to smooth state. Energy dissipation rate for the angles of 20^o and 30^o, was obtained 6.7% and 5.8%, respectively. With respect to energy dissipation rate in the angel of 20^o, modeling was contributed with the angel of 25^o and then, $23^o$and 27^o. According to Table 2. and Figure 9, with respect to energy dissipation rate or the percentage of energy dissipation change relative to smooth step state (Figure 10), the step with the Λ angle of 25^o was obtained as the most optimal state.

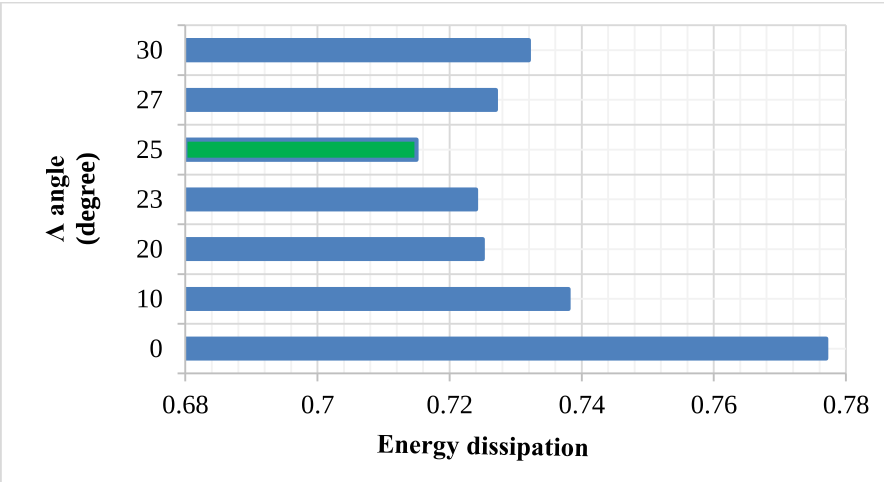


Figure 9. Energy dissipation with respect to *Λ* angel of the step in the studied stepped spillway

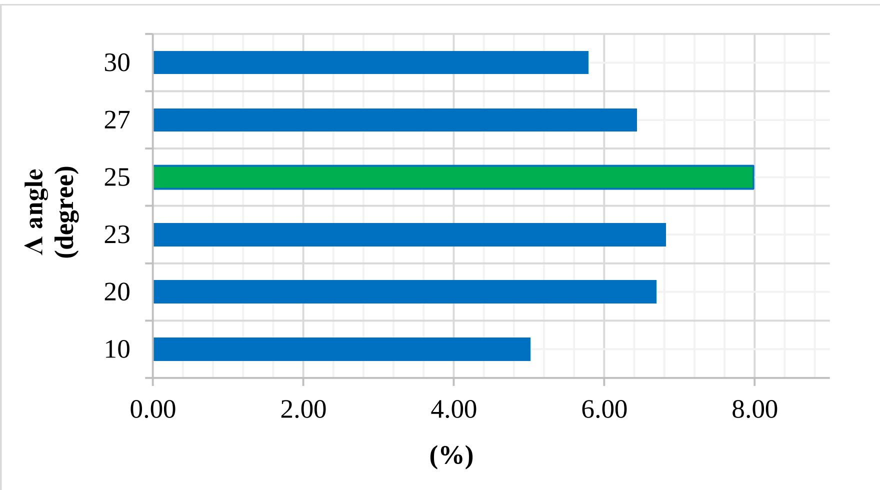


Figure 10. Energy dissipation with respect to the smooth floor of the step in the studied stepped spillway

5. Conclusion

Passing flow through large dams' spillway during flood is one of the most dangerous issues. To cope with such a problem, various solutions such as stilling basins have been presented. The most appropriate solution is to scatter flow energy during passing through the spillway slope. In this regard, concrete stepped spillways have been known as an effective strategy. Many studies have been conducted to investigate static and dynamic pressure distribution in the step surface in the stepped spillways based on numerical and analytical relations. Also, some relation have been proposed in this line. The importance of this issue can be sought in safe structural design and decreasing negative effects of flow on the spillway structure in direction of instant forces imposed on the step floors in the stepped spillways. In this study, it was attempted to determine exact error of 3D flow filed simulation for stepped spillways by creating an exact and calibrated numerical model based on the experimental studies. It was also attempted to investigate the most important hydraulic parameters through geometrical changes in the spillway model and present the most optimal geometry. In the following, the most important findings of the research are summarized:

- The maximum simulation error values for the flow velocity in the numerical model are 9.7% and 6.02% for the first step and the fifth step, respectively. Flow velocity profile in the longitude of the spillway shows that flow velocity at the initial sections is less that the end sections of the spillway.
- The maximum simulation error values for the flow depth in the numerical model are 7.7% and 2.8% for the first step and the fifth step, respectively.
- Energy dissipation rate is increased when the step changes from smooth state to Λ-shaped steps state. Such that, when the step has the angel of 10^o, energy dissipation rate is increased as much 5.01% compared to smooth state. Energy dissipation rate for the angles of 20^o and 30^o, was obtained 6.7% and 5.8%, respectively. With respect to energy dissipation rate in the angel of 20^o, modeling was contributed with the angel of 25^o and then, $23^o$and 27^o. According to Table 2. and Figure 9, with respect to energy dissipation rate or the percentage of energy dissipation change relative to smooth step state (Figure 10.), the step with the Λ angle of 25^o was obtained as the most optimal state.

6. References

[1] Chanson, Hubert. Hydraulics of stepped chutes and spillways. CRC Press, 2002.

[2] Cassidy, John J. "Irrotational flow over spillways of finite height." Journal of the Engineering Mechanics Division 91, no. 6 (1965): 155-176.

[3] Sorensen, Robert M. "Stepped spillway hydraulic model investigation." Journal of Hydraulic Engineering 111, no. 12 (1985): 1461-1472.

[4] Pegram, Geoffrey GS, Andrew K. Officer, and Samuel R. Mottram. "Hydraulics of skimming flow on modeled stepped spillways." Journal of hydraulic engineering 125, no. 5 (1999): 500-510.

[5] Tabbara, Mazen, Jean Chatila, and Rita Awwad. "Computational simulation of flow over stepped spillways." Computers & structures 83, no. 27 (2005): 2215-2224.

[6] Pedram, A and Mansoori, A. "Study on the end sill stepped spillway energy dissipation", Seventh Iranian Hydraulic Conference, Power and Water University of Technology, Tehran, Iran, (2008) (In Persian).

[7] Naderi Rad, A et al. "Energy dissipation in various types of stepped spillways including simple, sills, and sloped ones using FLUENT numerical model", journal of civil and environmental engineering 39, no 1 (2009) (In Persian).

[8] Stephenson, D. "Energy dissipation down stepped spillways." International water power & dam construction 43, no. 9 (1991): 27-30.

[9] Soori, S and Mansoori, A. "compared energy dissipation in Nappe flow and Skimming flow regime using FLOW-3D", International Conference on Civil, Architecture and Urban Development, Islamic Azad University, Tabriz, Iran, (2013) (In Persian).

[10] Pfister, Michael, Willi H. Hager, and Hans-Erwin Minor. "Bottom aeration of stepped spillways." Journal of Hydraulic Engineering 132, no. 8 (2006): 850-853.

[11] Pfister, Michael, and Willi H. Hager. "Self-entrainment of air on stepped spillways." International Journal of Multiphase Flow 37, no. 2 (2011): 99-107.

[12] Hamedi, Amirmasoud, Mohammad Hajigholizadeh, and Abbas Mansoori. "Flow Simulation and Energy Loss Estimation in the Nappe Flow Regime of Stepped Spillways with Inclined Steps and End Sill: A Numerical Approach." Civil Engineering Journal 2, no. 9 (2016): 426-437.

[13] Sedaghatnejad, S. "Investigation of energy dissipation in the end sill stepped spillways", Master thesis, Sharif University of Technology, (2009)..