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An Investigation of Flow Energy Dissipation in Simple Stepped Spillways by Numerical Model

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Abstract

Stepped spillways is a hydraulic and cost effective measure to dissipate energy of large water flows over the spillway of a dam and like other spillway types have its limitations and a measure to improve the energy dissipation effectiveness is proposed. The aim of this research is to evaluate energy dissipation in simple stepped spillways by taking into accounts some parameters by numerical method. In this study the governing equations are solved by finite volume discretization method and the standard $k-\varepsilon$ model is used for estimating the turbulence flow. Also, structured grid is used to accommodate the well-defined boundaries and the volume of fluid method is introduced to solve the complex free-surface problem. Results of the numerical method compared well with the experimental results of the other researchers.

Keywords: Simple Stepped Spillway, Volume of Fluid, Standard $k-\varepsilon$ Model, Energy Dissipation

1. Introduction

Flood that need to be accommodated by the spillway of a dam require energy dissipation measures. The first stepped spillway used in a dam made in ancient Greece about 1000 B.C. A stepped spillway is an energy dissipator having profile made up of steps and can be used in different types of dam such as Roller compacted concrete. During the recent decades the advent of modern technology and roller compacted concrete have brought the usage of stepped spillways to attention. That is because stepped spillway construction is compatible with the RCC technique (chanson and Gonzalez, 2005).

It is known that flow in a stepped channel could be in either a jet (nape) flow or skimming flow (Rajaratnam, 1990). In a stepped spillway, jet flow would occur at relatively smaller discharges and skimming flow occurs at larger discharges. Stepped spillways allow continuously dissipating a considerable amount of the flow kinetic energy, such that the downstream stilling basin, where the residual energy is dissipated by hydraulic jump, can be largely reduced in dimensions (Barani et al., 2005). Tabbora et al. (2005) conducted studies on stepped spillway by using finite element analysis. They applied k-ε model to account for turbulence. Chatial and Tabbara (2004) studied ogee spillways numerically. They used finite element method and k-ε model for this purpose. Tabbara et al. (2005)

took velocity boundary condition to study energy dissipation over stepped spillway and ogee spillway for initial boundary condition and they applied a flow profile assuming that the profile reduced the solution time. To achieve their studies, they used ADINA software which used finite element to solve the problems. Salmasi (2010) used ANN in investigation of flows on stepped chutes and his results indicated that the ANNs are powerful tools for modeling of Hydraulic characteristics of flow over stepped spillway with skimming regime.

The aim of this research is to evaluate energy dissipation in stepped spillways by taking into accounts parameters such as; number of steps (N), step height (S), horizontal step length (L), characteristic height of step (m), flow discharge per unit width (q) and overall slope of stepped spillway (α) by numerical method. In this research the governing equations are solved by finite volume discretization method and the standard $k-\varepsilon$ model is used for estimating the turbulence flow. In this research the structured grid is used to accommodate the well-defined boundaries and the volume of fluid (VOF) method is introduced to solve the complex free-surface problem.

2. Material and Methods

2.1. Governing Equations

The governing equations of incompressible, viscous fluid are a continuity equation and three momentum equations in three directions; these equations are known as Navior- stokes Equations. In fact, these equations express conservation of mass and momentum from mathematical points of view.

Based on Eulearan points of view, if a particle of a fluid is considered as a fixed volume in computational space, the exerted forces on this particle and the principle of conservation of mass are expressed with partial differential equations.

In this paper the authors presents a new configuration, simple stepped spillway, and numerically simulate this new configuration with using a finite volume code with the $k-\varepsilon$ closure to model the turbulence unsteady flow. The volume of fluid (VOF) method is an interface capturing scheme that has been used to model the free surface flow (Nikseresht et. al., 2008).

The momentum equation for the j direction of the turbulence flow is:

$$\frac{\partial}{\partial t}(\rho u_j)+\frac{\partial}{\partial x_i}(\rho u_i u_j)=-\frac{\partial P}{\partial x_j}+\frac{\partial}{\partial x_i}\left[(\mu+\mu_t)\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right]+\rho g_j+F_j \tag{1}$$

Where ρ is the density, P is the pressure, μ is the molecular viscosity, μ_t is the eddy viscosity which is determined by $k-\varepsilon$ closure model and F is any external forces.

Let $\vec{U}$ be the velocity vector field, then the incompressible continuity equation is:

$$\nabla \cdot \vec{U} = 0.0 \tag{2}$$

Note that the dynamic condition, i.e., continuity of pressure at the interface is automatically implemented. The kinematic condition, which states that the interface is convicted with the fluid, can be expressed in terms of volume fraction C as follows (Nikseresht et al., 2008):

$$\partial_t C+\vec{U}\cdot\nabla C=0 \tag{3}$$

In the VOF method, the interface is described implicitly (Nikseresht et al., 2008), the data structure that represents the interface is the fraction of C, each cell that is filled with a reference phase, named phase 1. The scalar field of C is often referred to as the color function. The magnitude of C in the cells cut by the free surface is between 0 and 1 (0<C<1) and away from it is either zero or one.

μ and ρ at any cell (denoted by ij) can be computed using a simple volume average over the cell:

$$\rho_{ij}=C_{ij}\rho_L+(1-C_{ij})\rho_a \tag{4}$$

$$\mu_{ij} = C_{ij}\mu_L + (1-C_{ij})\mu_a \tag{5}$$

Where the subscripts L and a denote Liquid and air respectively.

The main parameters influence on energy dissipation in stepped spillways are the number of steps (N), steps height (S), length of steps (L), width of steps (b), initial flow energy of upstream (E1), discharge per unit width (q), and the increment of steps height due to steps, inclination or end sills. Therefore, we have eq. 1:

$$E_L = E_L(E_1, q, l, s, g, m) \tag{6}$$

By dimensional analysis we then have:

$$\frac{E_L}{E_1} = \frac{E_L}{E_1}\left(\frac{y_c}{s}, \frac{s}{l}, \frac{m}{s}, N\right) \tag{7}$$

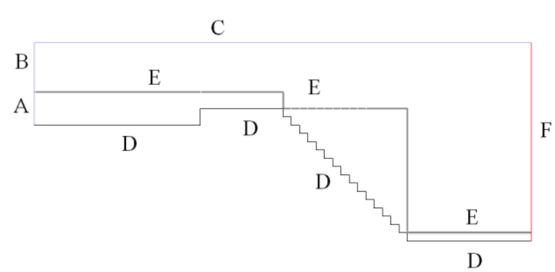
Which is none dimensional.

2.2. Mesh Generation, Boundary Conditions and Discrimination of Equations

To generate meshes for the models m structured meshes were used, the size of meshes was chosen 5 mm after several trial and Errors. The main reason for choosing this size was keeping y^+ in the range 30< y^+ <300 in boundary layers of walls. A commercially available computational fluid dynamics (CFD) program, which solves the flow filed, is used. The program basically uses finite volume method to accomplish numerical study of flow over stepped spillway. The power law method was applied to discretize the parameters.

Finally, the so-called SIMPLE algorithm was used to couple the velocity and pressure. Flow field calculation continues so that the residuals are less than 10-6. In this research, unsteady Flow was initially modeled and calculations go on to reach steady state condition. Boundary conditions that were used were depicted in Fig. (1). In this figure A is Velocity inlet boundary condition, B and C are air inlets boundary condition in terms of zero pressure, D is wall boundary condition, F is outlet boundary condition in terms of zero relative pressure, and E is the initial free surface condition. In the considered models, the length of reservoir and downstream are 1m, the height of reservoir is 10 cm and total height of A and B is 50 cm.

Figure 1: Boundary conditions and numerical model of a stepped spillway



2.3. Model Calibration

First, a classical test which is the flow over a step is solved. The geometry, dimensions, flow field and the reattachment length of the circulation zone downstream of the step is depicted in Fig. (2). To check the accuracy of this numerical analysis, the numerical velocity at x position of.05 meter from the step, versus y (depth of the flow) are compared with the laboratory data in Fig. (3), and shows a good agreement. In table (1) the numerical reattachment length (X_r) is compared with laboratory reattachment length (Ruck and Makiola, 1998). Fig. (4) depicts the stream lines of flow field downstream of the step.

Figure 2: Flow over a step and eddies that appear down stream of step

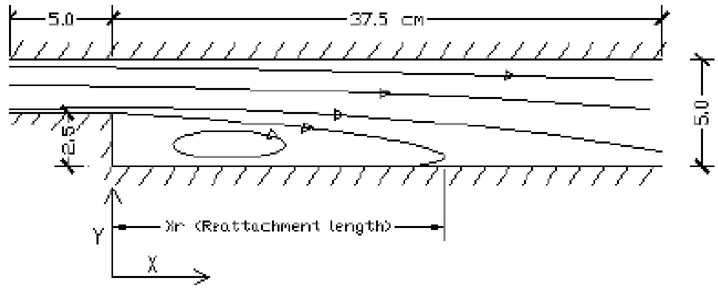


Table 1: Results of X_r for laboratory and numerical tests

Method	X_r (reattachment length)
Numerical	20.1
Laboratory	21.5
Percentage of Error	6.97

Figure 3: Changes of velocity along depth (y) in standard *k-ε* model

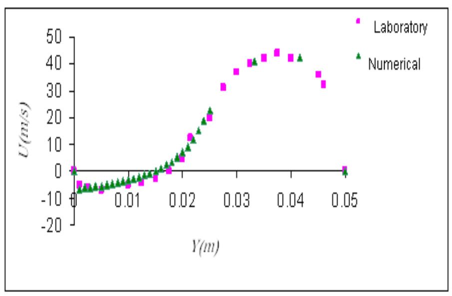
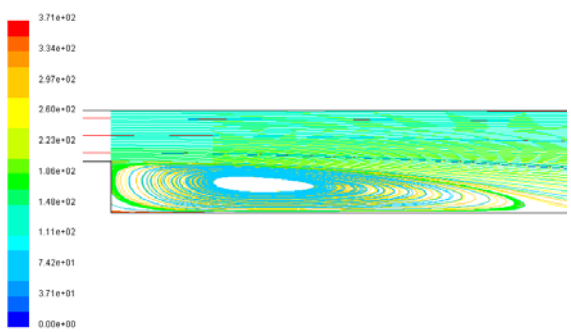


Figure 4: Streamline of flow over step



For Showing the robustness and versatility of the used code, stepped spillways similar to the laboratory model of Salmasi (2003) with discharge flow of 0.025 to 1.366 m3/(sec. m) was solved. In this setting the number of steps is 5 and 10 and the height and length of steps are equal to 0.1722 (m) and .085 (m) with a chute slope of 45 degree. The energy dissipation in both laboratory and numerical methods were compared in the table (2). The percentage of error between these two methods is 5.8% to 0.1% which shows a good agreement. Fig. (5) Shows velocity vector field in the domain. In fig. (6) The vortices which dissipate the energy in each step are shown in one step typically.

Table 2: Results of laboratory and numerical simulation for calculating $\frac{E_L}{E_1}$

Number of steps	q m^3/(sec. m)	yc(m)	Numerical $\frac{E_L}{E_1}$	Laboratory $\frac{E_L}{E_1}$	Percentage of Error
5	0.025	0.040	0.944	0.906	4.3
	0.039	0.053	0.926	0.882	5
	0.056	0.069	0.892	0.895	0.3
	0.068	0.078	0.867	0.874	0.8
	0.083	0.089	0.820	0.819	0.1
10	0.467	0.038	0.900	0.946	5.16
	0.742	0.040	0.934	0.944	1.1
	0.972	0.052	0.894	0.927	3.7
	1.177	0.050	0.879	0.930	5.8
	1.366	0.065	0.878	0.907	3.3

Figure 5: Velocity vector of flow over stepped spillway

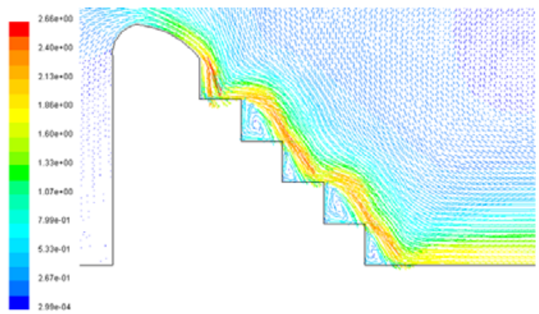
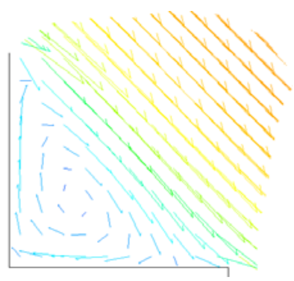


Figure 6: Velocity vector of flow in one step



3. Results and Discussions

In this research five series of stepped spillways were studied, each of them was examined for three different discharges per unit width, 0.019, 0.0537 and 0.0937 m3/ (sec.m). Designed height of the spillways (Hd) were 0.05, 0.1, 0.15 m, critical depth (y_c) were 0.0334, 0.0667, and 0.1 m. Table (3) includes the geometric charactistics, flow type, and the energy dissipation in simple stepped spillway. In all these groups, the height of dam (Hdam) was 0.8m, and length of steps was 0.05 m. In Group 4 and 5, the length of steps was changed. In these recent groups S, N, Hdam were 0.1, 8, and 0.8 respectively. In group 4 L was 0.075m and in group. L was 0.1m.

Table 3: Geometric characteristics, flow type, and energy dissipation of simple stepped spillway with numerical modeling solution.

Group	$H_d\,(m)$	$q\,(\frac{m^3}{s.m})$	$y_c\,(m)$	$S(m)$	$L(m)$	H_{dam}	N	Type Flow	$\frac{E_L}{E_1}\%$	α (degree)
1	0.05	0.019	0.0334	0.1	0.05	0.8	8	NA	78.79	63.34
	0.1	0.537	0.0667	0.1	0.05	0.8	8	TR	65.22	63.34
	0.15	0.0987	0.1	0.1	0.05	0.8	8	SK	60.56	63.34
2	0.05	0.019	0.0334	0.05	0.05	0.8	16	SK	83.96	45
	0.1	0.537	0.0667	0.05	0.05	0.8	16	SK	74.97	45
	0.15	0.0987	0.1	0.05	0.05	0.8	16	SK	66.94	45
3	0.05	0.019	0.0334	0.025	0.05	0.8	32	SK	86.87	26.56
	0.1	0.537	0.0667	0.025	0.05	0.8	32	SK	78.97	26.56
	0.15	0.0987	0.1	0.025	0.05	0.8	32	SK	69.52	26.56
4	0.05	0.019	0.0334	0.1	0.075	0.8	8	NA	78.57	53.13
	0.1	0.537	0.0667	0.1	0.075	0.8	8	TR	66.28	53.13
	0.15	0.0987	0.1	0.1	0.075	0.8	8	SK	59.47	53.13
5	0.05	0.019	0.0334	0.1	0.1	0.8	8	NA	77.81	45
	0.1	0.537	0.0667	0.1	0.1	0.8	8	TR	66.42	45
	0.15	0.0987	0.1	0.1	0.1	0.8	8	SK	58.96	45

For with q equaled to 0.014, 0.0537, 0.0987 m3/ (sec.m) the designed height of spillway was 0.05, 0.1, 0.15m and critical depth was 0.0334, 0.0667, 0.1m. In group 6, 7 and 8, the height increment of steps were 0.01, 0.02, 0.03m. Figures (7) to (10) show the flow profile over stepped spillways in the numerical models. In Figures (11) and (12) the profile of velocity in models were presented. According to these figures, different types of flow in different stepped spillways may create.

Figure 7: Profile of flow, transition flow, in simple stepped spillway group 5, Hd=0.1^{m}

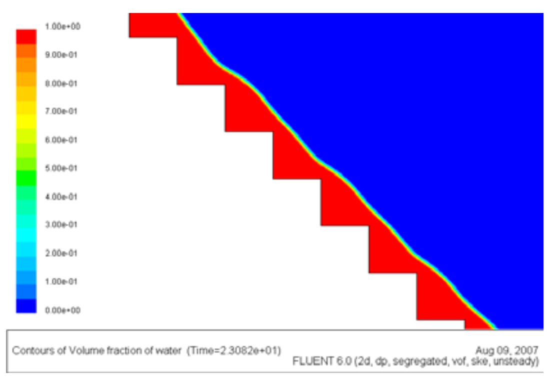


Figure 8: Profile of flow, skimming flow, in simple stepped spillway group 5, Hd=0.15m

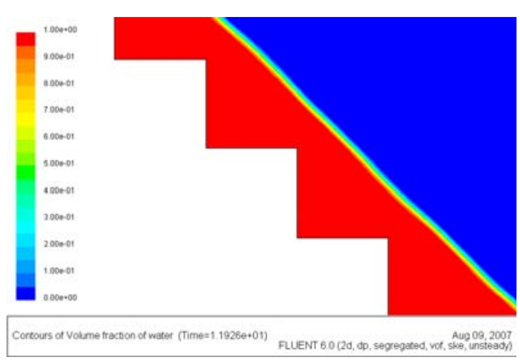


Figure 9: Profile of flow, transition flow, in simple stepped spillway group 5, Hd=0.05m

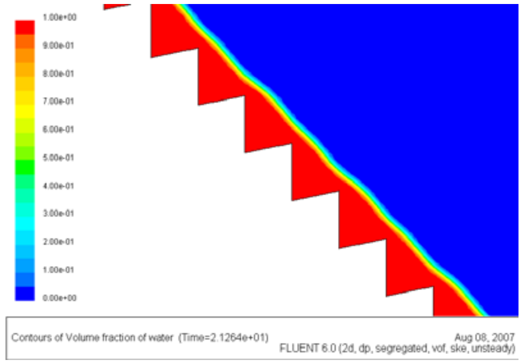


Figure 10: Profile of flow, nappe flow, in simple stepped spillway group 5, Hd=0.05^{m}

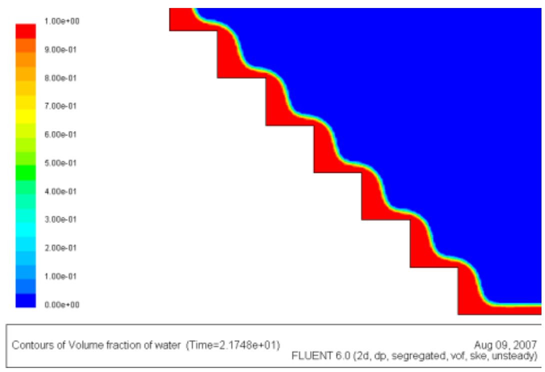


Figure 11: Velocity vectors in nappe flow over simple stepped spillway, groups 5

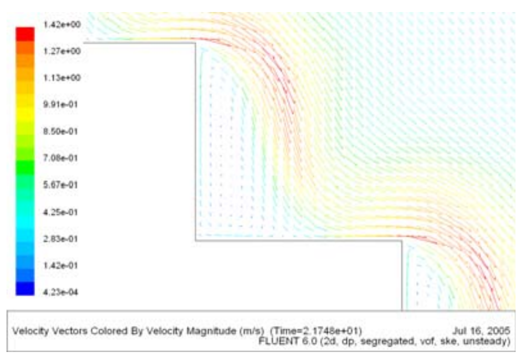
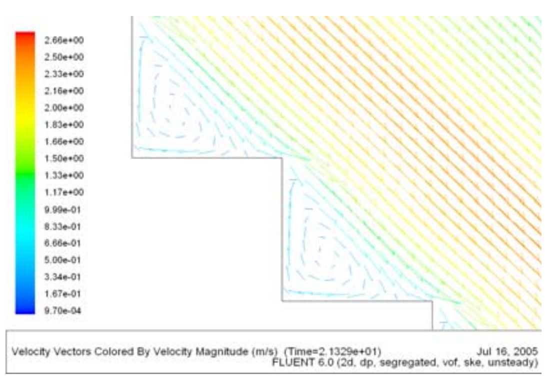


Figure 12: Velocity vectors in skimming flow over simple stepped spillways group 2



The results of numerical analysis of flow over simple stepped spillway were depicted in Figures (13), (14) and (15). In figure (13), the variations of steps height was presented. It is obvious that the more the height of steps decrease the more Energy will dissipate over spillway. According to Figure (14) when the number of steps increases, more energy will dissipate along the spillway. Figure (15) shows that the decrease of slope in spillway causes more energy to dissipate.

Figure 13: Variation of steps height in simple stepped spillways

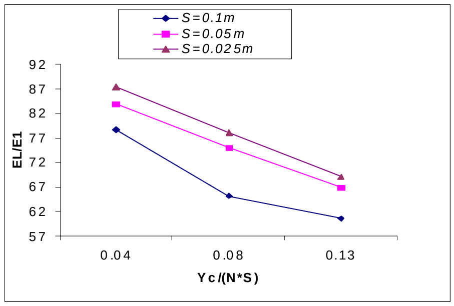


Figure 14: Variation of Number of steps in simple stepped spillways

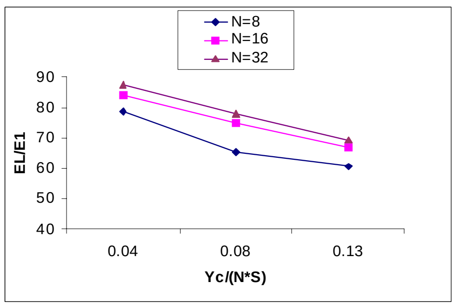
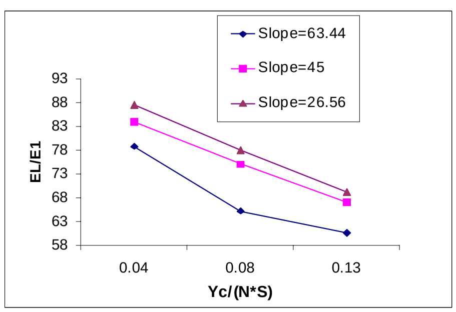


Figure 15: Slope variation in simple stepped spillways



In table (4), the result of numerical-analysis of flow is compared with results obtained from Experiment equations proposed by Rajaratnam (1990), chanson (1994), and Christodoulou, (1993). The results are in terms of the amount of energy dissipated. For calculating the error between the results the following relationship was used (Eq. 8):

$$Error = \frac{\left| \left(\frac{E_L}{E_1}\right)_{Experimental} - \left(\frac{E_L}{E_1}\right)_{Numerical} \right|}{\left(\frac{E_L}{E_1}\right)_{Experimental}} \quad (8)$$

Table 4: Comparison of numerical results with those from Rajaratnam (1990), chanson (1994) and Christodoulou (1993) for simple stepped spillway with skimming for group 3

$q(\frac{m^3}{s.m})$	$H_d(m)$	$\frac{E_L}{E_1}\%$ **Numerical Method**	$\frac{E_L}{E_1}\%$ **Ranjaratnam**	**Error%**	$\frac{E_L}{E_1}\%$ **Chanson**	**Error%**	$\frac{E_L}{E_1}\%$ **Christodoulou**	**Error%**
0.019	0.05	86.87	92	5.5	93.44	7.03	93.42	7.01
0.537	0.1	78.97	84.9	8.16	87.72	11.11	76.17	2.36
0.0987	0.15	69.52	78.5	11.43	81.34	14.53	54.21	28.2

In table (5) the comparisons of numerical results with those from experimental equations of chanson (1994), chamani and Ranjaratnam (1994) is presented.

These results were obtained for numerical group 4 and 5. In these numerical models, nappe flow was mainly studied and errors were about 1-9 percent.

Table 5: Comparison of numerical results with those from Chanson (1994) for simple stepped spillway with nappe and skimming flow for group 4 and 5

$H_d = 0.05(m)$ $q = 0.019(\frac{m^3}{s.m})$	$\frac{E_L}{E_1}\%$ **(Numerical Method)**	$\frac{E_L}{E_1}\%$ **(Chanson)**	**Error%**
Group4 (nappe flow)	78.35	86.2	9.1
Group4 (skimminf flow)		79.22	1.09
Group5 (nappef flow)	77.81	86.2	9.7
Group5 (skimming flow)		74.76	4.07

In tables (6), comparison of numerical results with experiment results of researchers such as chamani and Rajaratnam (1999), chanson (1994), chanson (2001) and Boes and Hager (2003) for simple stepped spillway were presented which were for group 2 and 5.In tables, TR stands for Transition, SK and NA represent for skimming and nappe, respectively.

Table 6: Comparison of numerical results with experimental income for determining flow type in simple stepped spilllway

$H_d(m)$	**Numerical Method**	**Boes and Hager (2003)**	**Chanson (1994)**	**chanson (2001)**
0.05	NA	NA	NA	NA
0.1	TR	NA	SK	TR
0.15	SK	SK	SK	SK

4. Conclusion

1. Increasing the number of steps, directly increase energy dissipation of spillway providing that the height of dam remains fixed. In simple stepped spillways, the decrease of steps height reduces the amount of energy which dissipated a long spillway if the height of dam is fixed. Decreasing the spillways slope with fixed dam height, increase energy dissipation of spillway. The increase of steps length in the case of fixed number of steps and steps height increase the amount of energy which dissipated along the stepped spillway. In other words, this is the least economical and efficient stepped spillway. Increasing discharge of flow of stepped spillway reduces its efficiency in dissipating energy and energy dissipation is independent of flow type.
2. By conducting this numerical study, we can conclude that numerical method is a robust way of determining flow field over stepped spillway and can rival experimental and laboratory study.

While experimental studies are highly affected by laboratory conditions, different numerical study conditions Can be modeled and consider each conditions effect promptly.

3. VOF, flow surface model, and the $k-\varepsilon$ turbulent model are suitable for modeling flow over stepped spillways. VOF model can be used for all flow type modeling and hence, it obviates the determine flow type. The discrepancies between numerical and experimental approaches are very close; error is within 1 to 28 percent. Therefore, numerical method is suitable for studying flow over stepped spillway.
4. Due to the employment of VOF model to determine free-surface, it takes relatively large amount of time to reach a stable flow situation over steps. The existence of eddy and turbidity on steps cause the run time to increase.

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