Energy dissipation performance of the trapezoidal stepped spillway

Erdinc Ikinciogullari*

Department of Civil Engineering, Bingol University, Bingol, 12000, Turkey.

**Corresponding Author: erdincikinciogullari@gmail.com*

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ABSTRACT

Stepped spillways are a more effective type of spillway in energy dissipation than conventional chute channels. Therefore, the dimensions of the energy breaker at the downstream of stepped spillways can be smaller. This is an alternative especially when the downstream pool cannot be built in sufficient length due to the terrain conditions. In this study, the energy dissipation performance of trapezoidal stepped spillways was investigated numerically using Flow3D software. Four different models and three different discharges were utilized for this purpose. The results showed that the trapezoidal stepped spillway is up to 30% more effective than classical stepped spillways in energy dissipation. The depth of the trapezoidal step and the bottom base length of the trapezoid significantly affected the energy dissipation rate for the trapezoidal stepped spillway.

Key words: Computational Fluid Dynamics (CFD); Energy dissipation rate; Flow3D; Step geometry; Trapezoidal stepped spillway.

INTRODUCTION

Stepped spillways are used as an alternative weir to provide more energy dissipation. According to the literature, the first example of a stepped spillway is estimated as the Akarnania stepped spillway in Greece in 1300 BC (Chanson, 2000). The construction of stepped spillways has become quite economical and practical since the progress of roller-compacted concrete (RCC) technology (Frizell and Mefford, 1991).

Stepped spillways dissipate more flow energy on the discharge channel because the flow hits the steps. For this reason, stepped spillways are more economical than conventional chute channels in terms of the cost of the downstream basin (Boes and Hager, 2003; Chanson, 1998; Frizell and Mefford, 1991; Rice and Kadavy, 1996). Besides, the cavitation risk decreases because the flow energy decreases along the stepped spillway (Chanson, 1993).

In stepped spillways, a nap flow regime occurs at low flow rates and a skimming flow regime occurs at high flow rates. It was first mentioned by Ohtsu & Yasuda (1997) that there is a transition flow regime between the nap and skimming flow regimes. The transition flow regime looks like neither the nap flow regime nor the skimming flow regime (Fig. 1). The transition regime is undesirable by designers because of the large amount of vibration (Chanson, 1996).

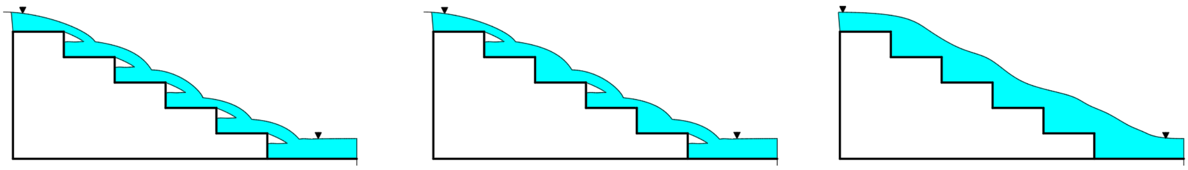


Figure 1 Flow regimes on the stepped spillway: a) nap flow regime; b) transition flow regime; c) skimming flow regime (Takahashi et al. 2001)

From the literature review, it was observed that the first period works were generally in the form of design principles (Boes and Hager, 2003; Chanson, 2001; Essery & Horner, 1971; Sorensen, 1985). Felder et al. (2012a, 2012b) experimentally studied a stepped spillway with different chute angles and different step configurations. Based on their results, researchers emphasized that one of the most important criteria for residual energy is the chute angle. Zare and Doering (2012a, 2012b) experimentally investigated the inception points on the stepped spillway with different threshold configurations. They emphasized that the use of rounded steps dissipates 3% more energy than conventional steps.

Mero and Mitchell (2017) designed five different stepped spillway models and experimentally examined the effect of the step shapes on the energy dissipation rates. The researchers designed a different step geometry by placing reflectors on the steps. As a result of the study, they concluded that the energy dissipation rates of stepped spillways with reflectors are much higher than classical stepped spillways. The energy dissipation rate decreases as the discharge increases for all models.

The use of Computational Fluid Dynamics (CFD) methods has been increasing since the development of computer technology. Many researchers have analyzed the effects of different step geometries on the energy dissipation rates numerically (Arjenaki and Sanayei, 2020; Ashoor and Riazi, 2019; Ghaderi et al., 2021, 2020; Hekmatzadeh et al., 2018; Li et al., 2020, 2018; Mohammad et al., 2016; Reeve et al., 2019; Shahheydari et al., 2015; Tabbara et al., 2005). In this study, trapezoidal stepped spillways (TSS), which have not been studied in the literature, were analyzed numerically using Flow3D software. Different configurations were designed to see the effect of TSSs on energy dissipation. The numerical results of the classical stepped spillway were validated using the laboratory results (Mero and Mitchell, 2017).

MATERIAL AND METHOD

Numerical Model

Flow3D® software is a general-purpose CFD software that can be used to solve fluid problems (Flow Science Incorporated, 2016). This software can calculate the problem using the general mass equations and the Reynolds-Averaged Navier-Stokes equations (RANS). These equations are shown in Eqs. (1) and (2).

$$\frac{\partial U_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i}\left(v\frac{\partial U_i}{\partial x_j} - \overline{u_i' u_j'}\right) + S_i \tag{2}$$

where U_i=Reynolds average velocity, x_i=location, S=source term, t=time term, ρ=density of the fluid, p=Reynolds average pressure, and υ=kinematic viscosity.

Flow3D® software utilizes the Volume of Fluid (VOF) method for modeling the free surface. The VOF method is described as Eq. (3):

$$\frac{\partial F}{\partial t} + \frac{1}{V_f} + \left(\frac{\partial}{\partial x}(FuA_x) + \frac{\partial}{\partial y}\left(FvA_y\right) + \frac{\partial}{\partial z}(FwA_z)\right) \tag{3}$$

where A=average flow field and F is the fraction function value between zero and one (0-1). When the value of F is 0, this means that the cell is empty. When F is 1, the cell is full (Flow Science Incorporated, 2016).

Geometric model

The experimental results of the classical stepped spillway designed by Mero and Mitchell (2017) were utilized to validate the numerical results. The classical stepped spillway was designed with a width of 0.296 m, a height of 0.25 m, and a base width of 0.50 m. A total of five steps were designed, with a step height of 0.05 m, a step length of 0.10 m, and an angle of the discharge channel of 26.6° (Fig. 2).

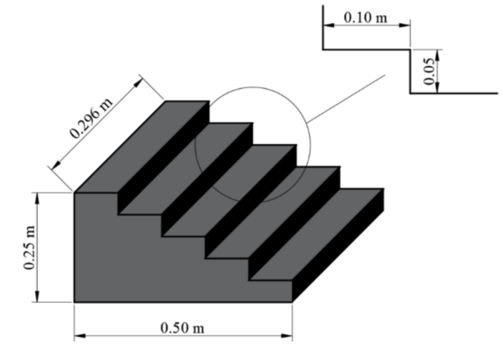


Figure 2 The model geometry designed by Mero and Mitchell (2017)

Four different TSS models were designed for the scope of the study. These models, designed with the Solidworks program, were saved as a .stl extension and transferred to Flow3D software. l_r is the depth of the trapezoidal step and l_1 is the bottom base length of the trapezoid in Fig. 3. Three different discharges (0.0121, 0.00831, and 0.00684 m^3/s) and four different trapezoidal geometries (l_r=0.01–0.03 m and l_1=0.03–0.05 m) were utilized for the numerical analyses. The flow regimes were determined according to the literature (Boes and Hager, 2003). The hydraulic characteristics of the study are summarized in Table 1.

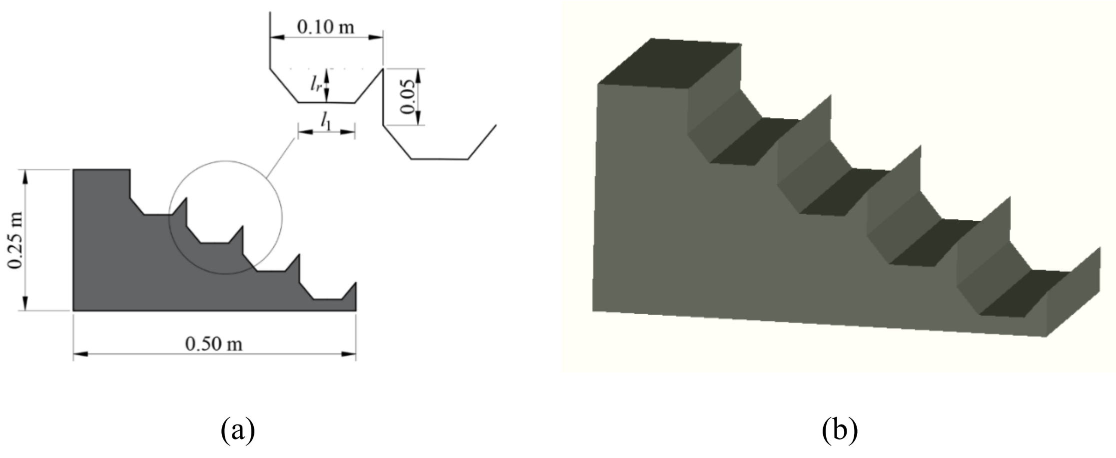


Figure 3 The design of the TSS; a) two-dimensional, b) three-dimensional

Table 1 Hydraulic characteristics

Analyze No	Model No	Q ($m^3.s^{-1}$)	Step height (h) (m)	Step length (l) (m)	l_r (m)	l_1 (m)	Flow regime
1	Model1	0.01210	0.05	0.10	0.01	0.05	Skimming
2	Model1	0.00831	0.05	0.10	0.01	0.05	Skimming
3	Model1	0.00684	0.05	0.10	0.01	0.05	Transition
4	Model2	0.01210	0.05	0.10	0.03	0.05	Skimming
5	Model2	0.00831	0.05	0.10	0.03	0.05	Skimming
6	Model2	0.00684	0.05	0.10	0.03	0.05	Transition
7	Model3	0.01210	0.05	0.10	0.01	0.03	Skimming
8	Model3	0.00831	0.05	0.10	0.01	0.03	Skimming
9	Model3	0.00684	0.05	0.10	0.01	0.03	Transition
10	Model4	0.01210	0.05	0.10	0.03	0.03	Skimming
11	Model4	0.00831	0.05	0.10	0.03	0.03	Skimming
12	Model4	0.00684	0.05	0.10	0.03	0.03	Transition

Energy dissipation rate

The energy at the upstream and downstream of the spillway was used to calculate the energy dissipation rate. In the experimental study (Mero and Mitchell, 2017), the energy was calculated using the critical flow depth. Since the channel is rectangular, it can be calculated with Eq. (4) for the critical flow depth. The energies at points (0) and (1) shown in Fig. 4 were calculated with Eqs. (5) and (6). Then, the energy difference between the two points is calculated with Eq. (7):

$$q = \frac{Q}{B} \quad \text{and} \quad y_c = \sqrt[3]{\frac{q^2}{g}} \tag{4}$$

$$E_0 = H_{dam} + y_c + \frac{V_c^{\,2}}{2g} = H_{dam} + 1{,}50 y_c \tag{5}$$

$$E_1 = y_1 + \frac{V_1^{\,2}}{2g} \tag{6}$$

$$E_L = E_0 - E_1 \tag{7}$$

where y_c=critical flow depth (m), Q=discharge (m^3/s), q=unit flow rate ($m^3/s.m$), B=channel width (m), g=gravitational acceleration (m/s^2), E_0=energy at point (0) (m); H_{dam}=spillway height (m); y_1=flow depth at the downstream of the spillway (m); V_c =critical flow velocity (m/s); V_1=flow velocity at point (1) (m/s); E_1=energy height at the downstream of the spillway (m), and E_L=energy difference between points (0) and (1) (m).

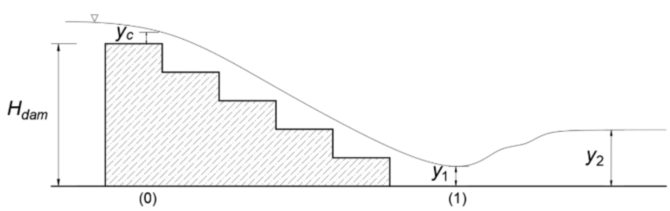
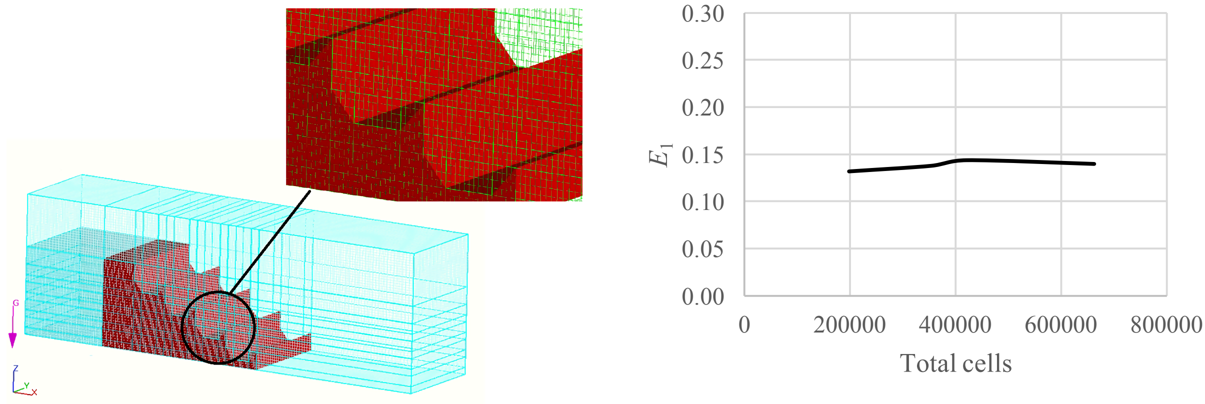


Figure 4 Longitudinal section of spillway

Mesh Domain, boundary conditions, and validation

A mesh block was used to design the domain of the trapezoidal model. Fourteen extra solution layers were placed inside this solution domain (Fig. 5a). Four different mesh domains were tried to find the correct mesh sizes. First, the total number of cells was selected as 198198. Then, the total number of cells was increased to 353925, 421008, and 662480, respectively. According to the results obtained, it was observed that after the total number of cells exceeded 400000, there was not much effect on the results (Fig. 5b). For this reason, the mesh domain with the biggest cell size of 1.27 cm, the smallest cell size of 0.50 cm, and the total cell number of 421008 was judged to be sufficient for the study (Table 2).



(a) (b)

Figure 5 a) Mesh domain structure and b) Mesh independency

Table 2 Mesh domain characteristics

Mesh domain sizes (Max.-Min.) (cm)	Total mesh number	E_1 (m)
1.00-0.80	198,198	0.132
0.94-0.67	353,925	0.138
1.27-0.50	421,008	0.144
1.30-0.35	662,480	0.140

All the boundary conditions were designed according to the experimental conditions (Mero and Mitchell, 2017). The discharge boundary condition (*Q*) was utilized at the upstream of the channel. The outflow condition (*O*) was used at the channel downstream. Furthermore, the channel bed and the walls were defined as the wall boundary condition (*W*). The upper plate of the channel was defined as the symmetry boundary condition (*S*). A flow region (0.25 m deep and 0.296 m wide) was defined at the spillway upstream (Fig. 6).

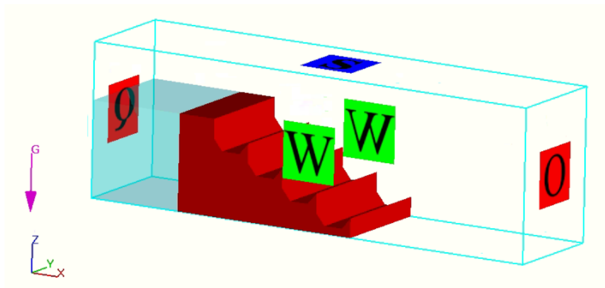


Figure 6 Boundary conditions

Validation of the numerical model

As mentioned above, the numerical results were validated with the experimental results (Mero and Mitchell, 2017). The numerical results using the RNG k-ε and Standard k-ε turbulence models are shown in Fig. 7. It was observed that both turbulence models were compatible with the experimental results (Mero and Mitchell, 2017). However, the error rates increase at maximum flow rates. Deviations in these values might result from rounding errors in numerical iterations or from readings in the test results. The standard k-ε model is more converged than RNG k-ε. Therefore, the Standard k-ε turbulence model is more suitable for this study.

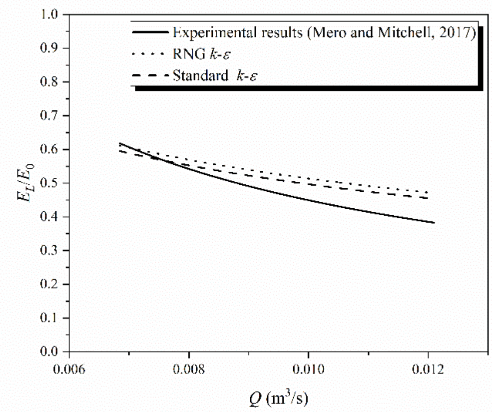


Figure 7 Convergence of the numerical results

RESULTS AND DISCUSSION

Spillways are water structures that transfer the flow from the upstream to the downstream. It is known that the flow velocity at the downstream of spillways is higher due to the kinetic energy. For this reason, designers use stepped weirs to reduce the costs of the energy breaker pool. In this study, trapezoidal shape steps have been designed as a new type of stepped spillway. The study results have been supported using velocity vectors plotted in a vertical transverse section; the velocity and pressure distribution; total hydraulic head, and energy dissipation graph. As shown in Fig. 8, the three-dimensional velocity profiles on the TSS were designed for the skimming flow regime (Q=0.0121 m^3/s). The TSSs had lower velocities than the classical stepped spillway. Besides, as the l_r increases, the flow velocity at the downstream of the spillway decreases. Besides, it was observed that the TSSs dissipate more flow turbulence. Also, the fluctuations in the flow surface of the trapezoidal spillways are not observed in classical stepped spillways. It is thought that more air enters the flow due to the step geometry of the TSS. The same situation has been encountered in the literature (Arjenaki et al., 2020; Felder et al., 2012b; Ghaderi et al., 2020) for different step geometries.

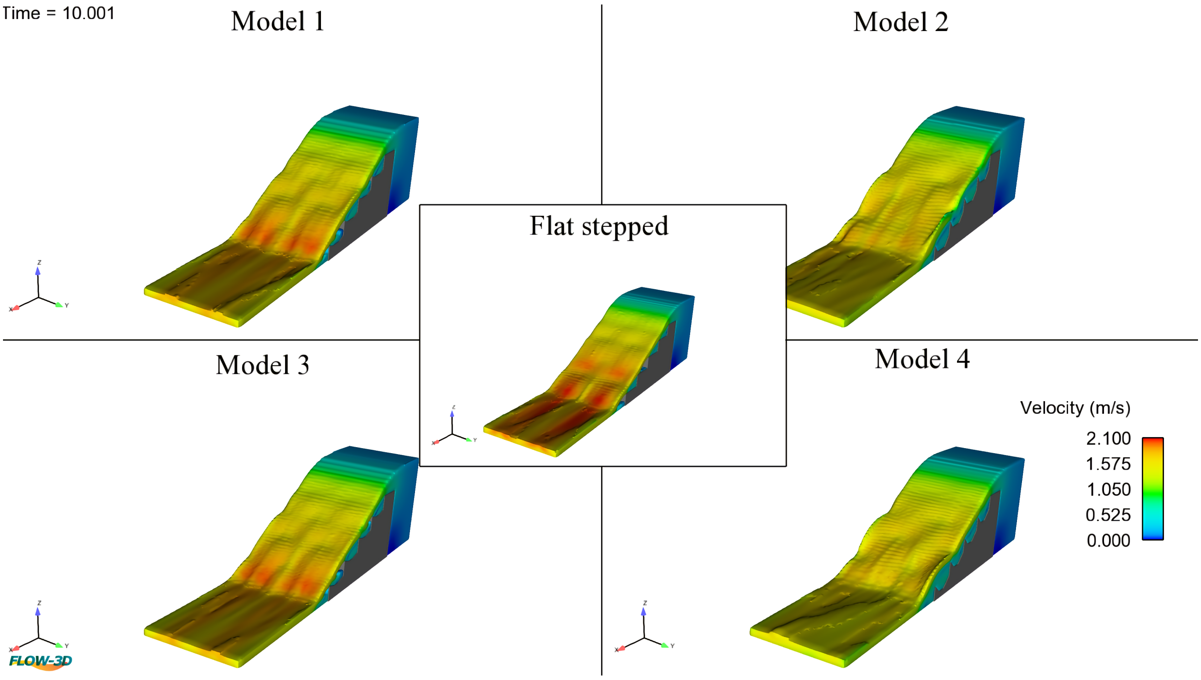


Figure 8 Three-dimensional velocity profiles for skimming flow regime

Figure 9 shows a comparison of the velocity contours at the TSSs. The highest velocity magnitude was recorded in the overlying flow above the step edge and the smallest velocity value was towards the bottom. For all models, the flow was confined in the recirculation zones under the pseudo bottom. On the other hand, the trapezoidal models' steps have a greater amount of vortex flow.

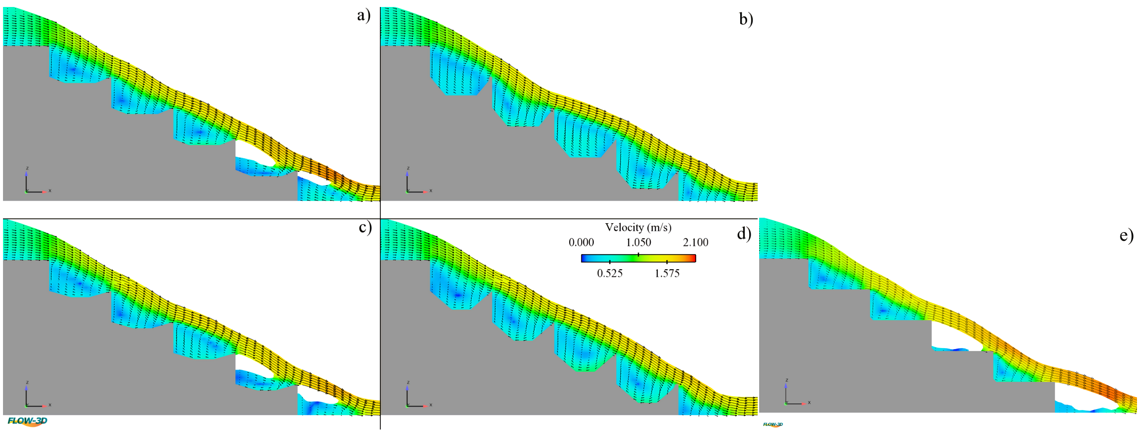


Figure 9 Velocity vectors of models: a) Model 1, b) Model 2, c) Model 3,

d) Model 4, and e) Classical stepped

For all models, the pressure variations are shown in Fig. 10. At the start of the steps, a low-pressure value was noticed. On the other hand, the highest pressure value was found near the conclusion of the TSSs' steps. At the different stages of the models, there was never a negative pressure value. As a result, it can be stated that the TSSs do not exhibit cavitation phenomena.

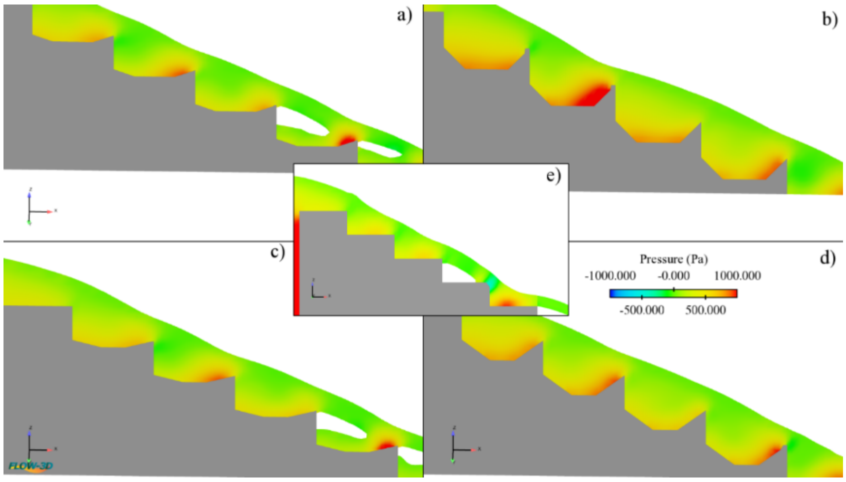


Figure 10 Pressure contours of models: a) Model 1, b) Model 2, c) Model 3, d) Model 4, and e) Classical stepped

Figure 11 shows the three-dimensional simulation output of the total hydraulic head for all models (for Q=0.0121 m^3/s). The total energy downstream of the classical stepped spillway is more than those of the TSSs. To compare the energy head of the TSSs, the total hydraulic head on the transverse section of the models is shown in Fig. 12. Hence, it was observed that the total energy head downstream of the spillways decreased with increasing l_r and l_1.

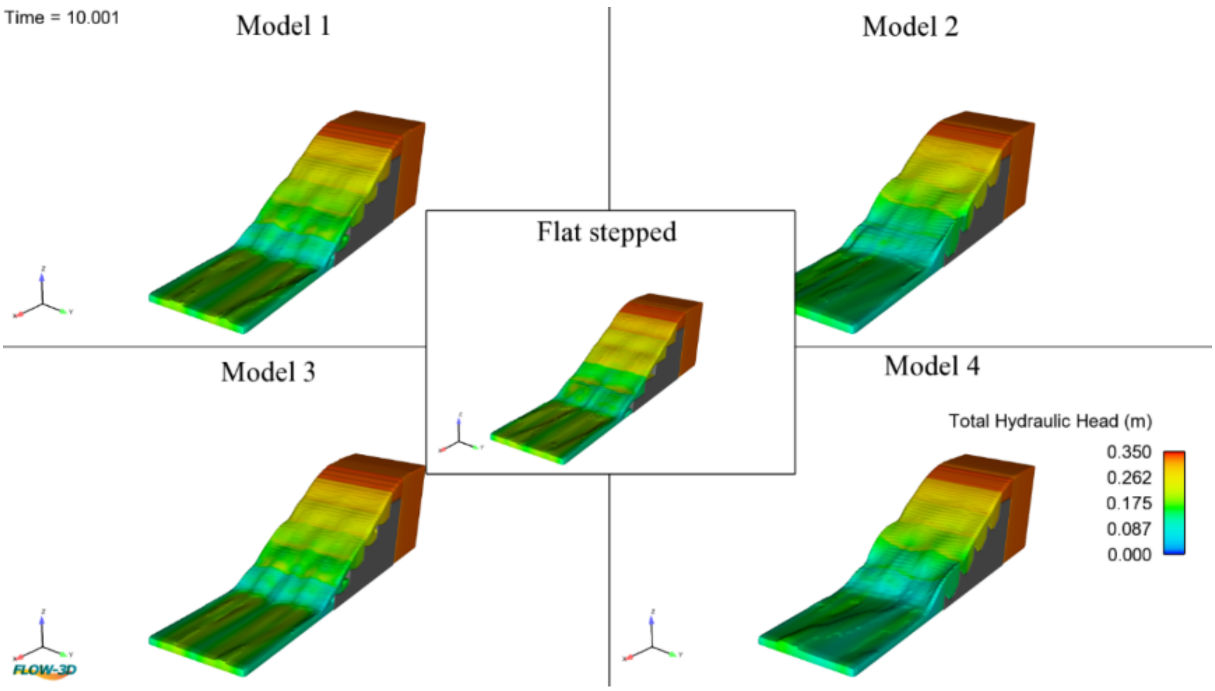


Figure 11 Three-dimensional total hydraulic head of the models

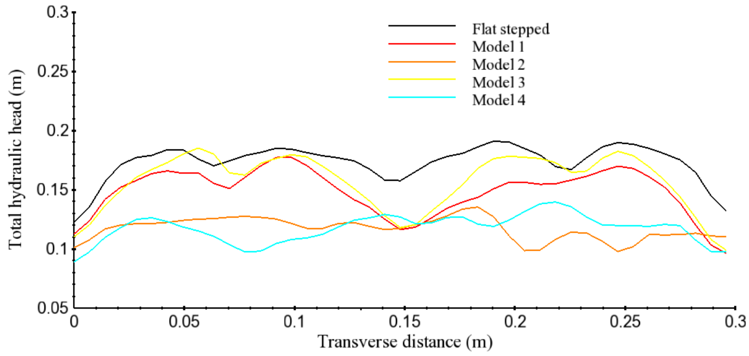


Figure 12. The total hydraulic head of the models on the transverse section

The energy dissipation rates of all the models used in this study are illustrated in Fig. 13 as a function of the dimensionless critical flow depth (y_c/h). According to the results, the TSSs are generally more efficient than the classical stepped spillway for energy dissipation. In the models designed as l_r=0.01 m, the energy dissipation rate of the TSSs is lower than those of the flat stepped spillway for the transition flow regime. However, in the models designed as l_r=0.03 m, the energy dissipation rate of the TSS is higher than that of the classical stepped spillway for the transition flow regime. Model 2, designed with l_r=0.03 m and l_1=0.05 m, was the most effective energy dissipator and this model dissipates up to 30% more energy than the flat stepped spillway. Then, Model 4 was the second best for the energy dissipation rate. According to the results, l_r and l_1 affected the energy dissipation rate for the TSS. As the l_r and l_1 increased, the energy dissipation rate increased for both flow regimes. However, it was observed that the l_r was more effective than the l_1 for the energy dissipation rate.

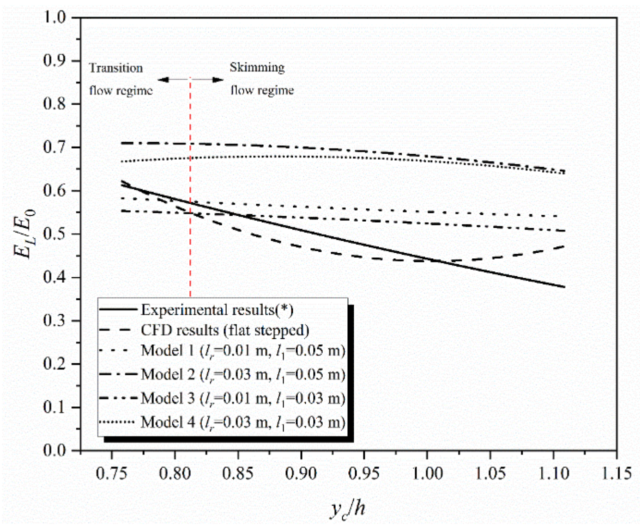


Figure 13 Comparison of the energy dissipation rate of the used models

(*) Mero and Mitchell, 2017

CONCLUSION

The energy dissipation performance of trapezoidal stepped spillways (TSS) was investigated numerically using Flow3D software. A total of 12 analyses were conducted for four trapezoidal models and three discharges. The laboratory results conducted by Mero and Mitchell (2017) were used to validate the numerical results on the classical stepped spillway. The results of the study are stated below:

- As the discharge increased, the energy dissipation rate decreased. This situation is in good agreement with the literature.
- The depth of the trapezoidal step (l_r) and the bottom base length of the trapezoid (l_1) affected the energy dissipation performance of the TSS. The energy dissipation rate increased as l_r and l_1 increased. However, l_r was more efficient than l_1.
- There was no cavitation phenomenon for the TSS due to the high pressure value on the steps.
- Recirculation regions occurred under the pseudo bottom for all models, but there is vortex flow on the steps of the trapezoidal models.
- The TSS was up to 30% more efficient than the classical stepped spillway for energy dissipation.
- The amount of concrete needed for TSSs is less than for the classical stepped spillways. However, the cost of the labor for TSSs is higher than for classical stepped spillways and the construction of these steps is difficult and time-consuming.
- However, these structures might be used for downstream area restricted terrain conditions or in chute channels constructed in touristic areas for a stylish design.

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