Journal of the Brazilian Society of Mechanical Sciences and Engineering (2024) 46:415
https://doi.org/10.1007/s40430-024-05004-8

TECHNICAL PAPER

Three-dimensional analysis of the performance of circular stepped spillways in the skimming flow regime

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Received: 11 September 2023 / Accepted: 22 May 2024 / Published online: 1 June 2024

Abstract

By creating an artificial rough bed, stepped spillways increase energy dissipation during the spillway and reduce the risk of cavitation and the dimensions of the stilling basin. Combining stepped spillways with labyrinth spillways in order to improve their performance can be an attractive idea. Therefore, in this research, the hydraulic characteristics of the flow, the amount of energy dissipation and the residual energy of the flow downstream of the stepped spillway with a circular labyrinth configuration, with different numbers of cycles, were compared with the conventional stepped spillway. Validation of the numerical model was done using the results of the physical model. Four three-dimensional configurations of stepped spillway including: conventional stepped, two-, three- and four-cycle circular labyrinth were modeled using OpenFOAM open source for the skimming flow regime. In order to simulate the flow, InterFOAM solver and RNG K-ε turbulence model were used. The results of the numerical model showed that the combination of the circular labyrinth with the stepped spillway causes an increase of 7.4, 28 and 18.3 percent of energy dissipation in circular forms of two, three and four cycles compared to its classical type for a constant discharge and $y_c/h = 1.68$. Therefore, among the circular labyrinth configurations, the three-cycle form (3CSS) has the highest dissipation rate. In addition, in the three-cycle circular labyrinth configuration, compared to other conventional and labyrinth configurations, it has resulted in less negative pressure in the upper half of the vertical face of the steps.

Keywords Circular labyrinth stepped spillway · Three-cycle circular configuration · OpenFOAM · Energy dissipation

1 Introduction

Spillways are constructed to facilitate the controlled release of surplus water accumulated in a dam reservoir from the upstream to the downstream area, ensuring the safety of the dam structure. Stepped spillways, a type of spillway known for their uncomplicated design and ease of construction, have been employed for more than 3500 years [1]. Stepped spillways have been found to be a more efficient method for dissipating energy compared to conventional chute channels. Hence, the dimensions of the downstream energy breaker for stepped spillways can be minimized. This serves as a viable option, particularly when the terrain conditions prevent the construction of a downstream pool of adequate length [2]. These spillways achieve water flow division by introducing air into the stream through the use of steps. The adoption of this natural aeration method decreases the expenses related to constructing energy-dissipating structures within the downstream pool [3]. Additionally, stepped spillways, known to be 70–80% more efficient in dissipating energy compared to conventional chute channels, also mitigate the risk of cavitation by absorbing flow energy on the steps. [4]. These characteristics enable stepped spillways to have a beneficial impact on the ecological balance of the stream [5], while also providing versatility for their use as cascade structures in water treatment plants [3]. Nowadays, these

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structures, extensively utilized in the construction of roller compacted concrete dams (RCC), are notably recognized for their practicality and cost-efficiency in the construction process [6]. Stepped spillways are primarily employed to optimize energy dissipation and enhance the operational life of the structure [5].

Stepped spillways have garnered notable attention in academic research, with their origins dating back to ancient times and their continued extensive use in contemporary engineering practices. Once professional practices commence, researchers typically focus on establishing design criteria [7–9]. Furthermore, gabions were employed in stepped spillway designs owing to their ease of construction [10, 11]. Felder et al. [12] conducted experiments on three spillway models, utilizing classical, pooled and combined step configurations. In 21 experiments, a channel angle of 8.9°, a channel width of 0.50 m, a step width of 0.318 m and a step height of 0.05 m were employed. In the study mentioned above, researchers utilized end sills to produce the pooling effect of water. These experiments revealed that the combination model exhibited the highest rate of energy dissipation, while the conventional stepped spillways showed the lowest. However, the researchers do not recommend the combined model because it shows some strong flow instabilities and unsteady flow that are not suitable for ensuring the safe operation of the spillway structure. Felder et al. [13] studied the aeration rates and energy dissipation capacities of various combinations of pooled designs, in addition to the traditional stepped model. The research was carried out in a canal measuring 0.52 m in width, with steps 0.20 m wide and 0.10 m high, covering discharge rates ranging from 0.02 to 0.155 m3/s. The results indicate that the energy dissipation of the pooled configurations is lower compared to the conventional model. The researchers noted that the new designs do not offer any advantages in terms of aeration.

As computer and software technologies have advanced, there has been a notable recent increase in studies utilizing the computational fluid dynamics (CFD) method [14–16]. The majority of these studies were conducted using commercially available software programs. However, the licensing fees for these softwares pose a financial burden. Ghaderi et al. [14] studied the hydraulic performance of spillways incorporating trapezoidal labyrinth-shaped steps (TLS). They utilized the Flow3D software for their numerical analysis and then confirmed their findings by validating them against the experimental results of Felder et al. [13]. They highlighted that the TLS spillway outperforms the classical stepped spillway in terms of energy dissipation performance. The findings indicated that the TLS stepped spillway exhibited a lower residual head and a larger friction factor compared to the classical stepped spillway. Ghaderi et al. [17] explored the hydraulics of classical stepped spillways and pooled stepped spillways. They utilized Flow3D software in conjunction with the RNG turbulence model to analyze the effects of standard and notched thresholds. They employed the physical model developed by Felder et al. [13] to validate their numerical study. The investigation indicated that the flat step configuration demonstrated the most effective energy dissipation performance. In models with pooled notched thresholds, the flow remains stable, and these notched models are capable of dissipating roughly 5.80% more energy compared to the standard pooled models. Their research indicated that the configuration of the pool (simple or notched) did not significantly impact the location of air entrainment.

Ma et al. [15] conducted numerical examinations to investigate the energy dissipation capabilities of interval-pooled stepped spillways. For their numerical analysis, they utilized the VOF (volume of fluid) method along with the RNG k-ε turbulence model. The experimental findings of Felder et al. [13] were used to validate the results. The researchers noted that interval-pooled stepped spillways generally dissipate a greater amount of energy compared to both normal pooled stepped spillways and classical stepped spillways. The study introduced the omega vortex intensity identification method to assess the energy dissipation. In the literature review, numerous innovative designs have been suggested for stepped spillways. For instance, Ghaderi and Abbasi [18] examined the energy dissipation capabilities of labyrinth spillways with rectangular, triangular and trapezoidal shapes using FLOW-3D model. They proposed that the trapezoidal labyrinth spillway represents the most efficient model. They showed this type of spillways has the lowest residual head compared to conventional stepped spillways. Ghaderi et al. [19] and Ghaderi et al. [20] also evaluated stepped-labyrinth spillways using Flow3D software. The results showed that the creation of a labyrinth shape in the steps of stepped spillways increases the amount of energy dissipation at the end of the spillway (the last step). In another study, Ghaderi et al. [14] investigated the design of a trapezoidal labyrinth stepped spillway with three cycles. In the mentioned research, the number of cycle's parameter was not investigated.

In this study, the effect of circular labyrinth stepped spillways in improving the hydraulic performance was investigated numerically using OpenFOAM open-source software. The originality of this study is to investigate the effect of the number of circular cycles on the velocity, pressure, energy dissipation and residual energy parameters in circular stepped-labyrinth spillways. The hydraulic parameters in the proposed spillway and conventional stepped spillway have been compared.

The structure of the entire manuscript is as follows: In the second section of this study, the methodology of the work is explained. This section includes flow regime detection, dimensional analysis, geometrical model, numerical model, problem domain, validation and mesh sensitivity for circular labyrinth models. In the third section, the results of the study in terms of flow pattern, water surface and velocity profile, flow pressure, energy dissipation and residual energy are presented and discussed. Then in the fourth section, the conclusion of the study is stated.

2 Methodology

2.1 Flow regime detection

The flow regime on stepped spillways depends on the amount of flow rate and the geometry of the steps. According to Fig. 1, the flow regime on the stepped spillways is divided into three types: nappe (jet), transition and skimming [21].

In order to identify the type of flow regime governing stepped spillways, several experimental and analytical relationships have been presented. The research results have shown that the type of flow depends on the normalized critical depth (y_c/h) and the dimensionless step parameter (h/l), where y_c is the critical flow depth, h and l are the height and width of the step, respectively. Empirical Eqs. (1), (2) and (3) are among the presented relations under which the skimming flow regime is created.

$$\frac{yc}{h} \geq 0.8 \quad 0.4 \leq \frac{h}{l} \leq 0.9 \quad [22] \tag{1}$$

$$\frac{yc}{h} \geq 1.01 - 0.37\left(\frac{h}{l}\right) \quad [10] \tag{2}$$

$$\frac{yc}{h} \geq 1.05 - 0.465\left(\frac{h}{l}\right) \quad 0.2 \leq \frac{h}{l} \leq 1.25 \quad [23] \tag{3}$$

According to Eqs. (1) to (3) and Table 1, the flow regime in this research will be skimming.

2.2 Dimensional analysis

The most important parameters in the flow passing over the stepped spillway are:

(1) Fluid characteristics including dynamic viscosity (μ), density (ρ) and gravitational acceleration (g)
(2) Hydraulic characteristics of flow including flow depth (y) and flow velocity (V)
(3) The geometric characteristics of the spillway include step height (h), step width (l), number of steps (N_0), spillway height ($H_{spillway}$) and spillway width (W)

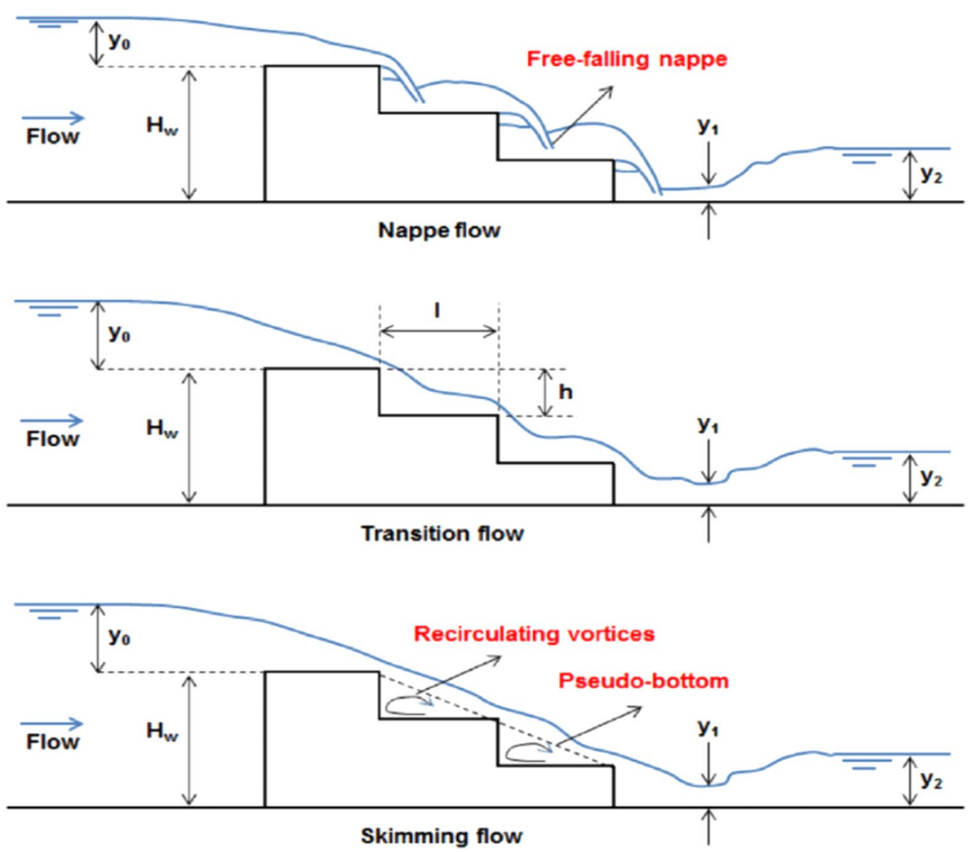


Fig. 1 Flow regimes through stepped spillways

Table 1 Hydraulic characteristics and the type of flow regime formed on the studied stepped spillway

Discharge (m^3/s)	$y_c=(q^2/g)^{(1/3)}$	Step Height, h (m)	Step width, l (m)	h/l	y_c/h	Regime of flow
0.04	0.08	0.1	0.2	0.5	0.84	skimming
0.065	0.12	0.1	0.2	0.5	1.17	Skimming
0.08	0.13	0.1	0.2	0.5	1.34	Skimming
0.095	0.15	0.1	0.2	0.5	1.50	Skimming
0.105	0.16	0.1	0.2	0.5	1.65	Skimming
0.113	0.168	0.1	0.2	0.5	1.68	Skimming

In this research, the conventional geometric form of the stepped spillway has been transformed into a circular labyrinth form. The amount of relative energy dissipation ($\eta\%$) for each step of spillway can be defined as follows:$\eta\% = \Delta H/H_0$ which;$H_0 = \Delta Z + Y + \left(V_0^2/2g\right)$ is the upstream head and $H = y\cos\theta + \left(V^2/2g\right)$ is the water head downstream of the spillway before the jump, $V_0 = Q/(Y^*W)$ and $V = Q/(y^*W)$. If $W \gg y$, where y is the downstream depth and W is the width of the section, the energy dissipation in stepped spillways depends on the number of steps and the characteristics of step height, step width and flow rate. On the other hand, in the circular labyrinth stepped spillways, in addition to the mentioned parameters, the parameters N_c, L_T and W_T are also among the involved parameters. Therefore, the parameters in the stepped spillway of the current research are related to each other in the form of Eq. (4):

$$f\left(H_{\text{spillway}}, N_0, N_c, l, h, V, y_c, L_T, W_T, g, \rho, \mu\right) = 0 \tag{4}$$

Using Buckingham's Pi theorem and selecting the parameters ρ, y, V as repeated parameters, the relative energy dissipation can be considered as a function of the following dimensionless parameters:

$$\frac{\Delta H}{H_0} = f\left(\frac{y_c}{h}, \frac{y_c}{l}, \frac{H_{\text{spillway}}}{W_T}, \frac{L_T}{W_T}, R_e, Fr, N_0, N_C\right) \tag{5}$$

For flow in open channels, the ratio of viscous force to inertia (Reynolds number) can be ignored. Also, since the number of steps and cycles for models is the same, N_0 and N_C parameters can be omitted.

2.3 Geometrical model

The energy dissipation performances of stepped spillways designed using circular labyrinth-shaped steps were investigated for different configurations in this study. A total of three models were used as circular labyrinth steps. In addition, the physical model of Felder et al. [12] was utilized to validate the numerical results. In the model used by the researcher, ten conventional steps were used. The length and width of the steps are 0.1 m and 0.2 m, respectively. The crest length and height are 1.0m, and the width of channel is 0.52 m, as shown in Fig. 2.

Within the scope of the study, circular labyrinth steps were designed for three models. The geometric variables in this form of spillway are: (N_c) the number of circular cycles, (L_T) the total length of each circular cycle that equals to $\left(L_T = \left((N_C + 1)a + N_C L_c\right)\right)$ and the channel width (W_T). Figure 3a shows the length of the appendage between the cycles and the side wall, and L_c is the circumferential length of this circular form.

The design for each model is shown in Fig. 3. Thus, a total of 24 analyzes were carried out, with 4 model and 6 discharge. Table 2 provides an overview of the characteristics of the tested models. In order to draw the geometry of the spillway, Gambit software was used. Figure 4 shows four types of three-dimensional configuration of stepped spillway: flat stepped spillway (FSS), two-cycle circular spillway (2CCS), three-cycle circular spillway (3CCS) and four-cycle circular spillway (4CCS) which were investigated in this research. Dimensional specifications of various circular labyrinth configuration forms are also presented in Table 2.

2.4 Numerical model

In the present study, OpenFOAM model was used for the numerical modeling of the flow on the spillway. This model is coded in C + + programming language. To solve the

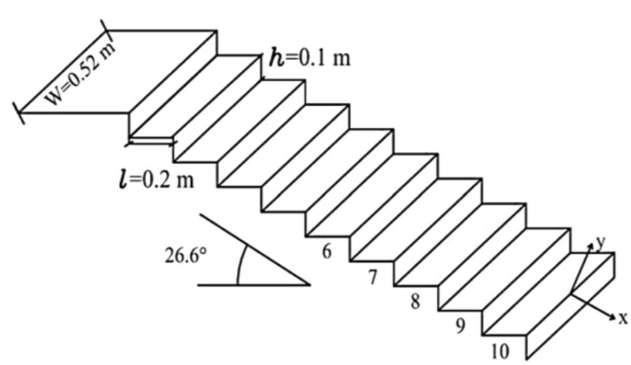


Fig. 2 Geometric parameters of the stepped spillway in the experiment of Felder et al. [12]

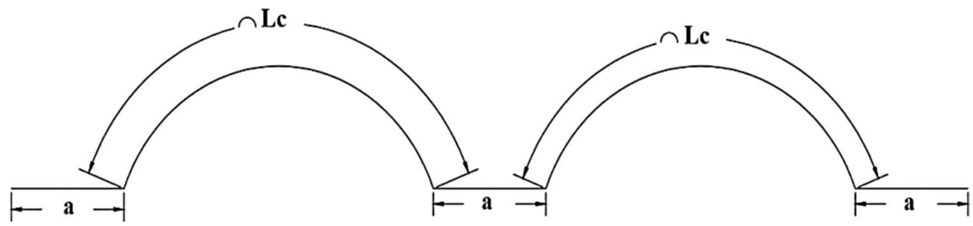


Fig. 3 Dimensional characteristics of circular cycles

Table 2 Dimensional specifications of circular labyrinth configurations

Configuration type	*Nc*	Diameter (cm)	*a* (cm)
Stepped—labyrinth with two-cycle circular form	2	23	2
Stepped—labyrinth with three-cycle circular form	3	14.67	2
Stepped—labyrinth with four-cycle circular form	4	10.5	2

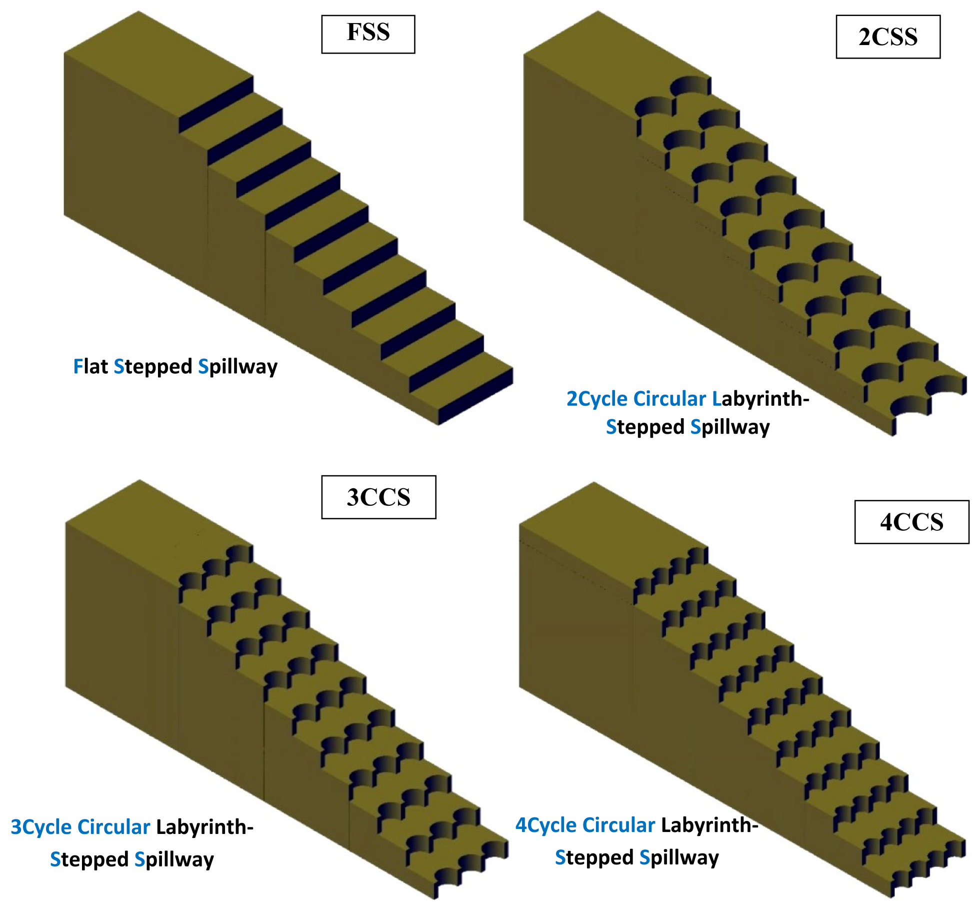


Fig. 4 Different configurations of stepped spillways in the present study

two-phase flow, the InterFOAM solver, which is developed based on the volume of fluid (VOF) method, is used. Finite volume method was used to discretize the momentum and continuity equations in the solution domain. Since water is an incompressible Newtonian fluid, pressure and velocity of flows are determined by the classical Navier–Stokes equations. These equations are developed based on the physical laws of conservation of mass and momentum. The 3D Reynolds averaged Navier–Stokes (RANS) equations in Cartesian coordinate system for incompressible and turbulent fluid flows are presented below:

$$\frac{\partial u^i}{\partial x^i} = 0 \tag{6}$$

$$\rho \frac{\partial u^i}{dt} + \rho u^j \frac{\partial u^i}{\partial x^j} = \frac{\partial p}{\partial x^i} + \frac{\partial p}{\partial x^j}\left[\mu\left(\frac{\partial u^i}{\partial x^j} + \frac{\partial u^j}{\partial x^i}\right)\right] + \frac{\partial \tau^{ij}}{\partial x^i} + \rho g^i \quad (7)$$

where x^i is one of the components of the Cartesian coordinate system ($i = 1, 2, 3$); t, u and τ are time, mean fluid velocity and deviatoric stress tensor, respectively; p and μ represent flow pressure and molecular viscosity; ρ and g are density and gravitational acceleration. A turbulence model should be added to model the nonlinear Reynolds stress term in the Navier–Stokes equation. For this purpose, in this research, the RNG K-ε turbulence model is used due to its high ability to simulate flow separation areas and the obtained results from the previous study [23–25].

2.5 Numerical domain and validation

Spillway solid models were designed using the Gambit program. Then, the background domain (3.50 × 1.40 × 0.52 m) was set using uniform cells as 0.08 m, and the snappyHexMesh utility was utilized for mesh generation. Finally, the boundary patches were determined as inlet, outlet, wall and atmosphere (Fig. 5). The main boundary conditions of the patches are summarized in Table 3. Here, the symbols

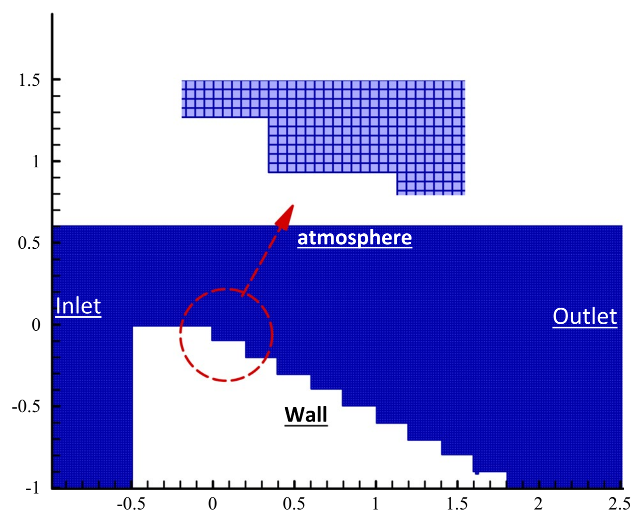


Fig. 5 Meshing and boundary conditions applied in the numerical model

U, p_rgh and alpha.water refer to velocity, dynamic pressure and the initial state of the phase fraction, respectively.

In order to analyze the mesh sensitivity and check the optimal mesh number, the model was evaluated in three mesh domains consisting of coarse (360,000), medium (430,000) and fine (510,000). As shown in Fig. 6, the graphs were plotted as a function of the dimensionless velocity (V/V_{90}) and flow depth (y/y_{90}) and compared with the experimental results of Felder et al. [12] at the eighth, ninth and tenth step edges. Here, y is the distance measured normal to the channel bed, V is the interfacial velocity, V_{90} is the characteristic interfacial velocity when the void fraction is 90% and y_{90} is the characteristic depth where the void fraction is 90%. As shown in Table 4, the V/V_{90} value was compared with experimental results for $y/y_{90} = 0.65$ at the 8th, 9th and 10th steps. The optimum error between experimental and numerical results used three mesh domains is 5.5, 1.6 and 0.7%, respectively. Thus, the fine mesh domain is enough for the numerical analysis.

2.6 Mesh sensitivity for circular labyrinth models

In order to identify the best computational mesh, a grid convergence index (GCI) was used to evaluate several computational meshes using the Richardson extrapolation approach proposed by Celik et al. [26]. This method is a frequently used and advised approach for assessing discretization error. The minimum refinement ratio was selected as 1.30, proposed by Celik et al. [26]. Figure 7a shows the distribution of the interfacial velocity with flow depth at the last step for coarse, medium and fine mesh grids. Then, the error bar is plotted (Fig. 7b). According to the results, the averaged apparent order (pave) was calculated as 3.76, and maximum discretization uncertainty was calculated as 4.9%, which corresponds to ± 0.087 m/s.

3 Results and discussion

Within the scope of the study, the energy dissipation rates of three new models including two-cycle stepped-labyrinth spillway (2CSS), three-cycle stepped-labyrinth spillway (3CSS) and four-cycle stepped-labyrinth spillway (4CSS) were compared with the flat stepped spillway (FSS). All

Table 3 Boundary condition

Parameters	Inlet	Outlet	Wall	Atmosphere
U	Variable height flowrate inlet velocity	Zero gradient	NoSlip	Pressure inlet outlet velocity
P_rgh	Zero gradient	Zero gradient	Fixed flux pressure	Total pressure
Alpha_water	Variable height flowrate	Zero gradient	Zero gradient	Inlet outlet

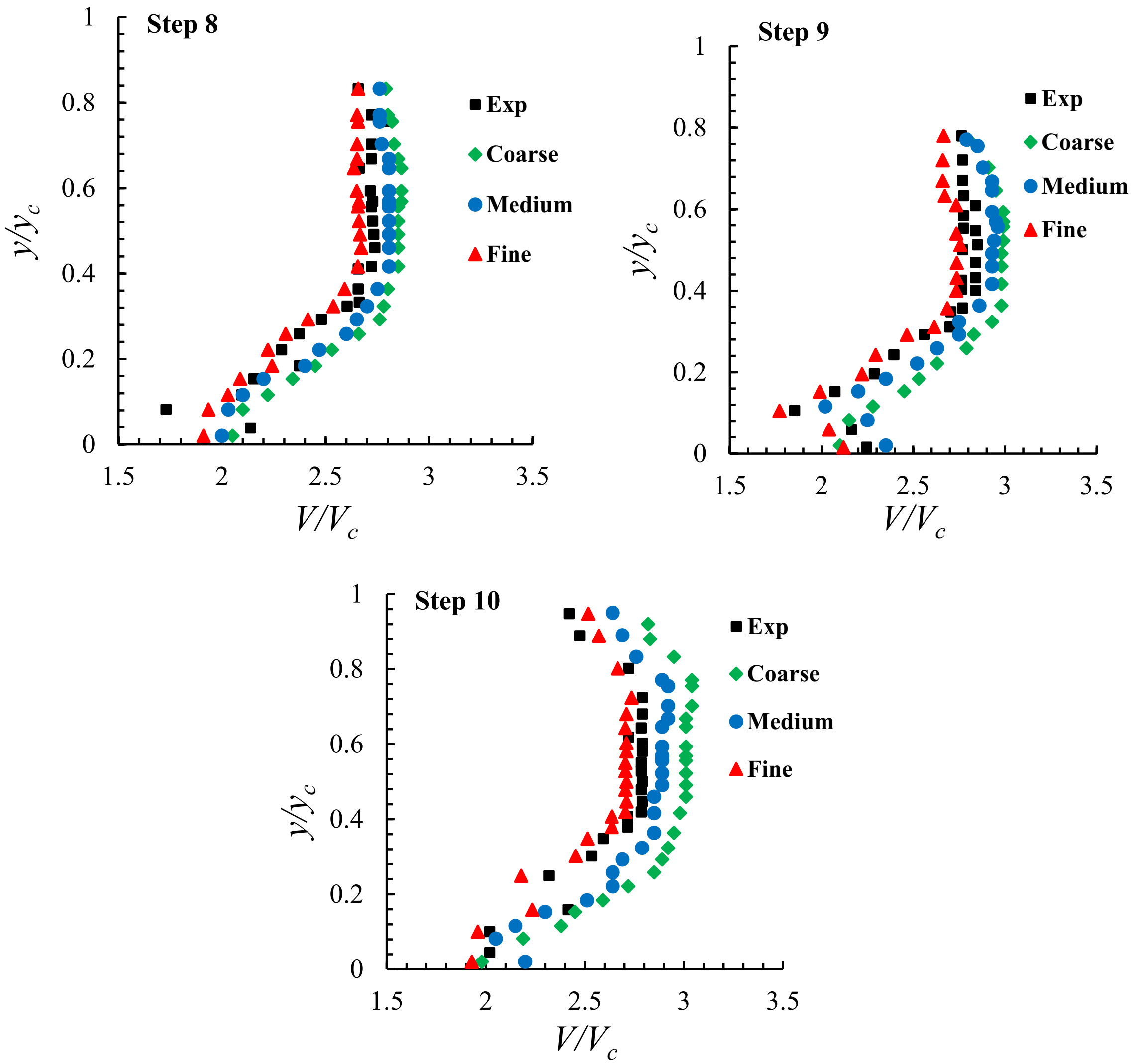


Fig. 6 Velocity distribution and error percentage of numerical and laboratory data in steps 8, 9 and 10 for Q = 0.113 m^3/sec

Table 4 Characteristics of cells in four mesh scenarios of the numerical model

Step no	Experimental and numerical result error%		
	Coarse mesh	Medium mesh	Fine mesh
8	7.5	4.3	1.3
9	5.1	3.5	1.0
10	3.7	1.8	0.9

analyses were carried out in a skimming flow regime for six discharges. The downstream energy (H_{max}) and residual energy (H_{res}) at the last step were used to compute the energy dissipation rate ($\Delta H/H_{max}$). As proposed in the experimental study of Felder et al. [13], the residual energy (H_{res}) was calculated with the average measurement taken from three points in the transverse direction. Then, the total head loss was calculated, as shown in Eqs. (8–10).

$$H_{max} = \frac{3}{2}y_c + H_{dam} \tag{8}$$

$$H_{res} = d_{local}\cos\theta + \frac{U_{local}^2}{2g} \tag{9}$$

$$\Delta H = H_{max} - H_{res} \tag{10}$$

3.1 Flow pattern

Figure 8 shows the streamline of the models. For the flat stepped spillway, according to the theories stated for the skimming flow regime, a pseudo-bottom is formed

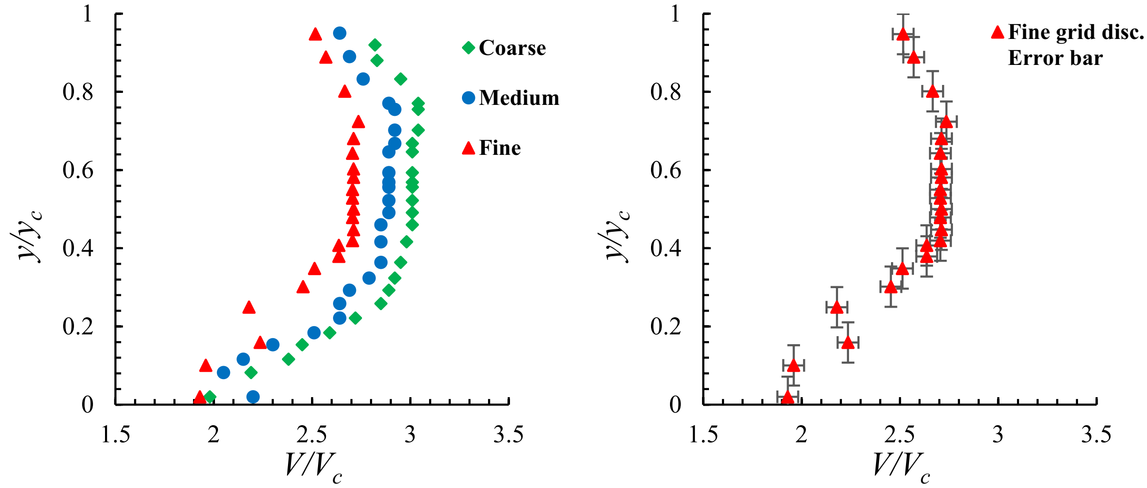
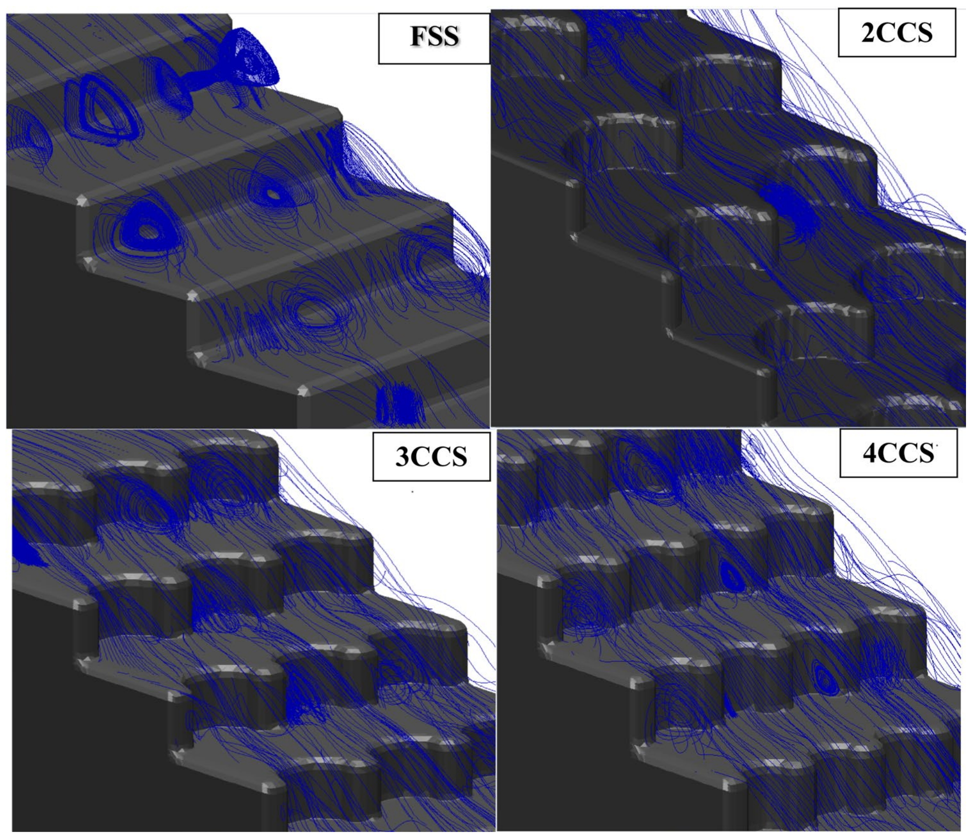


Fig. 7 Mesh convergence for interfacial velocity distribution at the last step of the trapezoidal labyrinth stepped spillway

Fig. 8 Streamlines formed on different stepped spillway configurations



and the flow slides down on the steps. Furthermore, the streamlines were parallel to the channel base. However, the streamlines were not parallel to the channel base and were more intense near the step edge for circular labyrinth stepped models. It was concluded that this situation causes more energy dissipation.

3.2 Water surface profile and velocity

Figure 9 shows the water surface profile and the velocity of the skimming regime flow passing over the flat stepped spillway and two-cycle, three-cycle and four-cycle circular spillways for a flow rate of 0.113 cubic meters per second.

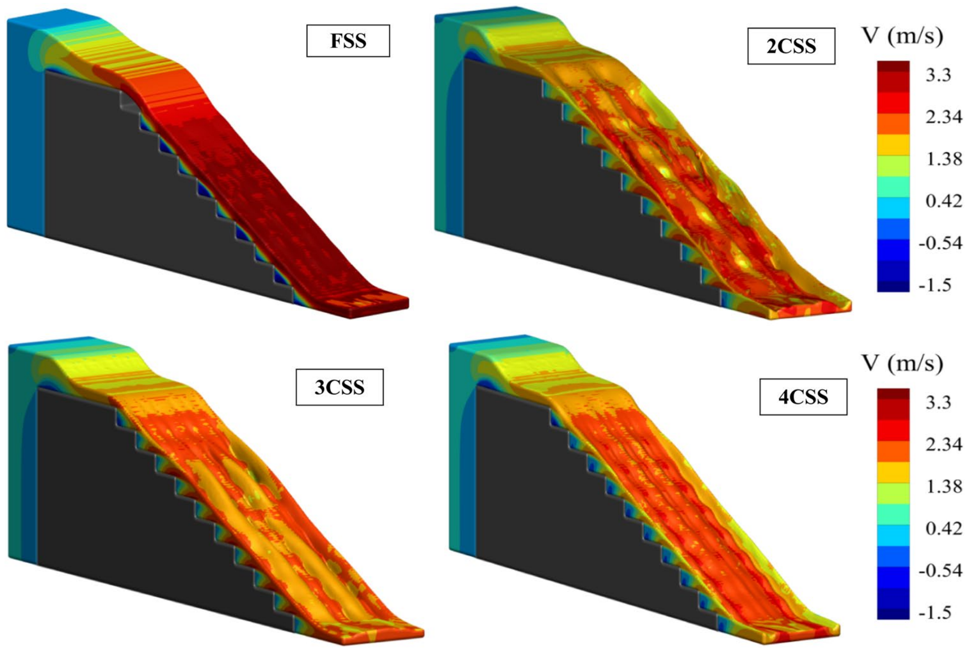


Fig. 9 Water surface profiles and velocity changes on flat stepped spillway, two-, three- and four-cycle stepped-labyrinth spillways

As it can be seen, in the case of the flat stepped spillway, the flow on a pseudo-bottom has slipped to the downstream side and the rotational flow is fully formed at the boundary between the steps. However, due to the shape of the circular stepped-labyrinth forms, considerable fluctuations have been created in the water surface and the interactions of the streamlines are clearly visible compared to the flat form (Fig. 10). The water surface profile in flat stepped spillways indicates a uniform and symmetrical surface across the entire width of the spillway, and the flow velocity has also been increased in accordance with the uniform form of the steps along the flow. However, due to the special geometry, the depth and velocity of the flow have taken changes in the circular stepped-labyrinth forms. In general, the downstream flow velocity for the circular stepped-labyrinth configurations has a decreasing trend compared to the flat form. Among them, the 3CSS configuration had the highest reduction rate (Fig. 9).

Figure 11 shows the depth profile of the flow velocity on the flat stepped spillway, two-, three- and four-cycle stepped-labyrinth configurations in the middle surface ($z/w = 0.5$), a quarter of the cross-section width ($z/w = 0.25$) and the side surface ($z/w = 0$) of the spillway in step 9. Note that, w is the width of the spillway and z is the transverse distance from the spillway wall. In the comparison between the circular stepped-labyrinth configurations, the 3CSS form has been associated with lower flow velocities in all transverse axes at the end step, which can increase the attractiveness of this configuration for designers. The results indicate that among the circular stepped-labyrinth configurations, the three-, four- and two-cycle forms are associated with the highest velocity reduction in the spillway axes at the end step, respectively. The reduction of the flow velocity in the central axis of the final step for two-, three- and four-cycle configurations compared to the conventional stepped spillway configuration

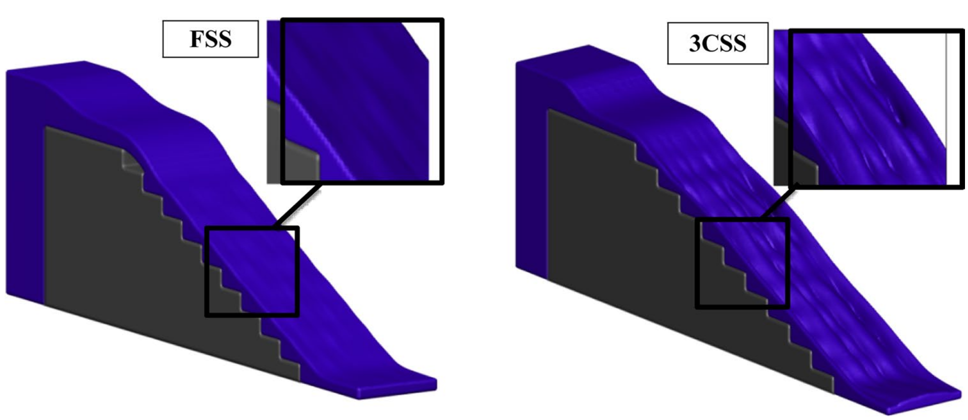


Fig. 10 The interference of streamlines in the configuration of the stepped-labyrinth spillways compared to the conventional stepped spillway

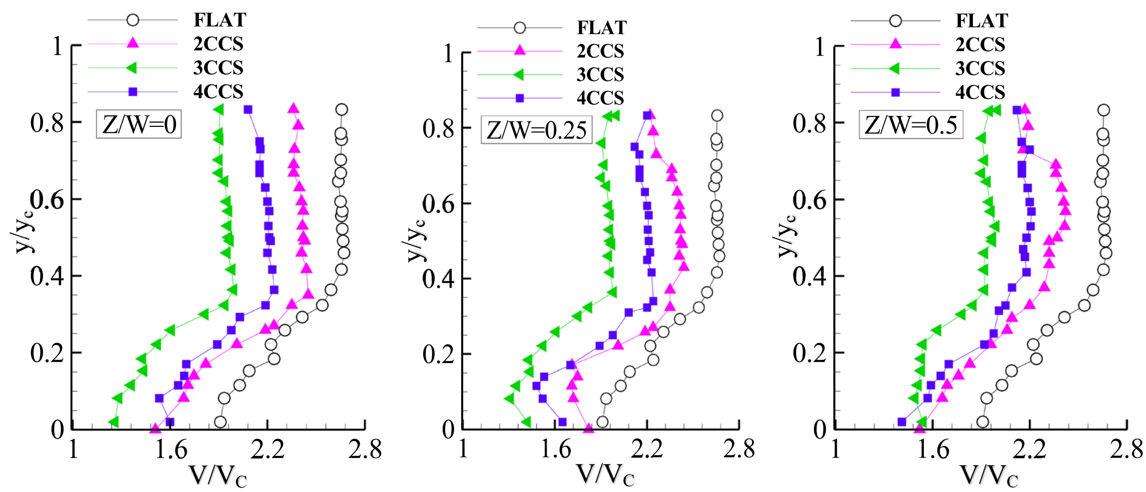


Fig. 11 Depth profile of the flow velocity on different configurations of the stepped spillway in different axes of the spillway in step 9

was 15.6%, 36.5% and 23.1%, respectively. The reason for the decrease in the flow velocity in the circular stepped-labyrinth configuration can be seen in the simultaneous combination of the characteristics of nappe and skimming flow. In these configurations, in addition to the issue of rotational flows, the collision of the flow occurs in each step, which is a characteristic of the nappe flow, and helps to dissipate more energy of the flow.

3.3 Flow pressure

Three-dimensional graphical changes of pressure on the horizontal and vertical face of the 9th step in the flow on different configurations of the stepped and stepped-labyrinth spillway along the $z/w=0$, $z/w=0.25$ and $z/w=0.5$ axes are presented in Fig. 12. The results confirm that the minimum pressure is related to the conventional stepped spillway form and occurred on the horizontal face of the spillway at

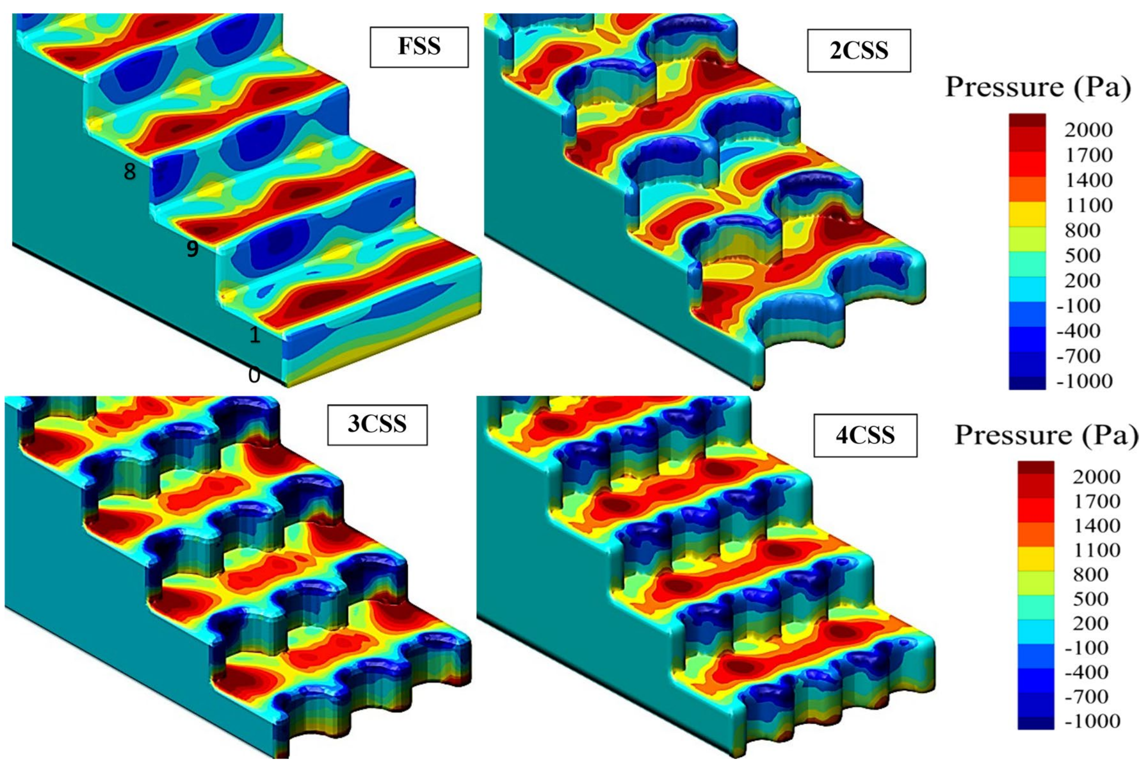


Fig. 12 Changes in flow pressure on the horizontal and vertical side of the steps in different axes of all configurations in steps No. 8, 9, 10

position $0.1 \leq x/l \leq 0.3$, and with the change of the spillway form to circular labyrinth, this minimum value has increased in all axes. Negative pressure has occurred in the upper half of the vertical face of the steps in all configurations.

Figure 13 shows that the position of the maximum pressure on the horizontal face has changed depending on the number of cycles in different axes of the spillway. The maximum pressure in all labyrinth configurations, except the $z/w = 0.25$ axis of the four-cycle labyrinth stepped configuration (4CSS), has a lower value than the conventional stepped spillway configuration. On the vertical side of the steps, in all configurations, moving toward the edge of the steps, the pressure tends to go from positive to negative values. In the middle axis ($z/w = 0.5$) and a quarter of the cross-section width ($z/w = 0.25$) of the labyrinth configurations in the areas near the bottom, the positive pressure values are higher than the conventional configuration. In the 3CSS configuration, a smaller amount of negative pressure has been created in the upper half of the vertical face of the step. This issue can make this configuration form more attractive than other forms in terms of performance.

3.4 Energy dissipation and residual energy

Since the kinetic energy of the flow downstream of the spillways is considerable, the subject of flow energy dissipation and the residual flow energy are important concerns of hydraulic structure designers. The use of steps in the body of the spillway was one of the initial ideas of the designers for this issue. The important issue is increasing the effect of these steps in the flow energy dissipation rate. Various options have been suggested by researchers in the past in order to increase the efficiency of steps in the energy dissipation. Taking advantage of the combined effect of stepped and labyrinth spillway is in line with this issue. For this purpose, in this research, the effect of the circular stepped-labyrinth configuration with different cycles was evaluated in terms of its effect on the rate of energy dissipation ($\Delta H/H_0$) and the amount of residual energy (H_{res}). Figure 14 shows the percentage values of relative energy dissipation for different forms of conventional stepped spillway, two-, three- and 4-cycle circular stepped-labyrinth spillways.

Examining the results shows that a higher energy dissipation rate has been achieved in all circular stepped-labyrinth configurations than the conventional form in skimming flow regime. The reason for this is the special geometry of these spillways, which leads to the combination of dissipation mechanisms in the nappe flow regime with the rotational flows of the skimming regime. Among the circular stepped-labyrinth configurations, the three-cycle form (3CSS) has obtained the highest dissipation rate. The reason for this issue can be pointed out in the complete formation of rotational currents at the intersection of the vertical and horizontal sides of the steps and also the impact of the flow with the floor in each step. For the discharge conditions of 0.113 cubic meters per second and $y_c/h = 1.68$, two-, three- and four-cycle circular stepped-labyrinth spillways have obtained about 7.4%, 28% and 18.3% more energy dissipation compared to the conventional stepped spillway, respectively. Figure 15 shows the dimensionless residual height or residual flow energy as a function of the ratio of critical depth to step height. It can be seen that under the conditions of the same flow, the dimensionless residual energy values for the conventional stepped spillway are higher than the stepped-labyrinth models. In case ($y_c/h = 0.84$), the dimensionless residual energy value is 3.85 for the conventional stepped spillway, while it is 2.75 for the three-cycle circular stepped-labyrinth spillway.

Figure 16 compares the present study and literature results for dimensionless energy dissipation versus ($\Delta Z/y_c$) which Δz is the vertical distance of the spillway crest to the last step. The energy dissipation downstream of the stepped spillway in pooled and trapezoidal configurations is higher than that of the classical stepped spillway, as said by Felder et al. [13]. The energy dissipation is lowest downstream of the all models for high discharge. However, three-cycle circular labyrinth and trapezoidal labyrinth in Felder et al. [13] have obtained higher dissipation values for high discharge compared with another configuration. As the discharge decreases, the energy dissipation downstream of the whole configuration increased. However, the three-cycle circular labyrinth models proposed in this study have the best energy dissipation performance for high and low discharges.

4 Conclusions

This study proposed a novel model for the energy dissipation performance of the stepped spillways using circular labyrinth steps. These models were arranged in two-, three- and four-cycle labyrinth-shaped steps to increase the study's originality, and the obtained results were compared. A total of 24 analyses were conducted using OpenFOAM software, the RNG k-ε turbulence model, and the obtained results were listed below:

(1) The calculation error up to 1.3% of the numerical and experimental result indicates the acceptable efficiency of the InterFoam solver in the OpenFoam software for simulating the flow over the spillway.
(2) The energy dissipation percentage increases with decreased discharge for all models.
(3) The energy dissipation performance of the models using circular labyrinth-shaped steps is around 18% higher than the classical one.

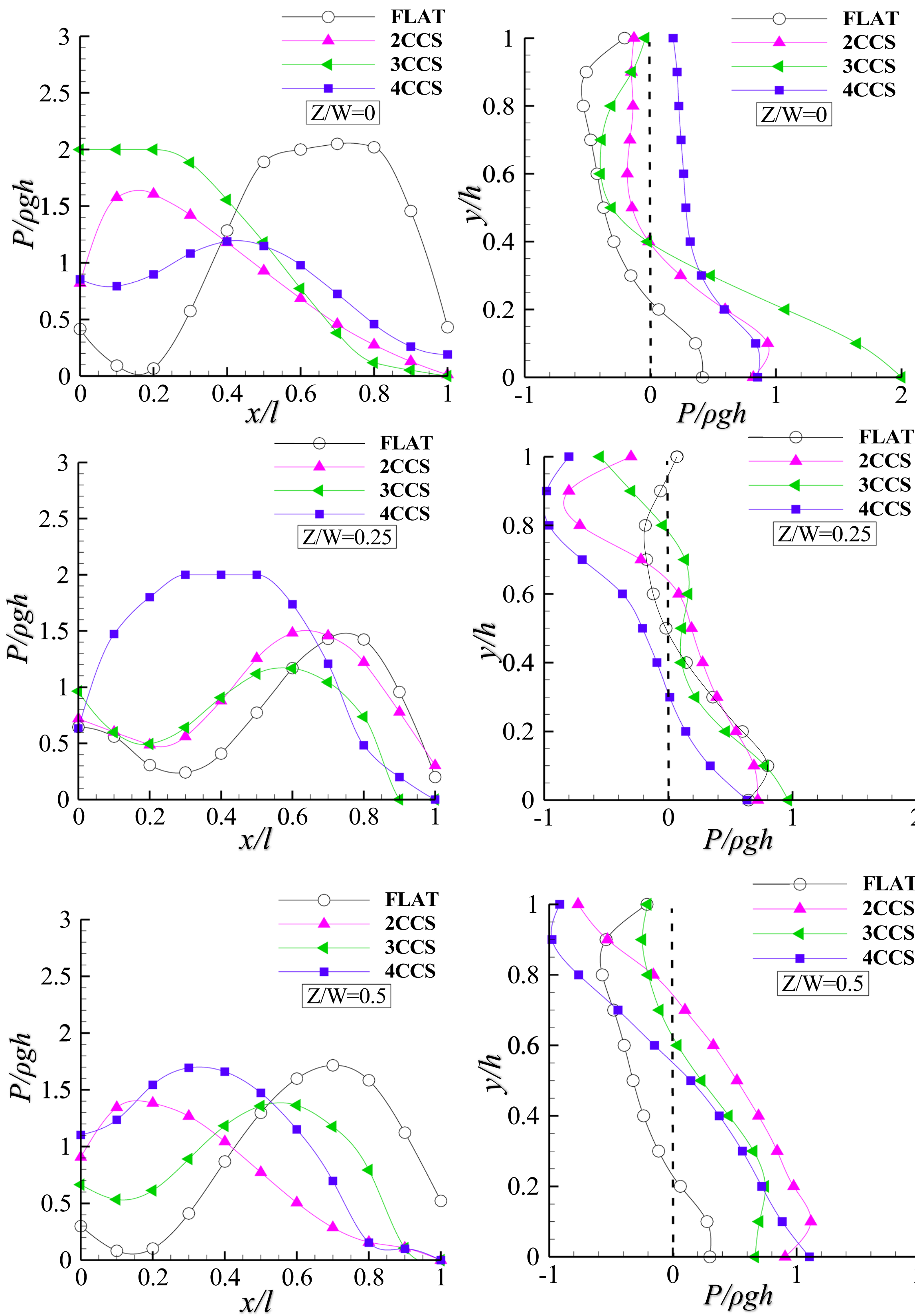


Fig. 13 Pressure profile on the horizontal and vertical face of step number 9 in different axes of stepped spillway configurations

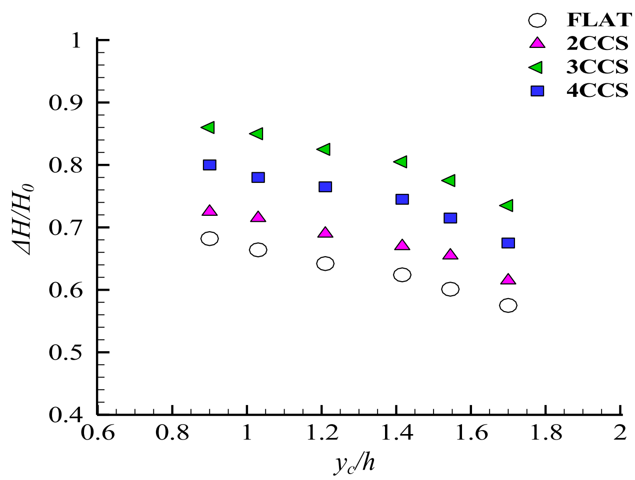


Fig. 14 Amount of relative energy consumption in the conventional stepped, two-cycle, three-cycle and four-cycle labyrinth spillways

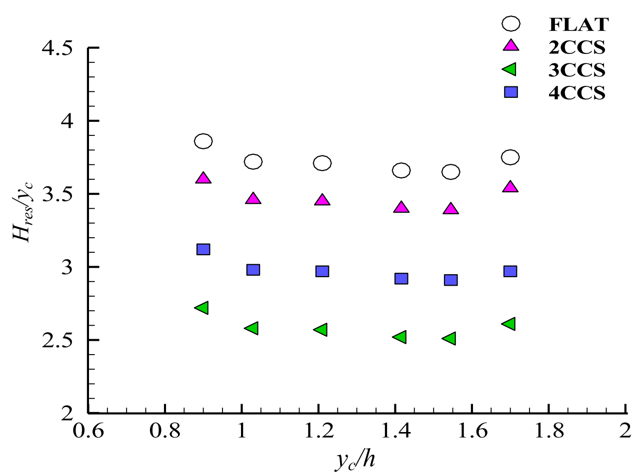


Fig. 15 Comparison of the amount of residual flow energy in a conventional stepped spillway with two-, three- and four-cycle circular stepped-labyrinth spillways

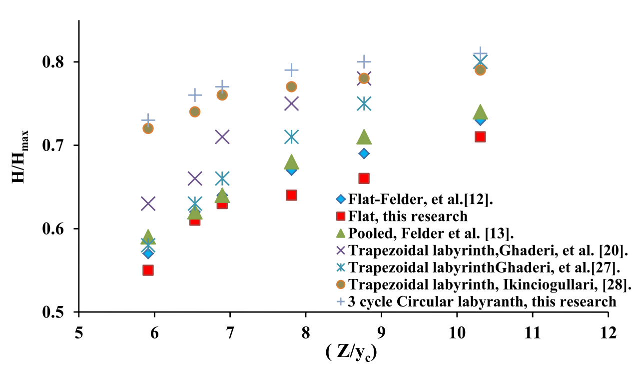


Fig. 16 Energy dissipation rate in the current research model and comparison with models studied by other researchers

(4) The three-cycle circular stepped spillway is more effective than the two- and four-cycle designed model in dissipating energy for high and low discharge and has been associated with a lower negative pressure value.
(5) The circular labyrinth stepped configurations have higher positive pressure values in the ($y/h \leq 0.25$) near the bottom than the classical one.
(6) The present study results were compared with the literature results. According to the results, the circular labyrinth models were generally more effective than the others for energy dissipation performance spatially for high discharges.

Author contributions Hamzeh Ebrahimnezhadian devised and designed the study, Dana Ghaderi collected data and performed the numerical simulations, and Mahdi Mollazadeh supervised the work and wrote the paper with input from all authors.

Funding This research received no specific grant from any funding agency in the public, commercial or not-for-profit sectors.

Declarations

Conflict of interest The authors declare that they have no conflict of interest. All authors declare that there are no other competing interests.

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