



# Numerical Investigation of the Effect of CEDEX Profile on the Hydraulic Parameters in the Stepped Spillway and the Performance of This Profile in Various Chute Slopes

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## Abstract

An important part in designing stepped spillways is making the spillway in order to direct the flow appropriately on the first step. In low discharges, the water flow moves over the spillway and arrives at the first step, and if the first step is high enough, the flow may leave the first step horizontally, skip some steps and land as a free jet of water on the lower steps, which might cause some damages to the structure. One of the solutions to this problem is to use CEDEX profile, transition steps between the ogee crest and the stepped chute. The present research carries out a numerical study of the effects of CEDEX profile on various hydraulic parameters and also the effects of the chute slope on the performance of this profile in preventing the flow jump. For this purpose, four models were created with different geometries and were studied in various discharges with FLOW-3D software. The results show that deploying CEDEX profile in the initial parts of the spillway leads to lower velocity and less risk of cavitation. Also, the results illustrate that CEDEX profile can shift the inception point of aeration to downstream. Furthermore, findings show that CEDEX profile, in the slope of less than 50°, can prevent flow jump in the first step. In steeper slopes, however, it fails to achieve the optimal performance.

**Keywords** Stepped spillways · CEDEX profile · FLOW-3D · Flow jet · Chute slope

## 1 Introduction

One of the main characteristics of stepped spillways is the high turbulence and air entrainment of their flows. Chamani and Rajaratnam (1999) and Baylar et al. (2006) studied the skimming flow and concluded that the air and oxygen that enter the flow in stepped spillways are more than the air entering smooth spillways. Stepped spillways are thought to be less prone to cavitation damage than smooth spillways because of air presence (Frizell et al. 2013). Pfister et al. (2006) realized that the cavitation index in specific discharges of larger than 30 cubic meters per second divided by width is less than 0.9. Amador et al. (2009) and Frizell et al. (2013) claimed that cavitation occurs precisely on the downstream of the edge of the steps close to their vertical side, where the pressure is at its lowest.

Sorensen (1985) compared the point of inception and the flow depth in stepped and smooth spillways and claimed that aeration of the free surface of the flow in stepped spillways occurs at a more upstream point than smooth spillways and that boundary layer growth takes place better in stepped spillways. Chanson (1994), Meireles and Matos (2009) and Hunt and Kadavy (2013) offered equations for calculating the point of inception in stepped spillways. It must be noted that Chanson (2002) and Amador et al. (2004) asserted that in the downstream of inception point and immediately after it, the flow turns into a rapidly varied one and it is only after that a gradually varied flow is formed.

However, the other advantages of stepped spillways are the higher energy dissipation in the toe of dam compared to smooth spillway (Peyras et al. 1992; Sorensen 1985; Christodoulou 1993; Rice and Kadavy 1996). Pinto et al. (2017) installed the piano key weir on stepped chute spillways and concluded that dissipation of energy in this model is less than the dissipation of energy when WES spillway is installed on the stepped chute.

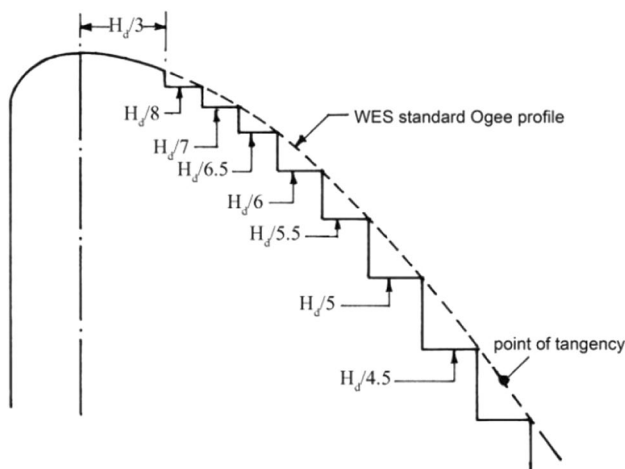
An important part of designing stepped spillways is building the spillway crest in order to direct the right behavior

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of the flow on the first step. In low discharges, the flow of water crosses the spillway, arrives at the first step, and if the height of the first step is large enough, it may pass the first step horizontally and skips the next steps as a free jet and land on the lower steps; this can cause damage to the dam structure (Chanson 1996). When the flow discharge increases, the flow jump over the steps is terminated. In his studies concerning spillways in Monksville dam, Sorensen (1985) improved the ogee structure of the spillway (WES) and added some smaller steps to the ogee profile apart from the steps designed for the stepped chute, thereby stopping the flow jump in low discharges. Chanson (1996), in his studies for predicting regime flow, concluded that in order to decrease the risk for flow jump on the first step, we must decrease the height of the first step as much as possible with deploying the first step in the most upstream point on the ogee spillway. In the CEDEX Hydraulic Laboratory in Spain, Mateos and Elviro (2000) presented the CEDEX profile that is a transitional region between the ogee crest and stepped chute in order to optimize the behavior of the flow moving from the spillway to the stepped chute.  $H_d$  (the design head of water on the spillway) has been defined as the criteria for calculating the dimensions of the steps in the transitional area and the horizontal distance between the first step and the spillway crest. The horizontal distance between the first step and the spillway crest is  $H_d/3$ , and the steps are patterned from small to large. Figure 1 shows the position and the dimensions of CEDEX profile on the stepped spillway.

Since experimental models of hydraulic structures are time-consuming and expensive and pose numerous problems concerning changes in scales, today, by using computers, we can simulate the behavior of the hydraulic structures numerically with spending a reasonable amount of time and



**Fig. 1** Location and dimension of steps of CEDEX profile (Mateos and Elviro 2000)

money. Liao and Wu (1995), Chen et al. (2002), Tabbara et al. (2005), De Carvalho and Amador (2009), Bombardelli et al. (2010), Morovati et al. (2016), Hamed et al. (2016) and Mansoori et al. (2017) are among the researchers who have used mathematical methods to study the hydraulic flow on stepped spillways, and their results showed an appropriate agreement with experimental results.

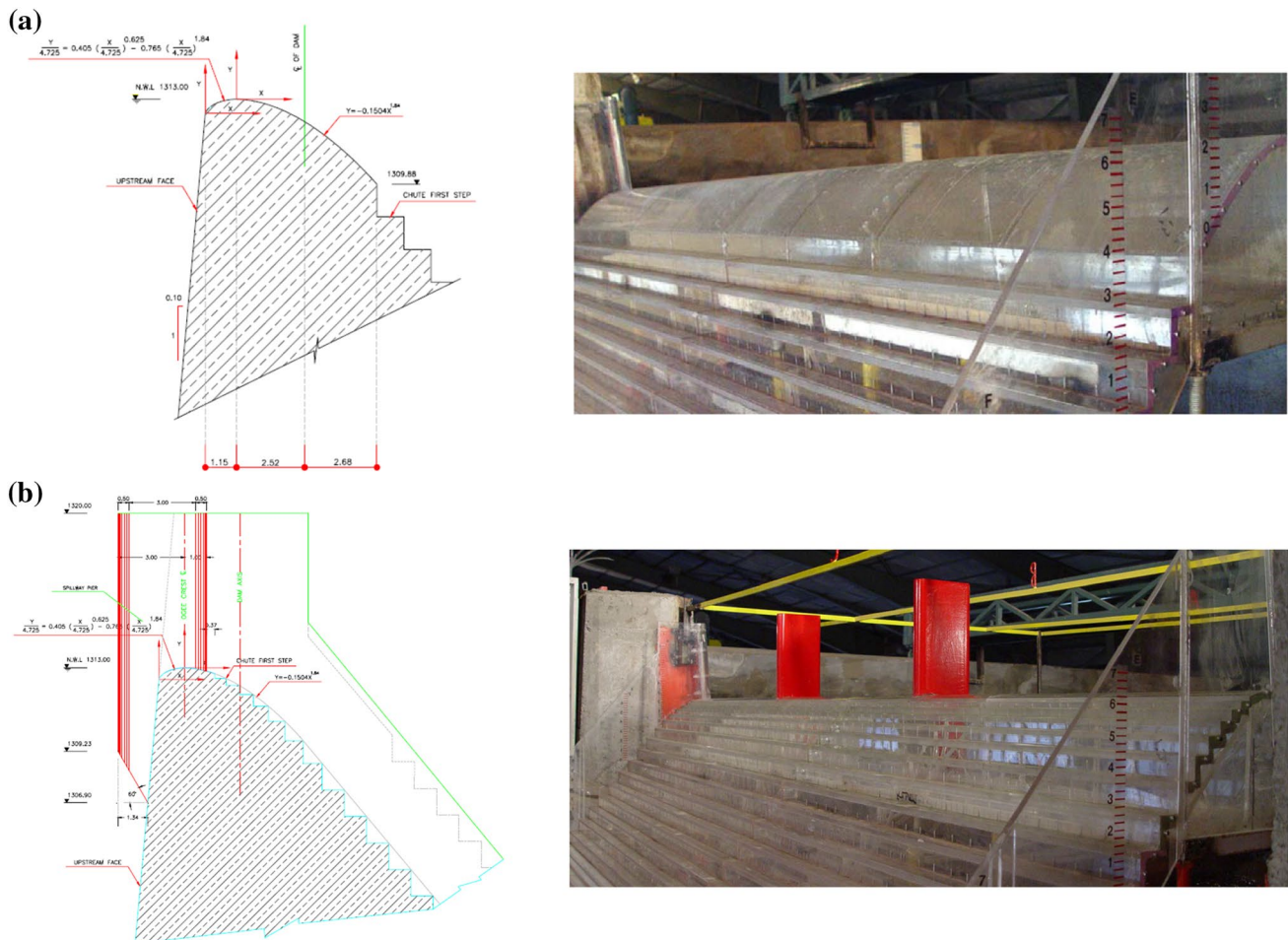
The present study carries out a numerical analysis of the effect of chute slope on the performance of CEDEX profile and the influence of the profile on the hydraulic parameters of flow using FLOW-3D, a CFD-based software.

## 2 Materials and Methods

### 2.1 Experimental Model

The present research uses the spillway and the chute system in Javeh Dam, which is a storage dam with RCC materials. The crest of the dam is standard WES with the equation of  $y = 0.1504x^{1.84}$ , and a stepped chute has been used in its downstream in order to transfer water. The height of the dam is 85 meters, and the dimensions of steps are 1(H):1.2(V). The spillway, the stepped chute and the conducting walls on two side walls were created from transparent Plexiglass that was created with a scale of 1:25 in Iran Water Research Institute (IWRI) in order to study the hydraulic of the flow. Experiments on the initial model and on the low discharges passing over the spillway (less than 140 cubic meters per second) showed that the flow of water moves from the farther edge of the spillway curve on the first step, jumps over the surface of the first step and lands on the next step as a free jet. In order to optimize the behavior of the flow moving from the spillway to the stepped chute, the geometric model was improved and CEDEX profile was used as the transitional area between ogee crest and the stepped chute. According to CEDEX profile design shown in Fig. 1, between the ogee spillway and the stepped chute, seven smaller steps with variable dimensions have been installed 1.367 meters downstream of the crest. Figure 2 shows the model characteristics in both “Primary” and “Modified” models (Javeh Dam Final Report 2011).

In the laboratory, some hydraulic parameters were measured that were discharge coefficient, flow discharge, static and dynamic pressure, fluid elevation and mean velocity in various determined points, but the results of two models were not compared with each other in order to investigate the effects of CEDEX profile on these parameters. Also, other vital hydraulic parameters like cavitation and inception point of aeration were not considered in designing this model. In addition, experiments were based on a constant slope of the chute (1(H):1.2(V)). Therefore, in order to examine the



**Fig. 2** Characteristics of created models in IWRI: **a** primary model and **b** modified model (Javeh Dam Final Report 2011)

performance of CEDEX profile in preventing the flow jump, some simulations with various slopes seem necessary.

## 2.2 Numerical Model

As mentioned earlier, the model used in the present article consists of the spillway and the chute in Javeh Dam. The dam was created and tested in the laboratory in two “Primary” and “Modified” models. The same two models have been used in the present numerical study for examining the effects of CEDEX profile on the parameters of the mean velocity, cavitation and the inception point in discharges of 200, 400 and 500 cubic meters per second. Apart from these two laboratory models, two complementary models called “Steeper Slope” and “Milder Slope,” with slopes of 55 and 45°, respectively, were designed to analyze the effects of the chute slope on the performance of CEDEX profile in discharges of 100, 70 and 40 cubic meters per second.

The software used in this research is FLOW-3D, which is a general-purpose computational fluid dynamics (CFD)

software. It employs specially developed numerical techniques to solve the equations of motion for fluids to obtain transient, three-dimensional solutions to multi-scale, multi-physics flow problems (Hirt and Nichols 1988). The RNG  $k-\epsilon$  model (ReNormalized Group theory) was chosen for the flow turbulence modeling. Various researchers, such as Yakhot et al. (1992), Cheng et al. (2006), Nikseresht et al. (2013) and Rahimzadeh et al. (2012), have investigated the most appropriate turbulence model for numerical simulation of spillways, and results showed the superiority of low Reynolds stress model to others, but this model does not exist in FLOW-3D. Despite this fact, in their research, RNG  $k-\epsilon$  model showed better agreement with the experimental results in comparison with standard  $k-\epsilon$  and standard  $k-\omega$  models.

The meshing range and the dimensions of the calculating cells are of great importance in numerical simulation. In the present study, the criteria for calculating the dimensions of the mesh cells are the geometrical characteristics of the steps and the depth of the water jet after jumping over the steps.

After trial and error, the most optimal meshing condition in a flow that does not jump was determined to be a mesh block with the cell dimensions of 10 cm in all the three directions. In the simulations of flows with jumps, since the flow jet was thin, the depth of the jet of water was taken as the criteria for calculating the dimensions of the meshes; as a result, 7-cm meshes were used. The size of cells and total mesh cells that were used are shown in Table 1.

### 3 Results and Discussion

#### 3.1 Validation

In order to verify the results of the numerical simulation, they should be compared to experimental or mathematical results. Since the present modeling is numerical and is based on experimental models, some of the results of the two models were compared. Studied parameters are the depth and the mean velocity of the flow on the spillway crest (in six discharges) and the inception point of aeration (in three discharges) that have been compared with experimental results in Table 2. According to this table, it can be seen that the maximum error of numerical results for the flow depth, mean velocity and the inception point are, respectively, 5.00, 5.66 and 4.44. The findings show the similarity between numerical and experimental results. Therefore, the results of the software are reliable.

The error function is defined as Eq. (1):

$$\text{err}\% = \left| \frac{f_{\text{num}} - f_{\text{exp}}}{f_{\text{exp}}} \right| \times 100 \quad (1)$$

**Table 1** Characteristics of meshing in every condition

Discharge	Cell size (cm)	Total mesh cells
500	10	900,000
400	10	900,000
200	10	900,000
100	7	2,623,900
70	7	2,623,900
40	7	2,623,900

**Table 2** Verification of numerical results with experimental results

Discharge m <sup>3</sup> /s	Flow depth on the crest (m)			Mean velocity on the crest (m/s)			Inception point of aeration (m)		
	Exp.	Num.	Err%	Exp.	Num.	Err%	Exp.	Num.	Err%
40	0.44	0.43	2.27	1.59	1.50	5.66	–	–	–
70	0.60	0.63	5.00	1.97	1.91	3.05	–	–	–
100	0.74	0.72	2.70	2.24	2.13	4.91	–	–	–
200	1.10	1.11	0.91	3.62	3.44	4.97	7.00	7.00	0.00
400	1.80	1.74	3.33	4.71	4.51	4.25	9.00	9.40	4.44
500	1.92	1.99	3.65	4.97	4.88	1.81	12.00	12.20	1.67

in which  $f_{\text{num}}$  and  $f_{\text{exp}}$  are the numerical and the experimental quantity of the mentioned parameters. It must be noted that the difference function in all sections follows Eq. (1).

#### 3.2 Flow Velocity

At points similar to the points determined in the previous section, the results of the flow velocity were also extracted. The results of  $v/v_c$  against  $L/h$  have been shown in Fig. 3, where  $v_c$ ,  $L$  and  $h$  are critical velocity, distance from crest and the height of chute's main steps (1.2 m). According to Fig. 3, in the "Modified" model, the flow velocity in the first steps is less than the amount of this parameter in the initial model. The reason for this is the existence of CEDEX profile steps in the ogee section of the spillway where the interaction between the flow and the steps decreases the flow velocity. Moving downstream, the difference between the velocities in the two models decreases, and from a point onward, the two curves are relatively matched. According to the following curves, the largest difference in flow velocity between the two models is 35%, 34% and 30% for a discharge of 200, 400 and 500 cubic meters per second.

#### 3.3 Cavitation Index

No reports have so far been given about damages caused by cavitation in dams with stepped spillways, but this does not mean that this phenomenon must not be studied while designing such spillways steps (Frizell et al. 2013). Numerous researchers have claimed that the risk of cavitation is greater at points near the edge of the steps (Amador et al. 2009 and Frizell et al. 2013). Therefore, in this research, the cavitation index was calculated near the edge of the steps, and the results of the two models were compared. In order to calculate the cavitation index, we can use the energy equation (Bernoulli Equation) between two points of a steady flow and finally have (Falvey 1990):

$$\sigma = \frac{P_0 - P_v}{\rho v_0^2 / 2} = -(C_p) \quad (2)$$

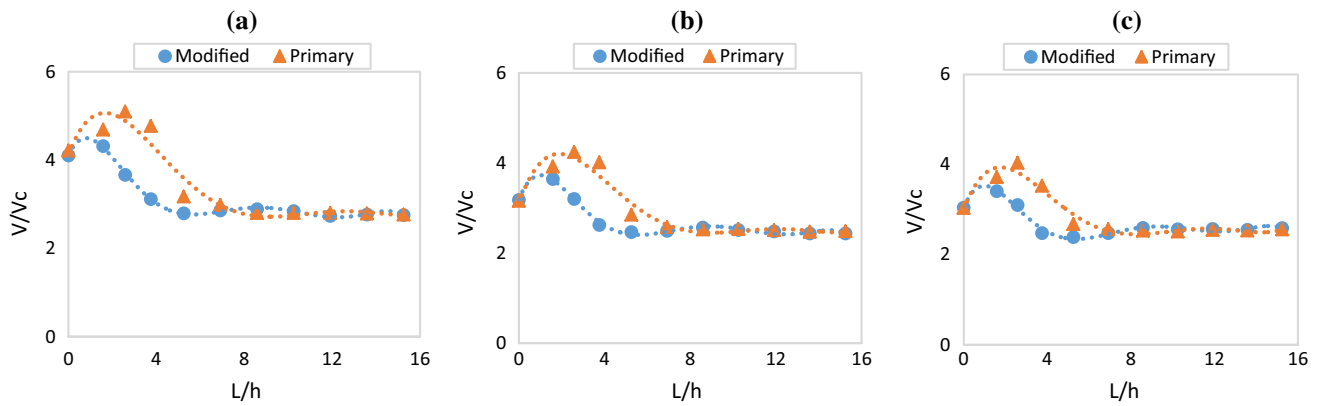


Fig. 3 Comparison of the flow velocity between primary and modified models at discharges of: a 200, b 400 and c 500 m<sup>3</sup>/s

As shown in Fig. 4, variations of  $\sigma$  against  $L/h$  have been shown. According to this figure, except for the first steps, the other points did not show a great difference between the numbers of the cavitation indices. CEDEX profile steps and their interaction with of those steps with the flow of water are the reasons why the index is high at these initial steps. Therefore, CEDEX profile steps can decrease the risk of cavitation, which is a favorable result for designers. The largest difference between the cavitation indices of the two models is 150%, 116% and 119% for a discharge of 200, 400 and 500 cubic meters per second, respectively.

### 3.4 Inception Point of Aeration

In this section, the influence of CEDEX profile on the aeration point of inception in stepped spillways is studied. Results of the numerical modeling show that installing CEDEX profile moves the point of inception downstream. Considering the fact that areas that are not aerated (the upstream point of inception) in the spillways are areas most vulnerable to cavitation, at first glance the influence of

CEDEX profile on the flow is considered a negative point. However, according to the results of Sect. 3.4 (cavitation index), CEDEX profile decreases the risk of cavitation in the initial parts of the spillway. Therefore, moving the point of inception for aeration downstream in the final model does not facilitate the occurrence of cavitation. In Fig. 5, the inception point of aeration in the two primary and modified models has been determined.

### 3.5 The Effect of Slope on the Performance of CEDEX Profile

The present research carried out a numerical study of the influence of the chute slope on the ability of the CEDEX profile to stop the flow jumps. For this purpose, two models with milder and steeper slopes than the modified model were designed and their numerical modeling was simulated for the discharges of 100, 70 and 40 cubic meters per second. Observing the flow in various discharges and slopes (Figs. 6, 7, 8), a decrease in the discharge led to an increase in the flow jump for the “Primary” model. Also, in the “Modified” and “Milder Slope” models, the flow jumps in all the

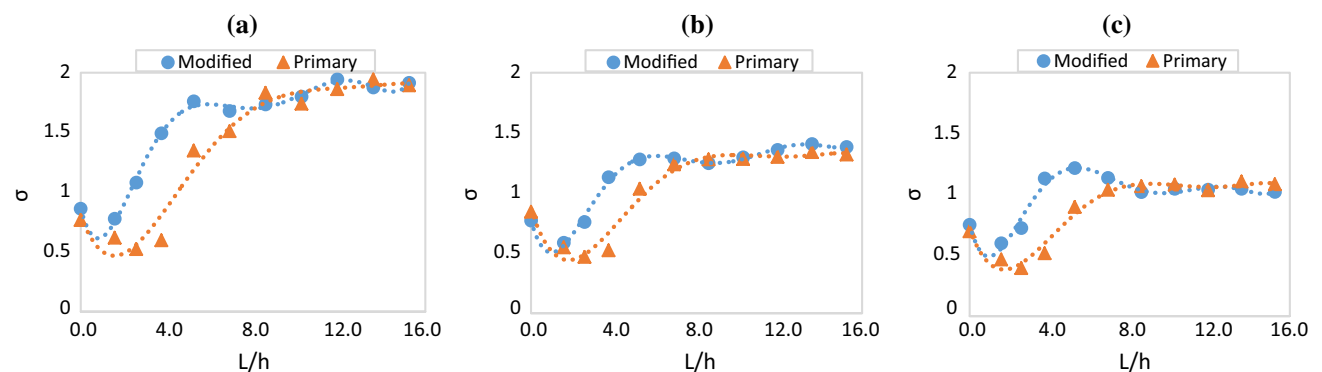
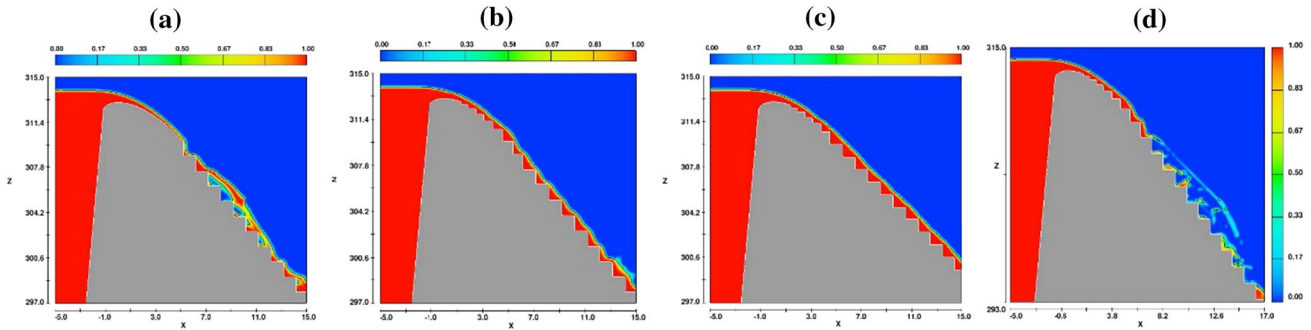
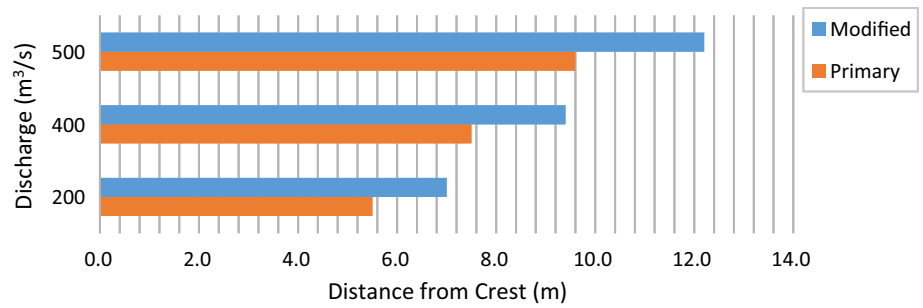
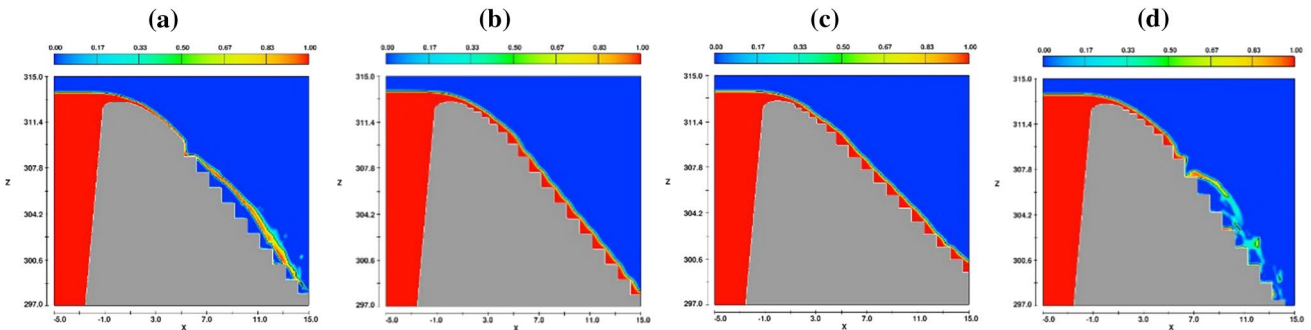


Fig. 4 Comparison of the cavitation index ( $\sigma$ ) between the primary and modified models at discharges of: a 200, b 400 and c 500 m<sup>3</sup>/s

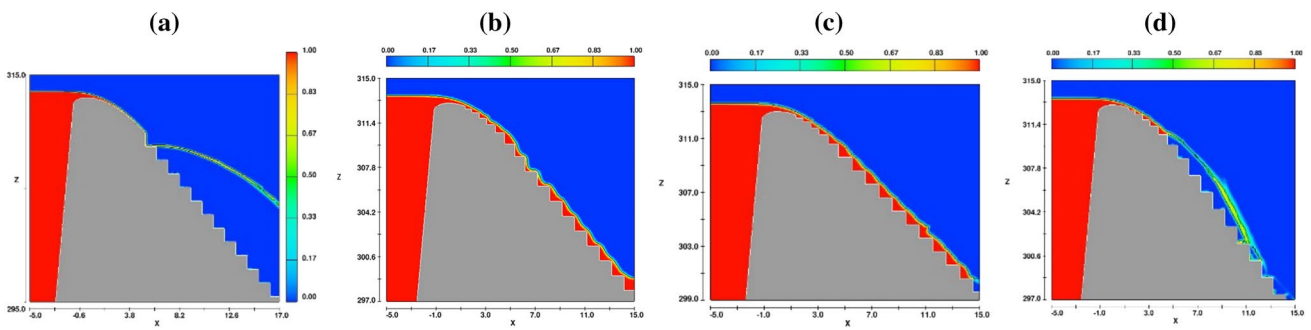
**Fig. 5** The inception point of aeration on the spillway in the primary and modified models at discharges of 200, 400 and 500 m<sup>3</sup>/s



**Fig. 6** The flow condition in the discharge of 100 m<sup>3</sup>/s and in the four models of: **a** primary, **b** modified, **c** milder slope and **d** steeper slope



**Fig. 7** The flow condition in the discharge of 70 m<sup>3</sup>/s and in the four models of: **a** primary, **b** modified, **c** milder slope and **d** steeper slope



**Fig. 8** The flow condition in the discharge of 40 m<sup>3</sup>/s and in the four models of: **a** primary, **b** modified, **c** milder slope and **d** steeper slope

discharges were stopped. In the “Steeper Slope” model that has a slope of  $55^\circ$ , irregular condition with jumps was observed for all the discharges. Therefore, it is necessary to pay special attention to the chute slope in designing such spillways.

## 4 Conclusion

The present research aims to study the effect of CEDEX profile on some hydraulic parameters and also examine the efficiency of CEDEX profile in stopping the flow jumps for low discharges with various chute slopes. For this purpose, numerical modeling was carried out using FLOW-3D which is a CFD-based software. The results showed an acceptable similarity with laboratory results. The studied model was the spillway and the chute of Javeh Dam, the laboratory model of which was built both with CEDEX profile and without it in Iran Water Research Institute (IWRI). In the model without CEDEX profile and in low discharges, the flow jumped over the initial steps of the spillway. Decreasing the discharge increased the length of the jumps. CEDEX profile was installed in the area between the ogee spillway and the stepped chute in order to solve the above problem.

Results of the numerical modeling showed that installing CEDEX profile between the spillway and the stepped chute, in the initial parts of the spillway, decreases the flow velocity and the cavitation risk, and from a certain point, the amounts of those parameters match. Also, CEDEX profile can move the inception point of aeration downstream.

Two other models with slopes of  $45^\circ$  and  $55^\circ$  were added to the laboratory models (with a slope of  $50^\circ$ ) in order to examine the efficiency of CEDEX profile against different slopes. In low discharges, CEDEX profile was able to stop flow jumps in slopes of  $45^\circ$  and  $50^\circ$  but was inefficient against a slope of  $55^\circ$  and the flow still had irregular jumps.

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